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Translation

AIR DEFENSE OFFICER'S HANDBOOK

Ed. by

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AIR DEFENSE OFFICER'S HANDBOOK

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[Brief Annotation]

The handbook describes enemy air attack weapons, it outlines the tasks and structure of the Air Defense Troops, it gives a brief history of their development and examines the design principles of the weapons systems and the combat employment of the branches of air defense troops.

The handbook is intended for officers concerned with air defense questions.

FOREWORD

The Air Defense Troops securely guard the frontiers of our motherland.

This is ensured by constant high combat readiness, by stability in defending the protected installations, by the mastery of the combat equipment and by the ability to hit the air enemy on the first round (launch) and in the first attack.

The personnel of the Air Defense Troops are hard at work carrying out the party's plans and are always ready to carry out the combat mission.

A modern air defense system includes diverse weapons and military equipment which have high combat capabilities. The realization of these capabilities in the course of combat operations demands from the personnel profound knowledge of the air attack weapons and the methods of their employment, the operating principles of the weapons systems and the bases for the tactics of the branches of air defense troops.

In the practical activities of Air Defense Troop officers, the need arises to analyze and quantitatively evaluate the capabilities of weaponry to destroy air attack weapons in terms of certain conditions of a combat situation as well as the obtaining of reference data on the operating principles of the weapons systems and the particular features of their combat employment. This necessitates the turning to various sources of information which in a number of instances creates certain difficulties.

The present handbook provides a generalized description of military-technical and operational-tactical questions related to air defense as based upon materials found in the unclassified Soviet and foreign press.

The handbook has been worked out under the editorship of Doctor of Military Sciences, Prof G. V. Zimin by the group of authors including:

G. V. Zimin (Foreword, 1.1, 1.2, 2.1, 2.2, 2.3), F. T. Buturlin and Ya. I. Nizdran' (5.1, 5.2), S. K. Burmistrov (3.1, 3.2, 8.2), V. P. Demidov (3.3, 3.4, 6.1, 8.1), A. S. Mal'gin (7.1, 7.2), F. K. Neupokoyev (6.2, 6.3, 6.4) and O. Ye. Orlov (4.1, 4.2).

The handbook has been prepared for publishing by S. K. Burmistrov.

1. AIR DEFENSE

1.1. Tasks and Structure of Air Defense

1.1.1. Tasks and Structure of Air Defense Troops

The Air Defense Troops are a service of the USSR Armed Forces. They have the mission of protecting major administrative-political centers, industrial installations, Armed Forces groupings as well as other major objectives comprising the basis of the state's economic and military might against enemy air strikes. The Air Defense Troops carry out their missions independently and in cooperation with the other Armed Services by destroying enemy air attack weapons (SVN) in the air.

In organizational terms the Air Defense Troops consist of air defense field forces and formations and these in turn are comprised of units and subunits of branches of troops including the antiaircraft missile troops (ZRV), the air defense aviation, the radar troops (RTV) as well as the units and subunits of special troops, the rear units and facilities.

The antiaircraft missile troops (ZRV) are one of the basic branches of troops. In cooperation with the fighter aviation, they are capable of preventing enemy air strikes against the nation's major installations as well as troop groupings.

They are armed with antiaircraft missile complexes (ZRK) of varying purpose and range.

The antiaircraft missile troops possess great fire power and high accuracy in hitting the SVN over the entire range of their flight altitudes and speeds, at great distances away from the defended installations at any time of the day and in any weather as well as under conditions of radio jamming.

In organizational terms today's ZRV consist of units having fire and technical subunits as well as control (equipped with automatic control systems) and service subunits. In the system of defending the nation's installations ZRV groupings can be created consisting of several antiaircraft missile units.

The air defense aviation is a branch of the Air Defense Troops with the mission of covering important sectors and installations against an airborne enemy. It includes fighter aviation (IA) units. The IA is based on units armed with missile-carrying fighters capable of destroying the SVN both at the distant approaches to the protected installations as well as in close combat. The supersonic all-weather fighter-interceptors with powerful missile weapons can hit enemy aircraft and cruise missiles (KR) in a broad range of altitudes under any weather conditions and at any time of the day. The presence of long-range missile-carrying interceptors in the aviation ensures the destruction of aircraft carrying air-to-ground guided missiles before they reach the launch line.

The radar troops (RTV) as a branch of the Air Defense Troops have the mission of continuously scanning the air space, conducting radar reconnaissance of the enemy SVN in the air and providing information on them needed by the command for taking decisions and supporting the combat operations of the antiaircraft missile troops [and] air defense aviation.

The radar troops are equipped with various modern radars making it possible during any time of the year or day, independently of weather conditions and interference, to detect the SVN at all altitudes, to identify and determine their precise coordinates as well as provide target designation for the antiaircraft missile troops and fighter guidance.

The rear units and facilities are designed to carry out the rear support missions for the combat operations of the Air Defense Troops.

1.1.2. Tasks and Structure of the Field and Naval Air Defense

The field [organic] air defense is a component part of combined-arms combat and operation. It is organized by the combined-arms commanders under any situation for the purposes of attacking the enemy in the air and repelling strikes against troops and other installations.

The successful carrying out of air defense, particularly the destruction of aircraft carrying cruise missiles in flight, helps to win superiority over the air enemy, to win air supremacy as well as maintain high troop morale.

The aim of air defense is achieved by the carrying out of a number of tasks, the basic ones being: the conducting of reconnaissance for the air enemy and the warning of troops of this; the providing of a cover against air strikes and against air reconnaissance of the troop groupings and rear installations; destroying enemy airborne parties in flight; participation jointly with the Air Defense Troops in repelling the first massed air enemy strike.

In addition, the missions of field air defense can also be: supporting the overflight of one's own airborne parties, long-range and naval aviation; the air blockading of surrounded enemy groupings and so forth.

The field air defense is a branch of troops which includes antiaircraft missile, antiaircraft artillery and radar units and subunits.

Troop air defense is organized as a unified system in accord with the overall concept of the combined-arms commander and includes the following elements: reconnaissance of the air enemy and warning of the troops, the firing of antiaircraft weapons, fighter air cover and the control system.

The field air defense system is based upon the firing of the antiaircraft missile and antiaircraft artillery units and subunits.

The basic principles in the organization and conduct of modern field air defense are considered to be the following: constant readiness to repel air enemy strikes, the concentrating of the basic air defense resources on covering the main troop groupings and major rear installations, close cooperation of the air defense resources between themselves and with the covered troops, continuity of combat operations, maneuverability (mobility), high efficiency, stability and impassability, continuous and flexible centralization of control.

Air defense of the troops and rear installations is carried out by the field air defenses and fighter aviation in cooperation with the Air Defense Troops.

Naval Air Defense is a most important type of combat support for fleet operations. This is organized in the aim of repelling enemy air strikes against the naval forces and its shore facilities.

Proceeding from an assessment of the naval forces as air defense objects, two basic tasks of naval air defense have been established: covering the naval bases, the points where ships have been dispersed and the naval shore facilities; covering the naval forces at sea.

The successful carrying out of the missions of naval air defense is possible only with the integrated use of the navy's own air defense resources, the air defense troops and the air defense resources of the military districts (fronts).

Air defenses for the naval bases, the ship dispersion points and the shore installations as well as the ships in coastal areas are provided by the Air Defense Troops in cooperation with the air defense resources of the navy and military districts (fronts).

The ship antiaircraft weapons are the basis of air defenses for naval forces at sea. The Air Defense Troops and the military districts (fronts) strengthen their defenses within the range of their air defense resources.

The basic missions of air defense in a naval theater of war are the following: reconnaissance of the air enemy and the warning of the naval forces and shore facilities of it; preventing the enemy from conducting air reconnaissance and aircraft mine laying; covering the naval forces at sea and in bases against air strikes.

In organizing air defenses for naval ships at sea, the principles are observed of concentrating the basic efforts of the air defense resources on covering the naval forces carrying out the main missions as well as in the most probable sectors of enemy air operations as well as the principle of constant combat readiness to repel enemy air strikes.

1.2. The State and Development Prospects of Air Defense

1.2.1. Historical Information

The birth of air defense. The rise and development of air defense (AD) go back to the period of World War I when aviation began to be widely employed for military purposes. In 1913 in France and then in 1914 in Russia and Germany, special antiaircraft cannons were developed to fire at airborne targets.

In the Russian Army field guns and naval cannons were adapted for this as well. The first battery for firing at aircraft with 75-mm naval cannons was organized in October 1914. In 1915, a special antiaircraft cannon was manufactured and the Russian Baltic Military Plant built the world's fighter, the RBVZ S-16. The air observation, warning and communications (VNOS) service was organized to detect enemy aviation, to observe its operations and to alert the air defense resources and the population of cities about an air danger.

Among the measures complementing AD were also: the creation of shelters, the organizing of fire fighting, the carrying out of camouflaging and blackouts in cities, the setting up of dummy installations and warning the population of an air danger.

During the years of World War I, for the first time in military practice the principles were set down for the air defense of the nation's installations and the troops; the procedures and methods of combating an air enemy were worked out.

AD during the years of the Civil War. One of the first AD subunits of the young republic was the "Steel Antiaircraft Artillery Battalion (Armored Train)" built in Petrograd at the Putilov Plant. By the spring of 1918, the Red Army had around 200 antiaircraft batteries and 12 fighter detachments.

The organized subunits were employed for the AD of Petrograd, Moscow, Tula, Astrakhan', Baku, Odessa as well as the troops on the fronts.

In the period of 1918-1920, the tactics of the AD troops were further worked out, the principles for the organization of AD in the major points of the nation were worked out and the elements of the operational art of the AD troops were born.

The development of AD during the period from 1921 through 1941. In 1924, in Leningrad, from the individual battalions the first Antiaircraft Artillery (ZA) Regiment of the RKKA [Worker-Peasant Red Army] was organized, and in 1927, the first Antiaircraft Artillery Brigade. In the 1920's, the organizational structure of the nation's AD was based on the AD posts which were organized as AD sectors on the territory of the border military districts, the commanders of which were responsible for the AD in the borders of the district. During this same period a network of VNOS posts was organized in the border zone and around the major centers of the nation.

In 1927, the Sixth Section was organized at the RKKA staff and in April 1930, a headquarters in charge of AD questions. In April 1932, this was put directly under the People's Commissariat for Military and Naval Affairs. The RKKA AD Headquarters was entrusted with practical leadership of the AD service for the entire territory of the nation as well as for unifying the activities of all the civilian departments, institutions and public organizations in this area.

From 1 July 1934, the RKKA AD Headquarters was headed by one of the outstanding military leaders, Arm Cmdr. 1st Rank S. S. Kamenev, and in September 1936 this position was assumed by the Arm Cmdr. 2d Rank A. I. Sedyakin.

Other important measures were also carried out to strengthen AD. In the military districts, AD headquarters were organized and these were headed by the AD chiefs of the military districts who were directly under the district commanders, and in special terms under the chief of the RKKA AD.

In the 1930's, the AD troops were provided with new military equipment. During these years our IA was provided with modern Soviet-produced aircraft such as the I-15, I-16 and I-153, and from 1940 with the more advanced types such as the Yak-1 and MiG-3 and in 1941, the LaGG-3. Antiaircraft artillery received new models of antiaircraft guns such as the 1931 and 1938 76.2-mm models, the 1939 85-mm and automatic 37-mm, the PUAZO-2 antiaircraft fire control equipment in 1935 and the PUAZO-3 in 1939. The AD Troops were equipped with Soviet-produced searchlights, sound locaters and barrage balloons. During this same period, Soviet industry developed production of optical range-finders (the DYa type). In 1939, the VNOS service received the first Soviet-produced surveillance radars, the RUS-1, and in 1940, the RUS-2. From 1934 through 1939, the number of ZA increased by almost 3-fold and the IA by 1.5-fold.

There was also an improvement in the organizational forms and structure of AD troop control. In 1937, for the AD of the important industrial and administrative centers of the nation (Moscow, Leningrad and Baku), AD corps were organized while there were AD divisions and separate brigades for defending other important cities and areas (Kiev, Minsk, Odessa, Batumi, Khabarovsk and others).

These formations included all the branches of the AD troops, with the exception of the fighter aviation which continued to remain under the air force's commanders of the military districts. However, the IA was based in accord with the AD missions and participated in all the operational exercises of the AD troops. With the start of a war in operational terms the IA was to be put under the commanders of the AD formations.

In February 1941, the entire border territory of the nation was divided into AD zones (according to the number of military districts) and these zones were headed by deputy commanders for AD of the military districts. At the center the Red Army AD Main Directorate (GU) was organized. It was entrusted with the planning of the operational employment of the AD Troops, keeping the records of their weapons and directing combat training. From 14 June 1941, the AD GU was headed by Col Gen and subsequently Chief Mar Art N. N. Voronov. Maj Gen N. N. Nagornyy became the chief of staff of the AD GU from the moment of its organization. The measures carried out significantly strengthened Soviet AD.

AD during the years of the Great Patriotic War of 1941-1945. The start of the Great Patriotic War caught the nation's AD in a period of its rearming. The Yak-1 and MiG-3 which Soviet aviation was receiving possessed better performance than the Nazi aircraft but there were not enough of them in the troops. The ZA still had few of the new 37-mm automatic antiaircraft guns and 85-mm guns.

At the beginning of July 1941, the GKO [State Defense Committee] adopted a number of measures to strengthen the cover for Moscow and Leningrad, the Donets Basin, the Moscow, Yaroslavl' and Gor'kiy industrial centers as well as for organizing the defenses of certain strategic bridges across the Volga. For this purpose significant air, antiaircraft artillery, machine gun and searchlight units were formed. Subsequently AD was organized for the industrial centers of the Volga and the Volga Riverway.

The Moscow AD was a classic example of protecting a large center against air attack. No capital of the capitalist states had such strong AD during the entire World War II. This was provided by the I AD Corps under the command of Maj Gen Art D. A. Zhuravlev and the VI Fighter Air Corps under the command of Col I. D. Klimov and which in operational terms was subordinate to the I Corps.

By the start of the German air raids (22 July 1941), these formations had over 600 fighters, more than 1,000 antiaircraft medium- and small-caliber guns, around 350 antiaircraft machine guns, over, over 600 antiaircraft searchlights, 124 barrage balloon posts and 612 VNOS posts. The presence of such extensive resources and the able organization of their control broke the enemy's attempts to make mass air raids against the Soviet capital.

The Leningrad AD was also strong and this was provided by the II AD Corps and the subordinate VII Fighter Air Corps.

On 9 November 1941, the GKO approved a decision according to which the position of commander of the national AD Troops was introduced, while the national AD Staff and other headquarters bodies were organized. Maj Gen M. S. Gromadin was appointed the first commander of the national AD Troops and deputy NKO for air defense.

For the purposes of better cooperation with the AD resources, in January 1942, fighter aviation which had been assigned to cover installations was put completely under the command of the national AD. As a result, centralized troop control was ensured on the operational and tactical levels.

In line with the significant increase in the size of the AD Troops in April 1942, a partial reorganization was carried out in the structure of the national AD Troops. The Moscow AD Front was formed with AD armies being created in Leningrad and somewhat later in Baku as well. The first operational formations of the AD Troops appeared.

The changeover of the Soviet Army to broad offensive operations substantially altered the conditions for the conduct of combat operations by the AD Troops.

One of the important tasks of the national AD Troops during this period was the defense of rail lines and water barriers, the airfields of the frontal and long-range aviation, trains and river vessels underway as well as establishing an air blockade over the surrounded enemy groupings (Stalingrad, Korsun-Shevchenkovskiy and others).

The necessity of ensuring close cooperation between the AD resources of the various Armed Services in combating the air enemy in the zone along the frontline required a further improvement in the AD structure.

In June 1943, the Directorate for the Commander of the National AD Troops was broken up and in its place two AD fronts were organized: the Western and Eastern. The AD troops defending Moscow were reorganized into the Separate Moscow AD Army. In March-April 1944, the Western and Eastern fronts as well as the Transcaucasian AD Zone were reorganized into the Northern, Southern and Transcaucasian AD fronts.

In line with the further successful offensive operations by the Soviet Army, for convenience of control, in December 1944, the formations which were defending installations deep in the nation's rear were made into a new, Central AD Front headquartered in Moscow while the Northern and Southern were changed into the Western and Southwestern AD fronts.

In the Far East, in March 1945, in accord with the GKO decree, on the basis of the Far Eastern and Transbaykal AD zones as well as the AD resources which had been regrouped from the European USSR, three AD armies were organized: the Maritime, Amur and Transbaykal and these were parts of the fronts.

In the course of the Great Patriotic War the AD Troops honorably carried out the missions entrusted to them by the Communist Party and Soviet government. The chief result of their combat activities was that they protected large industrial and administrative centers of the nation, thousands of population points and troop groupings against destruction and annihilation by Nazi aviation and thereby significantly contributed to the rapid growth of the nation's military-economic potential. During the wartime, the AD Troops destroyed more than 7,300 aircraft and much other enemy military equipment, thereby making a major contribution to the common cause of defeating the Nazi invaders.

In the course of the war the antiaircraft artillery and fire aviation developed organizationally as branches of the AD Troops. The VNOS service, the searchlight units and barrage balloon units underwent great development. Operational field forces, operational-tactical formations and formations and units of the branches of troops were created.

More than 80,000 soldiers, sergeants, officers and generals of the AD Troops received orders and medals, 92 men received the high title of Hero of the Soviet Union while the air squadron commander, Capt A. T. Karpov became a winner of two Gold Star Medals. For successful combat operations, 11 formations and units of the AD Troops received honorary names and 29 became guards units.

The development of AD in the postwar period. After the end of World War II, the United States and Great Britain maintained enormous air forces. The reactionary circles of the imperialist states began to carry out a hostile policy vis-a-vis the Soviet Union and the other nations of the socialist commonwealth.

Under these conditions, the CPSU Central Committee and the Soviet government, in adopting measures to further strengthen our nation's defense capability, devoted great attention to improving its air defenses. By 1952, the AD fighter aviation had been reequipped with jet fighters, a significant portion of which had radar sights. Antiaircraft artillery had received new antiaircraft artillery complexes consisting of 57-, 100- and 130-mm antiaircraft guns, a gun laying radar and antiaircraft fire control equipment. The VNOS troops received the P-3 and P-3a radars.

From 1952, the AD Troops began to receive antiaircraft missile equipment with missiles of varying range and purpose. A new branch of troops was established in them, the AD antiaircraft missile troops (ZRV). The air defense fighter aviation began to receive supersonic fighter-interceptors with air-to-surface missiles. The VNOS troops in mass amounts began to receive new fighter surveillance and guidance radars. A new branch of the AD troops arose, the AD radar troops (RTV) which were officially named this in 1955. Diverse automated control systems [ASU] and other equipment began to be received in mass amounts.

The increased demands made upon AD and the reequipping of the units with new weapons required a further improvement in the organizational structure of the AD troops and their control system. In February 1946, the position of commander of the AD troops was introduced and he was directly subordinate to the artillery commander of the Soviet Armed Forces. Col Gen M. S. Gromadin was appointed commander of the AD Troops while Col Gen N. N. Nagornyy was chief of staff.

In 1948, for the first time the regulations stated that the AD Troops, along with the Ground Troops, the Air Forces and the Navy were to be an Armed Service. This notion stemmed completely from the experience of the Great Patriotic War and reflected the objective pattern of the increased role played by the AD Troops in the postwar period with the advance in the SVN and the methods of their employment. During the same year, the AD Troops were made no longer subordinate to the artillery commander of the USSR Armed Forces. Mar SU L. A. Govorov became the commander of the AD Troops, and from 1952, Col Gen N. N. Nagornyy. In May 1954, the position of commander-in-chief of the AD Troops was established. Mar SU L. A. Govorov was appointed the first commander-in-chief in May 1954. Subsequently the commanders-in-chief were: Mar SU S. S. Viryuzov (1955-1962), Mar Avn V. A. Sudets (1962-1966) and Mar SU P. F. Batitskiy (1966-1978). In June 1978, Mar Avn A. I. Koldunov was appointed commander-in-chief of the AD Troops.

2. ENEMY AIR-SPACE ATTACK RESOURCES*

2.1. Classification of Resources

2.1.1. General Description of Air-Space Weapons and the Tasks Carried Out By Them

The military-political leadership of the basic imperialist states have assigned a decisive role to the air-space offensive weapons in achieving the goals of a war.

The air-space offensive weapons include the field forces, formations and units armed with air-space offensive weapons [SURN].

The SURN include ballistic missiles, aircraft, spacecraft, dirigibles and balloons.

The field forces, formations and units armed with the SURN include the air forces, navies and ground troops.

The most important components in the U.S. Armed Forces are the strategic offensive forces and the general-purpose forces.

The strategic offensive forces include units of intercontinental ballistic missiles (ICBM), the strategic aviation forces, formations and units and the formations of atomic nuclear-powered submarines.

The ICBM and strategic bombers are part of the U.S. Strategic Air Command. At present, there are strategic offensive forces in the United States, England and France.

The general-purpose forces include the field forces, formations and units of the air force tactical aviation, naval aviation, army aviation as well as the perational-tactical missile units and formations.

The basic missions of the SURN can include: undermining military-economic potential; disrupting the system of state and military control; winning air supremacy; isolating an area of combat operations; close air support for the ground troops and naval forces.

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* From materials of the foreign press.

The undermining of military-economic potential can be carried out by attacking the major military and industrial installations.

The disrupting of the system of state and military control can be achieved by attacking military-political centers, control centers and communications.

The winning of air supremacy is carried out by destroying aviation on airfields and in the air as well as neutralizing the air defense system.

The isolating of an area of combat operations is carried out for the purpose of preventing the bringing up of reserves, obstructing supply and impeding troop maneuvers by attacking rail junctions, bridges, troops and other objectives.

Close air support consists in continuous and effective firing for effect against the enemy from the air in the course of combat operations directly on the battlefield.

2.1.2. Classification of Air-Space Attack Weapons

The SURN include: land- and sea-based ballistic missiles, aerodynamic vehicles, spacecraft, dirigibles and balloons.

Ballistic missiles, depending upon range, are divided into close-range missiles (up to 1,000 km), medium-range (up to 5,000 km) and long-range (over 5,000 km). Missiles with a range over 5,000 km are termed intercontinental.

In accord with combat employment, ballistic missiles are divided into tactical, operational-tactical and strategic.

Strategic missiles include the medium- and long-range missiles.

Ballistic missiles can be land and sea based. The land-based missiles are launched from silos or mobile launchers while the sea-based ones are launched from nuclear missile submarines.

Land-based intercontinental ballistic missiles are launched from launching silos. These are designed to hit major administrative-industrial installations, missile launching positions and other objectives. Such missiles have long ranges (up to 12,000 km), great speed (up to 7.5 km per second) and altitude (1,000 km and more).

The ICBM have high combat readiness and can attack at any time of the year or day regardless of the weather conditions. For example, modern ICBM include the Minuteman-2, Minuteman-3 and Titan-2 missiles.

The sea-based intercontinental ballistic missiles with a range of 8,000-12,000 km are launched from nuclear missile submarines from a depth of around 30 m at the moment the sub reaches the launch position. The missile is ejected from the launch tube by compressed air and at a height of 20-30 m above the water surface the first-stage engine is fired. On board, inertial systems are employed to control the flight of such missiles. These ICBM are designed to hit various military-industrial installations. The Trident-1 and Trident-2 are advanced sea-based ICBM.

The land-based medium-range ballistic missiles are launched from launching silos and are controlled in flight by inertial systems. These are designed to hit various military-industrial installations.

The sea-based medium-range ballistic missiles (MRBM) are capable of hittingtargets up to a distance of 5,000 km. These are also launched from nuclear missile subs from a depth of 30 m. Each sub of the existing classes carries 16 missiles each. The MRBM are designed mainly to hit major administrative-industrial installations, forts, bases and other objectives. The Polaris A-3, Poseidon C-3, the M-2 and M-20 are among the modern MRBM.

The operational-tactical ballistic missiles are capable of hitting targets to a distance of hundreds of kilometers. The missiles are launched from surface mobile launchers and this makes it possible to maneuver them in the field.

These are used for close troop support and for hitting targets in the operational-tactical depth which are beyond the reach of aviation due to strong air defenses.

Among the present-day operational-tactical missiles are such missiles as the Lance and Pershing. Descriptions of the ballistic missiles are given in Table 2.1.

2.2. Aerodynamic Attack Weapons

The aerodynamic attack weapons include strategic bombers, tactical fighters, carrier-launched ground attack planes, unmanned aircraft, and army aviation airplanes and helicopters.

Heavy strategic bombers possess a great range, up to 18,000 km, and are capable of operating at high, medium and low altitudes. They carry a bombload of up to 30 tons and more as well as various weapons for attacking installations and lements of the AD system, reconnaissance equipment, as well as ECM [electronic countermeasures] equipment for neutralizing various radio electronic devices.

The heavy strategic bombers over the next few years will remain one of the basic strategic means of attack.

The further modernization of strategic combers will be aimed at increasing combat effectiveness by arming them with new SRAAM missiles and subsequently the ALCM and ASALM, as well as increasing the capability of the ECM equipment.

These aircraft will basically be employed in a nuclear war, however considering the experience of combat operations in Vietnam, the partial use of strategic bombers in limited wars is not excluded. These aircraft include the various modifications of the B-52 and the new B-1 aircraft which is being developed.

Medium strategic bombers are used for carrying out missions in nuclear and limited wars. Considering their range, they can hit objectives at a distance of 2,000-4,000 km. For the purposes of increasing the bomber flight range, mid-air fueling can be carried out. The payload versions of such aircraft can vary. They can carry nuclear and conventional bombs, air-to-ground missiles and equipment for setting up active and passive jamming. The navigation equipment makes it possible for the bombers to fly at low altitudes.

Table 2.1

Name	Launch Weight, tons	Warhead Capacity, megatons	Range, km	Control System	Propulsion Unit	Location of Launcher
Titan-2 LGM-25C	150	Single 10	to 15,000	inertial	Two-stage LPRE	Silo
Minuteman-2 LGM-30F	32	Single 1-2	11,000	"	Three-stage SPRE	"
Minuteman-3 LGM-30	35	Multiple--MIRV 3 x 0.2	13,000	"	Three-stage SPRE	"
Polaris A-3	16	Multiple--MIRV 3 x 0.1	4,600	"	Two-stage SPRE	Sub
Poseidon C-3	29	Multiple--MIRV 10 x 0.05	4,600	"	Two-stage SPRE	"
Trident-1	32	Multiple--MIRV 8 x 0.1	8,000	"	Three-stage SPRE	"
Trident-2	57	Multiple--MIRV 14 x 0.15	12,000	"	Three-stage SPRE	"
M-2	20	Single 0.5	3,000	"	Two-stage SPRE	same
M-20	--	Single 1.0	3,000	"	--	"
S-2	32	Single 0.15	3,000	"	Two-stage	Silo

LPRE--Liquid propellent rocket engine; SPRE--Solid propellent rocket engine.

The medium strategic bombers include: the comparatively new FB-111 aircraft with a variable wing configuration and capable of operating at low altitudes at supersonic speed; the supersonic Mirage IVA bomber and the subsonic Vulcan B-2 bomber.

The light (tactical) bombers are employed for attacking objectives in the operational-tactical depth and for air support for the ground troops.

Such aircraft are the English Buccaneer, the French Vautour of which there is a limited number in service.

The weaponry of the light bombers consists of conventional and nuclear bombs, guided and unguided missiles as well as ECM and reconnaissance equipment.

In line with the increased combat capability of the tactical fighters (the increased bombload and the introduction of air-to-surface missiles), the role and significance of the light bombers have declined. For this reason new types of light bombers are not being developed and the already existing ones are gradually being taken out of service.

Tactical fighters are used for carrying out the following missions: destroying nuclear weapons and their delivery systems, aircraft at airfields and air defense weapons; striking military-industrial objectives; close air support for the ground troops; conducting tactical reconnaissance; troop air defense.

Modern tactical fighters possess a range from 2,700 to 6,100 km, speeds from 1,000 to 2,500 km per hour, and flying altitudes from 60 to 18,000 m and can carry a bombload from 2 to 9 tons.

The basic U.S. Air Force tactical fighters are the F-4, F-15 and F-111A. The Royal Air Force has the multipurpose Harrier and Jaguar fighters while the French Air Force has the Mirage IIIE, Mirage 5F and Jaguar fighters. Among the advanced tactical fighters are the F-16, the Tornado and Mirage 2000.

Tactical fighters can carry conventional and nuclear bombs, air-to-ground tactical missiles, air-to-air missiles and ECM equipment. For example, in operating against ground targets, different versions of a combat load are possible for the F-4 aircraft: 18 340-kg bombs or 11 450-kg bombs; 4 Bullpup missiles or containers with unguided missiles.

Bombing can be carried out from various altitudes.

From the experience of the combat operations in Vietnam, the U.S. tactical fighters in attacking objectives, carried out missile- and fighter-avoidance maneuvers for the purpose of evading the AD weapons. In this war the tactical fighters were used as part of the assault and various support groups.

Modern tactical fighters have a number of systems (an integrated weapons control system, an integrated navigation-bombing system, and a terrain following system) which make it possible for them to reach the objective, make the attack and return to the airfield.

Carrier-based ground attack aircraft are part of the carrier aviation. These are used for operating from multipurpose (attack) aircraft carriers and for attacking land and sea targets. Depending upon the type of carrier, it can have around 100 different types of aircraft, including 50-60 carrier-based aircraft.

Modern carrier-based attack aircraft can operate at ranges up to 5,000 km, fly at speeds from 760 to 2,200 km per hour at altitudes from 60 to 14,000 m and carry a bombload up to 7 tons.

At present, the U.S. carrier aviation has heavy attack and reconnaissance aircraft the RA-5C, the A-4, A-6 and A-7 attack planes. They can all carry conventional and nuclear bombs, air-to-surface and air-to-air missiles, EMC and reconnaissance equipment.

The variations for the combat load of the carrier-based attack planes can differ, for example, the A-6 aircraft can carry two-three Bullpup or Standard ARM missiles, unguided missiles and three bombs weighing 907 kg each.

The A-6, A-7 and A-4 carrier-based attack planes were widely used in combat operations in Vietnam both for attacking targets as well as part of support groups.

Reconnaissance aircraft, as a rule, are reconnaissance versions of bombers, fighters, carrier-based attack planes and transports which have special equipment for conducting reconnaissance. In addition, there are also special reconnaissance aircraft, for example, in the U.S. Air Force the SR-71 and U-2 which are designed to conduct strategic reconnaissance.

The basic U.S. aircraft for tactical reconnaissance is the RF-4 which is employed for photographic and electric reconnaissance as well as for radar reconnaissance using the side-viewing radar.

Carrier-based aircraft includes the RA-5C reconnaissance aircraft and the Hawkeye and Tracer long-range radar surveillance aircraft; these are used for conducting reconnaissance in the interests of carrier task forces.

Unmanned aircraft are used for carrying out the following missions: for jamming the radars of the enemy air defense system; for conducting air reconnaissance (the BQM-34A, the 147J, H); for attacking targets and for complicating the air situation.

Unmanned aircraft can be launched from other aircraft and from ground launchers. These are controlled by a program or by an operator from a ground or airborne post.

In recent years abroad great attention has been given to developing small-sized remote controlled devices for conducting reconnaissance and neutralizing the radars.

Army aviation is employed for carrying out the following missions: close air support for the ground troops on the battlefield; ferrying ground troops to combat areas and dropping tactical airborne parties; logistical support and the evacuation of sick and wounded; conducting air reconnaissance.

In addition to the designated missions, helicopters are employed as flying command posts.

Army aviation consists of army aircraft and helicopter units and subunits.

The U.S. Army employs the following classes of helicopters:

The general-purpose (multipurpose) helicopters, the basic type of which is the UH-1D Iroquois helicopter;

The CH-54A, the CH-47B and CH-47C troop carrier helicopters;

The Iroquois and Hugh Cobra fire support helicopters;

The Caius and Caiova reconnaissance helicopters.

Army aviation also employs the Bird Dog and RU-21 airplanes.

The tactical and technical characteristics of basic military aircraft are given in Table 2.2.

2.3. Air-to-Surface and Air-to-Air Guided Missiles

The air-to-surface guided missiles are divided into strategic and tactical missiles.

Air-to-Surface Missiles

Air-to-surface strategic missiles include the SRAAM missiles which are in service on the strategic bombers and the ALCM, ASALM and SLCM which are being developed. These are being designed to attack targets at ranges from 200 to 2,600 km without entering the zone of active AD weapons. In addition, the ASALM missile can be employed for hitting airborne targets.

The air-to-surface strategic missiles possess great accuracy in hitting the targets and the capacity to be retargeted to other objectives in the course of the aircraft's flight. They significantly increase the capabilities of strategic aviation in breaking through the AD system.

The SRAAM missile was put into service in 1972. It is employed on the B-52G and H bombers to which can be suspended up to 20 SRAAM, as well as the FB-111 which is capable of carrying up to 6 SRAAM. The SRAAM missiles can be launched from the B-52 in various directions in relation to the aircraft's heading.

The ALCM missile has been developed as a subsonic (M = 0.5-0.7) cruise missile capable of flying at low altitudes (up to 60 m). It has a small effective reflective surface.

The ASALM missile is being developed as a supersonic (M = 4.5 at great altitudes) capable of flying in a broad range of altitudes from low to high, including with terrain following.

Table 2.2

Name	Crew	Maximum speed, km/hour / at altitude, m	Service ceiling, m	Range, km	Weapons		
					Cannons number--caliber, mm	Missiles	Bombload max., kg
B-52	6	$\frac{1{,}020}{6{,}300}$	over 15,000	18,000	4--20 on B-52H, 1--20, 6 barrel	to 20 SRAAM and ALCM GM [guided missile]	30,000
FB-111	2	$\frac{2{,}330}{12{,}000}$	approx. 20,000	6,600	--	to 6 SRAAM GM	16,000
B-1A	4	$\frac{2{,}330}{15{,}000}$	over 15,000	11,000	--	to 24 SRAAM, ALCM and ASALM	35,000
F-4	2	$\frac{2{,}330}{12{,}000}$	approx. 19,000	4,020	1--20, 6 barrel	4 Bullpup or Shrike, or 3 Sparrow	about 7,000
F-111	2	$\frac{2{,}655}{12{,}000}$	over 18,000	6,100	same	4-8 air-to-ground or air-to-air GM	13,600
F-15	1	$\frac{2{,}655}{12{,}000}$	to 21,000	4,800 (ferrying)	same	4-6 air-to-air or air-to-ground GM	5,500
F-16	1	$\frac{2{,}300}{11{,}000}$	over 18,000	approx. 3,700	same	6 Maverick GM or air-to-air GM	over 3,600
F-14	2	$\frac{2{,}500}{12{,}000}$	21,000	3,500	same	6 Phoenix	6,500
F-18	1	$\frac{2{,}100}{12{,}000}$	18,000	2,800 (ferrying)	1--20	4-6 air-to-air or air-to-ground GM	5,900
A-7A	1	$\frac{9{,}400}{12{,}000}$	12,000	5,400	1--20	4 Bullpup and 2 Shrike	6,800

Table 2.2 continued

Name	Crew	Maximum speed, km/hour at altitude, m	Service ceiling, m	Range, km	Weapons		
					Cannons number--caliber, mm	Missiles	Bombload max., kg
A-10A	1	≈ 800 1,525	7,620	approx. 4,560 (ferrying)	1--30	6 Maverick GM	7,250
Tornado	2	2,100 12,000	15,000	4,800 (ferrying)	2--27	air-to-air and air-to-ground GM	5,000
Jaguar	1	1,820 10,000	15,000	4,500 (ferrying)	2--30	2 Martel GM	4,500

The SLCM missile is being developed by the command of the U.S. Navy for launching from subs and surface vessels and possibly from aircraft and ground launchers. In its tactical and technical characteristics it is analogous to the ALCM missile.

The tactical air-to-surface missiles include the Bullpup, Maverick, Condor as well as the tactical Jumbo and SLCM missiles under development. These missiles, with the exception of the SLCM and Jumbo, are in service in the tactical and carrier-based aviation.

The Bullpup missile put into service at the beginning of the 1960's has several modifications. It is used to hit small-sized well protected ground targets.

The Maverick missile was put into service in 1972 and was designed for hitting AD radio electronic equipment, tanks, airplanes at airfields and other ground targets. Its basic arriers are the F-4 and A-7 aircraft which can carry 3-6 such missiles.

The Maverick missile has an electronic-optical guidance system the TV camera of which is located in the nose portion of the body. The missile is guided to the target by the maneuvering of the aircraft in such a manner that the crosshairs of the optical sight line up on the target. Then the crosshairs of the TV camera are lined up with the target and the missile is launched after which it is possible to aim the following missile.

The Condor missile is designed for hitting surface and ground targets with previously known coordinates (launchers of the anti-aircraft missile troops, command posts, industrial buildings and shore facilities and naval vessels). These missiles are in service on carrier-based aircraft.

U.S. military specialists are studying the possibilities of increasing the range of the Condor missile.

The SLCM missile (tactical) is being developed by the U.S. Navy for use from surface vessels at a range up to 500 km and from submarines to a range of 260 km.

The ECM missiles include the Quail decoy missiles and the Shrike, Standard ARM and Martel AS-37 antiradar missiles.

The Quail missile was put into service in the U.S. Strategic Aviation in 1961 and was basically designed for use as a "decoy" which would divert the antiaircraft guided missiles launched to destroy the strategic bombers. The Quail missiles on the screens of ground radars simulate signals from overflying heavy bombers. The range of the Quail decoy missile is 370 km.

The Shrike missile is an antiradar missile. It was put into service in 1964 and over this time has undergone several modifications. The Shrike is basically designed to hit the radars of enemy AD troops and has replaceable homing heads. It was widely used by the tactical and carrier-based aviation in Vietnam.

The Standard ARM missile is a second-generation antiradar missile. The missile is guided as part of the onboard system which determines the coordinates for the radars of enemy AD troops prior to the launching of the missile.

According to information in the foreign press, the Harm missile which is being developed will have a greater speed and more effective guidance system with a low cost. The basic tactical and technical data for the air-to-surface missiles are given in Table 2.3.

Air-to-Air Missiles

Air-to-air missiles can have long, medium and short ranges.

The long-range air-to-air missiles includes the Phoenix AIM-54A.

The Phoenix missile is designed to hit subsonic and supersonic airborne targets over a broad range of altitudes using a conventional warhead, under any weather conditions, during the day and at night. The warhead damage area is 7.5 m. The missile has a combined homing head which includes a semiactive pulse-doppler radar system operating in the initial and middle legs of the flight and an active pulse-doppler radar homing system.

The medium-range air-to-air missiles include the Sparrow-3 and Matra R-530.

The Sparrow-3 AIM-7F missile is one of the basic medium-range missiles with a semiactive radar homing head. It is designed to hit airborne targets under any weather conditions. A hybrid guidance system is also being developed for this missile and it includes a radar and infrared homing head.

The Matra R-530 missile was developed for the Mirage III, Mirage F-1 and Jaguar aircraft. It is equipped with a semiactive radar homing head. However, the missile's homing system cannot isolate targets flying at a low altitude against the earth's background.

Table 2.3

Name	Launch wt., kg	Warhead type / Mass or power	Max., firing range, km	Altitude, m	Speed, M	Engine type	Guidance system	Carrier aircraft
SRAAM AGM-69A	1,000	Nuclear 200 kt	300		4	SPRE Two-pulse	Inertial	B-52 to 20 GM, FB-111 to 6 GM, B-1A to 24 GM
ALCM AGM-86	850	Nuclear 340 kt	2,600	60-7,000	0.55	TJE	Inertial and correlation Tercom	B-52 to 20 GM, B-1A to 24 GM
ASALM	1,000	Nuclear 200 kt	1,300 for surface targets; 500 for airborne targets		5	Combined rocket-ramjet	Inertial with radar homing head	B-52 to 20 GM, B-1A to 24 GM
SLCM	1,000	Nuclear 340 kt	2,600	60-7,000	0.55	TJE	Inertial and correlation Tercom	B-52, B-1 surface vessels, subs
Bullpup AGM-12C	810	Conv. 454 kg	16	Inclined trajectory	2.2	LPRE with plant refueling	Radio-command	A-6, F105, F-4C, F-4D, F-4E
Maverick AGM-65A	210	Conv. 60 kg	40	"	1	SPRE	TV homing	F-4, A-7D
Shrike AGM-45A	≈180	Conv. 60 kg	over 25	"	2	SPRE	Radar passive	A-4, A6, A-7, F-4, F-105, F-111
Condor	960	Conv. 286 kg	100	"	1	SPRE	TV command	A-6, A-7, F-4

Table 2.3 continued

Name	Launch wt., kg	Warhead type / Mass or power	Max., firing range, km	Altitude, m	Speed, M	Engine type	Guidance system	Carrier aircraft
Standard ARM AGM-78	635	Conv. / 100 kg	over 25	Inclined trajectory	2	SPRE	Radar passive	F-4, F-105, A-6
Martel Aj-168	530	Conv. / 150 kg	60	"	1	SPRE	"	Mirage IIIE, Jaguar

Close air combat missiles began to be received for use in the middle of the 1960's and then modernized considering the experience of the Vietnamese War. The Sidewinder and Magique are among these missiles.

The following demands were made upon the close air combat missiles: the possibility of launching from a minimum distance; autonomy of operation excluding the need for extended tracking of the target before launching and extended guidance of the fighter after launching; independence from the fighter systems, in particular the radar systems; an increased area of possible launches ensuring the carrying out of attacks from many positions; broadening the range of G-loads at the moment of launching and during flight to ensure the tactical freedom of the carrier and the possibility of hitting a maneuvering target.

The Sidewinder AIM-3 missile is in series production and has nine modifications. The last modification of the missile, the AIM-9, has a fragmentation-HE warhead with an active photoelectric proximity fuze and an infrared homing head which ensures the attack on the target at any angle of approach.

The basic carriers of this missile are the F-4, F-14, F-15 and F-16 fighters which can carry two-four missiles.

The aiming and launching of the missiles in close air combat are to be carried out using helmet-mounted sights.

The Magique R-550 missile is used by the French Air Force and is designed to hit highly maneuverable airborne targets in close air combat. The missile has an infrared homing head. For detonating the warhead it comes with an impact fuze and a radar fuze.

The basic tactical and technical data for the air-to-air guided missiles are given in Table 2.4.

2.3.1. Space Systems

The U.S. military political leadership has devoted great attention to developing and employing various-purpose earth satellites. At present,

Table 2.4

Name	Launch wt., kg	Warhead Type wt. kg	Range, km	Speed, M	Guidance System	Carrier Aircraft
Phoenix AIM-54A	380	Rod n.a.	to 130	2.5	Radar semiactive and active	F-14A
Sparrow AIM-7E	205	Rod 30	25	4	Radar semiactive	F-4, F-15, F-16
Sparrow AIM-7F	228	Rod 40	n.a.	4	Radar semiactive	F-4, F-14, F-15
Sidewinder AIM-9H	n.a.	Rod 10	n.a.	2.5	Infrared	F-4, F-14, F-15, F-16, F-18, A-7, A-10
Sidewinder AIM-9	84	Fragmentation-HE 15	n.a.	2.5	Infrared all-aspect	F-14, F-15, F-4
Super R-530	200	Fragmentation 30	35	4.5	Radar semiactive	Mirage III, Jaguar, Mirage F-1
R-530	195	Fragmentation or Rod 27	18	2.7	Infrared or semiactive radar	Mirage III, Jaguar, Mirage F-1
Magique R-550	90	Fragmentation 12	7	over 2	Infrared	Mirage F-1

reconnaissance, communications, navigation, targeting, weather and other satellites have been developed and are in use.

Along with the development and operation of support satellites, the United States is also developing the reusable Shuttle manned spacecraft.

The LASP satellite is designed for conducting scanning and detailed photoreconnaissance. It is equipped with photographic and TV devices.

The Samos-M satellite is used for detailed photographing of individual areas and objects detected previously by scanning reconnaissance satellites. The data (photographic information from the satellite) is recovered by a return capsule.

The Ferret satellite is used for radar reconnaissance. With the aid of such satellites, data are secured on the tactical and technical characteristics of radio electronic equipment and its location.

In addition, the U.S. Air Force is developing and testing new reconnaissance systems which should obtain reconnaissance data on a close-to-real time scale.

Communications satellites are employed for the operational control of the U.S. Armed Forces located on overseas territories. The communications satellite systems possess the great advantage of ensuring stable communications under the conditions of the effect of nuclear explosions on the ionosphere. This is an important factor in a nuclear war.

The Transit navigation satellites are designed to ensure precise navigation of the nuclear missile subs, surface vessels and later on also strategic bombers. The system consists of three or four satellites and ensures the carrying out of the set missions. A global satellite system is being developed for determining location using the Navstar satellites.

The geodesic satellites of the Secor type are employed for mapping areas of the earth's surface and clarifying the shapes and dimensions of the earth. This will be employed primarily for the effective use of ICBM and missiles launched from nuclear subs.

The satellites of the meteorological space system are designed to provide the armed forces with weather data.

The reusable (up to 100 flights) Shuttle space (orbital) vehicle is being developed in the United States for carrying out the following missions: putting into orbit and returning satellites to earth; inspecting and intercepting satellites; transport and rescue operations; conducting reconnaissance.

3. PRINCIPLES IN THE THEORY OF DESIGNING AIR DEFENSE WEAPONS SYSTEMS

3.1. Characteristics of the Air Space Environment and Its Influence on the Propogation of Electromagnetic Oscillations and Aircraft Flight Conditions

3.1.1. Characteristics of the Earth's Atmosphere

The earth's atmosphere is a gaseous shell with a total weight of $5.25 \cdot 10^{15}$ tons, which is less than one-millionth of the earth's weight. Up to altitudes of H = 80-100 km, the chemical composition of dry air is homogeneous. As one moves away from the earth's surface, the following basic layers of the atmosphere are differentiated: troposphere, stratosphere, ionosphere and dispersion sphere (exosphere).

The *troposphere* is the area of the atmosphere next to the earth with an altitude from 7 to 18 km which increases as one moves from the pole to the equator and contains 0.8 of the atmosphere's mass.

The *stratosphere* is the portion of the atmosphere from the upper edge of the troposphere to altitudes of 80-90 km and characterized by strong and constant winds and by significant temperature changes.

The *ionosphere* is the portion of the atmosphere located above the stratosphere to altitudes of 800 km and characterized by the presence of free positive and negative charges formed under the effect of solar and cosmic radiations.

The *dispersion sphere (exosphere)* is the area of space above the ionosphere which gradually changes into near-earth space. The theoretical boundary of the atmosphere is 28,000 km above the poles and 42,000 km above the equator.

The *standard stmosphere* is a model of the atmosphere's structure representing the result of averaging observations and measurements over many years for such atmospheric parameters as atmospheric pressure, density, temperature, relative humidity, chemical composition of the air, the cloud cover and jet streams.

Atmospheric pressure is the pressure which the air has on a body located at a set point in space, H/m^2:

$$P = P_0 e^{-\frac{gH}{RT}}, \qquad (3.1)$$

where P_0--pressure at sea level;
g--acceleration of free fall, m/sec^2;
H--current reading of altitude, m, km;
R=287--gas constant for dry air, m^2/sec • degree;
$T=t°+273.15°$--air temperature, K.

For simplifying the computations, atmospheric pressure can be approximated by the following ratio:

$$P = P_0 e^{-\frac{H}{H_0}}$$

where $H = 8000T/T_0$--hypothetical altitude of "homogeneous" atmosphere;
T--temperature, K.

The value of P_0 is the pressure above sea level (in the USSR, above sea level at Kronshtadt) P_0 = 1013 mbat = 760 mm Hg = $1.013 \cdot 10^5$ H/m^2. The dependence of atmospheric pressure upon altitude is shown in Fig. 3.1.

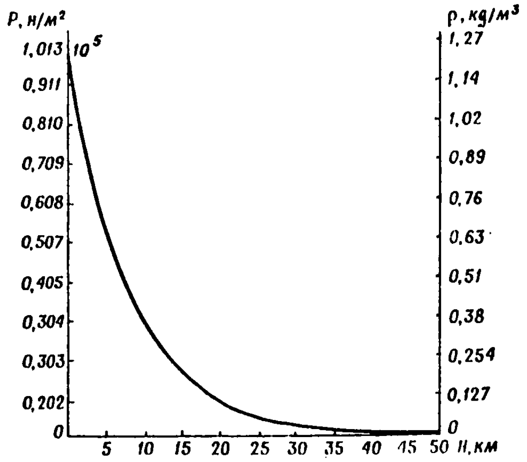


Fig. 3.1. Dependence of atmospheric pressure and air density upon altitude

Air density is the mass of air contained in a unit of volume, kg/m^3:

$$\rho = \frac{P}{RT} = \rho_0 e^{-\frac{H}{H_0}}. \quad (3.2)$$

where $\rho_0 = P_0/RT = 1.27$--the density of dry air at sea level, kg/m^3. The dependence of air density upon altitude is shown in Fig. 3.1.

Air temperature is the degree of its warming as measured in degrees according to the Kelvin thermodynamic scale (K) or by the 100-degree Celsius scale (°C). The mean air temperature for standard atmosphere depending upon altitude for the northern hemisphere is shown in Fig. 3.2.

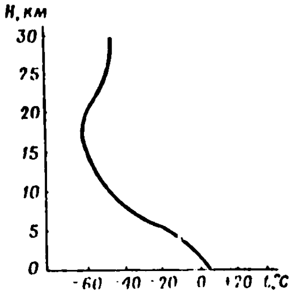


Fig. 3.2. Dependence of air temperature upon altitude

Relative air humidity R_0 is the ratio of water vapor pressure e_0 at a given point to the vapor pressure E_0 saturating the space with the set temperature t°C over a flat surface of pure water:

$$R_0 = \frac{e_0}{E_0} \cdot 100\%. \tag{3.3}$$

where

$$E_0 = 6.1 \cdot 10^{\frac{7.6t^\circ}{272+t^\circ}}.$$

Absolute air humidity is the quantity of grams of water vapor in 1 m^3 of air:

$$a_0 = 216.7 \frac{e}{T}. \tag{3.4}$$

The chemical composition of air characteristic for altitudes up to 100 km from the earth's surface is determined by the presence of nitrogen (78.09 percent), oxygen (20.95 percent), argon (0.95 percent), carbon dioxide (0.03 percent) and others.

High clouds (over 6 km) are cirrus, cirrocumulus and cirrostratus and consist of ice crystals.

Middle clouds (from 2 to 6 km) are altocumulus and altostratus.

Low clouds (below 2 km) are stratocumulus, stratus and nimbostratus.

Vertical development clouds are all types of cumulus clouds the formation of which is related to atmospheric convection within the limits of up to 10-11 km.

The number of clouds is expressed in fractions of the sky surface covered by them at the given moment. Completely clear skies have a point of 0 and completely overcast have 10 points.

Jet streams are areas of the troposphere within which constant high-velocity flows of air are observed. They are ordinarily found in the latitudes between 25 and 70° in each hemisphere. The maximum velocities of the stream lie at altitudes of 9-14 km (the jet stream axis). The length of the jet streams reaches several thousand kilometers while the width and height are hundreds and several kilometers, respectively. The distribution of the wind velocity scalar V_w is:

$P_w = \int_0^V P(V, H)\,dV$ — for the northern hemisphere at altitudes to 25 km above sea level as shown in Fig. 3.3.

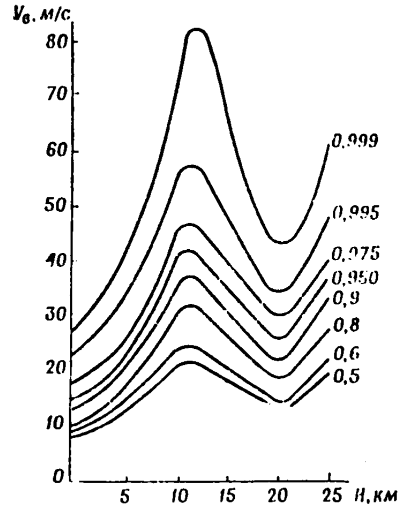


Fig. 3.3. Distribution of wind velocity scalar for northern hemisphere

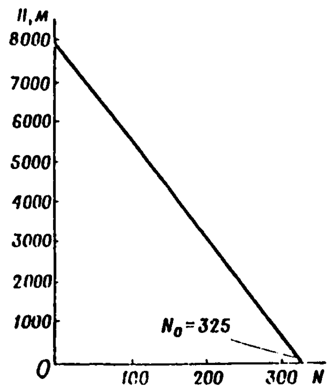


Fig. 3.4. Dependence of refraction index upon altitude

Influence of Atmosphere on Propagation of Electromagnetic Waves

The effect of the atmosphere's lower layers (the troposphere) and the upper layers (ionosphere) on the propagation of electromagnetic (EM) waves is expressed in the form of the bending of the propagation and absorption trajectory.

Refraction of EM waves is the bending of the EM wave propagation trajectory leading to the appearance of errors in determining the position of an aircraft.

The refraction phenomenon is caused by a change in the dielectric constant ε and, correspondingly, in the refraction coefficient n of the medium, since $n = \sqrt{\varepsilon}$.

In practice, a refraction index is used $N = 10^6 (n-1)$ indicating by how many millionths the refraction index $n > 1$. At the earth's surface $n_0 = 1.00026-1.00046$ or an average value of $N_0 = 325$. With a drop in pressure, temperature and humidity, the refraction index declines with altitude according to a linear law.

The gradient (rate of change) $dN/dH = -4 \cdot 10^{-2}$, 1/m. Correspondingly, the change in N depending upon altitude, will equal $N = (N_0 - 4 \cdot 10^{-7} \cdot H)$ and changes according to a linear law (Fig. 3.4).

Tropospheric refraction is the curving of the EM wave trajectory with their propagation in a medium with a variable refraction coefficient. The change in the refraction coefficient Δn (or ΔN) with altitude leads to a change in phase velocity $\Delta V_p = c/\Delta n$ and this causes the curving of the trajectory.

The nature and amount of refraction depend upon the value and sign of the vertical refraction index gradient (Fig. 3.5).

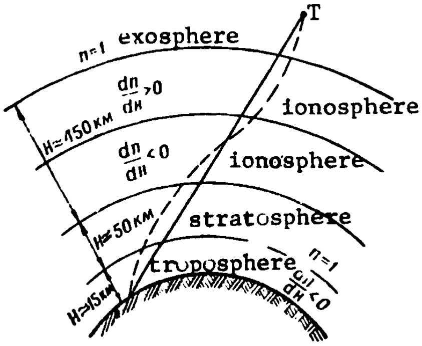


Fig. 3.5. Dependence of refraction upon value and sign of vertical refraction index gradient

Table 3.1

Type of refraction	dN/dH, 1/m	Curve radius for beam EM waves, km
Normal	$-4\cdot 10^{-8}$	$\rho_n = 25{,}000$
Critical	$-0.157\cdot 10^{-6}$	$\rho_c = R_e = 6{,}371$
Superrefraction	$<-0.157\cdot 10^{-6}$	$\rho_s < R_e$

With $dN/dH > 0$ there is a negative refraction (the deflection of the beam upwards) and with $dN/dH < 0$ there is a positive one (the deflection of the beam downwards) accompanied by the bending of the EM waves around the earth's surface. The types of refraction and the average values of the curve radii are given in Table 3.1.

The superrefraction phenomenon makes it possible to detect aircraft beyond the limits of direct visibility.

Errors in tropospheric refraction. The refraction of EM waves accompanied by the curving of the path causes an additional time lag and this leads to the rise of range errors ΔD and to an increase in the values of the target's elevation, that is, to the rise of errors Δε. The values of the errors of ΔD and Δε depending upon range and elevation, are shown in Figs. 3.6 and 3.7, respectively.

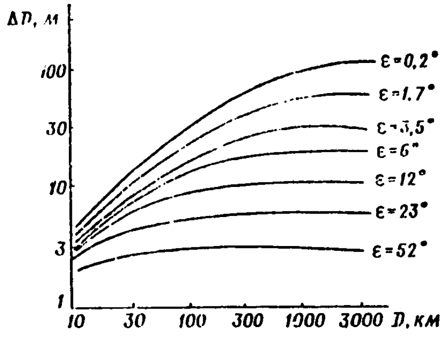


Fig. 3.6. Errors in tropospheric refraction for distance

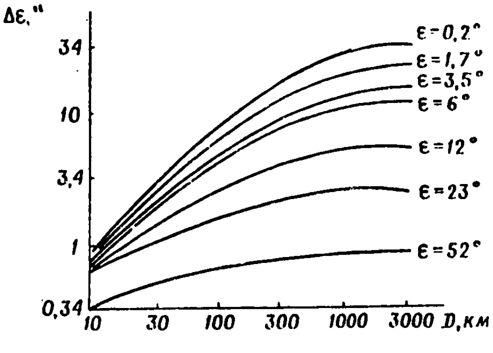


Fig. 3.7. Errors in tropospheric refraction for elevation

The maximum values of the errors, including the errors in measuring the doppler frequency, can be approximated thus (ΔD, m; Δε, " min.; Δf_d, hertz):

$$\left.\begin{aligned}\Delta D &= 0.007N_0\cos\varepsilon;\\ \Delta\varepsilon &= 0.0034N_0\operatorname{ctg}\varepsilon;\\ \Delta f_d &= f_d(n-1) = f_d N\cdot 10^{-6}.\end{aligned}\right\} \qquad (3.5)$$

Ionospheric refraction is the curving of the EM wave trajectory with propagation in an area of ionized gases.

The refraction coefficient for an ionized medium is:

$$n = \sqrt{1 - 80{,}8\frac{N_e}{f^2}}. \tag{3.6}$$

where N_e--concentration of free electrons, eℓ/m^3;
f--frequency of EM waves, hertz.

With a steady diminishing of n with altitude in a certain layer of the ionized region there occurs the total internal reflection of the EM waves at an angle equal to the angle of incidence θ_0.

This phenomenon is used for detecting various types of aircraft beyond the limits of the horizon (over-the-horizon radar).

The condition for the reflection of the EM waves of the given frequency (hertz) is:

$$f = \frac{\sqrt{80{,}8N_e}}{\cos\theta_0}. \tag{3.7}$$

where θ_0--angle of incidence of electromagnetic waves on lower boundary of ionosphere calculated from the normal to it.

The value $f_{cr} = \sqrt{80.8N_e}$ is termed the critical frequency.

The absorption and attenuation of EM waves in the troposphere occurs in the oxygen and in the water vapor of the troposphere as well as due to dispersion by hydrometeors.

In calculating the operating range of locating equipment (systems), this phenomenon is taken into account by introducing a coefficient for the absorption and attenuation of EM waves depending upon the frequency and characteristics of the medium.

The operating range of radars considering the absorption and attenuation factors is (in km):

$$D = D_0 \cdot 10^{-0{,}05\alpha l}, \tag{3.8}$$

where D_0--operating range of radar in free space, km;
α--absorption and attentuation coefficient of EM waves in troposphere, decibels per km;
ℓ--path of EM waves in absorbing medium, km.

The averaged value of the α coefficient depending upon frequency is shown in the graph (Fig. 3.8).

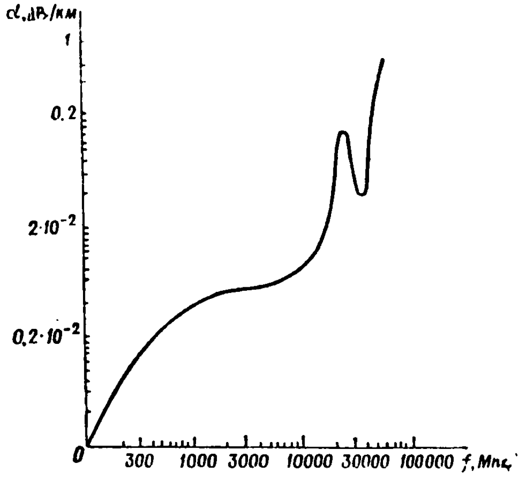


Fig. 3.8. Averaged value of attenuation coefficient depending upon frequency

The sharp increase in the value of the α coefficient at the frequency f = 22.2 gigahertz lies in the area of the water vapor resonance absorption.

The absorption of EM waves in the ionosphere is caused by the phenomenon of the colliding of free electrons with neutral molecules and gas ions.

The absorption coefficient is determined in decibels/kilometer:

$$\alpha = \frac{1,16\cdot 10^{-6}}{f^2} \nu N_e. \tag{3.9}$$

where ν--frequency of colliding of electronc with neutral atoms, hertz;
N_e--concentration of free electrons, eℓ/m^3.

3.1.2. Flight Conditions for Various Types of Aircraft

Physical flight conditions are the aggregate of the physical properties of the atmosphere and the physical phenomenon arising during the flight of an aircraft.

These conditions are significantly altered depending upon altitude, speed and trajectory of motion, upon the design and purpose of the aircraft, upon the time of year or day, upon the area of the flight and other factors. The significant development level of aerodynamics and the advances in developing propulsion units and new high-strength materials have made it possible to obtain high performance for modern aircraft.

The force of gravity F is a force in H in which a body weighing m at an altitude H is attracted to the earth:

$$F = \gamma \frac{mM}{(R_e + H)^2} = 4\cdot 10^{14} \frac{m}{(R_e + H)^2}. \tag{3.10}$$

where $\gamma = 6.67\cdot 10^{-11}$--gravitation constant, m^3/kg sec^2;
$M = 6\cdot 10^{24}$--the weight of the earth, kg;
$R_e = 6371\cdot 10^3$--radius of the earth, m.

Acceleration of free falling body at earth's surface g--acceleration under the effect of the earth's force of gravity.

As a consequence of the daily rotation of the earth, the amount of acceleration for a free falling body (m/sec^2) depends upon geographic latitude

$$g = g_0 (1 + 0{,}0052 \sin^2 \varphi). \quad (3.11)$$

where g_0=0.78--acceleration of a free falling body at the equator, m/sec^2;
ϕ--geographic latitude, degrees.

Depending upon height, the acceleration of a free falling body changes according to the law

$$g_H = g \left(\frac{R_e}{R_e + H} \right)^2. \quad (3.12)$$

Conditions of aircraft flight in earth's field of gravity without considering influence of atmosphere. According to the known value of g_H it is possible to determine the circular velocity V_{ci} of an aircraft (satellite) flying in a circular orbit at altitude H:

$$V_{ci} = \sqrt{g_H (R_e + H)}. \quad (3.13)$$

In particular, with $H = 0$ and $g_H = g$, we obtain a value of orbital velocity $V_1 = \sqrt{gR_e} \simeq 7.9$ km/sec, and this is the limit for aircraft in flights in circumterrestrial space.

Correspondingly, escape velocity $V_2 = \sqrt{2gR_e} \simeq 11.2$ km/sec.

The trajectories for the movement of bodies in the field of the earth's gravity at velocities lying between the orbital and escape velocities will be an ellipse the near focus of which coincides with the earth's center.

Flight conditions of aerodynamic vehicles. The relationship between the required speed of flight for aerodynamic vehicles, atmospheric pressure P and air density ρ at a given altitude is established by the energy equation (the Bernoulli equation):

$$\rho \frac{V^2}{2} + P = \text{const}. \quad (3.14)$$

Consequently, with an increase in altitude (with a reduction in the values of ρ and P) for maintaining the flight of the given type of aerodynamic vehicle, it is essential to increase the speed of flight in accord with equation (3.14).

In formula (3.14) the first component has received the name of the velocity head q:

$$q = \frac{\rho V^2}{2}.$$

Forces Effecting the Aircraft

Total aerodynamic force R is the resultant of all the forces of pressure and friction effecting the aircraft in the process of flight:

$$R = C_R S \frac{\rho V^2}{2}. \qquad (3.15)$$

where C_R--coefficient of total aerodynamic force;
S--wing area.

Lift Y is the projection of the total aerodynamic force on the perpendicular to the speed of the air flow:

$$Y = C_y S \frac{\rho V^2}{2}. \qquad (3.16)$$

where C_y--lift coefficient.

Drag Q is the projection of the total aerodynamic force on the direction of the speed of the free-flow stream and directed against the motion of the aircraft:

$$Q = C_x S \frac{\rho V^2}{2}. \qquad (3.17)$$

where C_x--drag coefficient being the total of the drag coefficients in the absence of C_{xo} and in the presence of C_{xi} of lift.

The values for the coefficients C_x and C_y and the relationships between the forces are shown in Figs. 3.9a and b and 3.10, respectively.

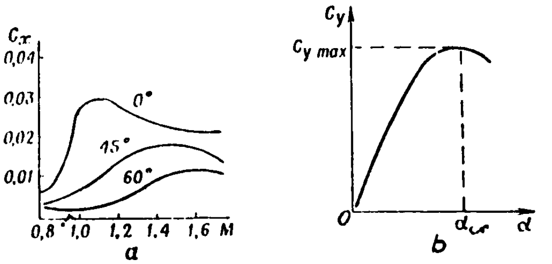


Fig. 3.9. Values for coefficients C_x (a) and C_y (b)

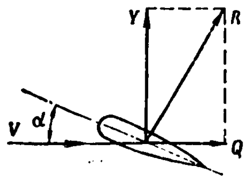


Fig. 3.10. Distribution of forces operating on aircraft

Any motion in essence is reactive as it is based upon the ejecting of mass in a direction which is reverse to the motion (the propellers of an aircraft eject air, a ship propeller ejects water and so forth).

However, only the movement of a jet aircraft does not require the presence of a surrounding medium (with the exception of an air-breathing jet engine) as the ejected mass of the propulsive mass is carried on the aircraft.

The thrust P is the basic value characterizing a jet engine as an element of an aircraft power unit:

$$P = \frac{G_{в} + G_{т}}{g} V_{c} - \frac{G_{в}}{g} V. \tag{3.18}$$

where G_B, G_T--the second weight expenditures of air and fuel, respectively, H/sec;
V_C, V--gas exhaust velocity and aircraft speed, respectively, m/sec.

The aerodynamic quality of an aircraft is the ratio of life Y to drag Q (the ratio of the lift coefficient to the drag coefficient):

$$K = \frac{Y}{Q} = \frac{C_y}{C_x}. \tag{3.19}$$

In the process of flight for an aircraft possessing a weight m, its structure is effected by the geometric total of the external forces ΣP causing the resulting acceleration a, m/sec^2:

$$a = \frac{\Sigma P}{m} .$$

The occurrence of acceleration is accompanied by the presence of the forces of inertia. The amount of the force of inertia J(H) depends totally upon acceleration and direction is always opposite to the direction of acceleration $J = -ma$.

Aircraft g-loads are a dimensionless ratio of the amount of the resultant of all forces effecting the aircraft to the amount of its gravity:

$$n = \frac{\Sigma P}{G} = \frac{a}{g} = -\frac{J}{G}. \tag{3.20}$$

Here $\Sigma P = ma$; $G = mg$; $J = -ma$.

The resultant of all the forces ΣP can be broken down into components using the axes of a body-axis system (x_1, y_1, z_1), that is, ΣP_{x_1}; ΣP_{y_1}; ΣP_{z_1}.

For the values of these components, the longitudinal and transverse g-loads of the aircraft (n_{y_1} and n_{z_1}) are calculated:

$$n_{x_1} = \frac{\Sigma P_{x_1}}{G} = \frac{P - Q}{G} \text{ --longitudinal g-load;}$$

$$n_{y_1} = \frac{\Sigma}{G} \text{ --normal g-load;}$$

$$n_{z_1} = \frac{\Sigma P_{z_1}}{G} \text{ --lateral g-load.}$$

The thermal barrier of an aircraft is the aggregate of design and operational limitations related to a rise in the temperature of the aircraft skin and its individual parts with an increase in flight speed.

Air flow deceleration is a drop in the local air velocity to zero in the boundary zone on the forward edge of the body passing through the flow.

The dynamic temperature of the aircraft's surface is the rise in temperature due to the conversion of the kinetic energy of the air flow into potential energy with its deceleration:

$$\Delta T_{dyn} = (T + 273^\circ)\left(1 + \frac{M^2}{5}\right), \tag{3.21}$$

where M--the ratio of flow velocity to the speed of sound;
$T + 273^\circ$--absolute temperature of surrounding air.

The theoretical dependence of dynamic temperature upon aircraft speed is shown in Fig. 3.11.

The decline in the relative strength of modern aviation materials, including stainless steel, depending upon temperature is shown in Fig. 3.12.

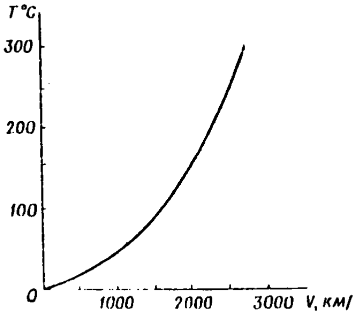


Fig. 3.11. Change in dynamic temperature depending upon aircraft speed

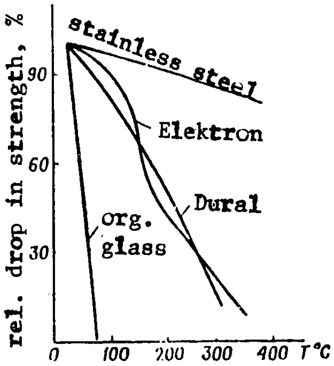


Fig. 3.12. Relative reduction in strength of materials with rise in temperature

The flight conditions of aerodynamic vehicles are determined by a number of constraints which influence the nature of their combat employment (Fig. 3.13).

The upper limit is determined by the tolerable pressure in the air intake ducts and the lower one by the structure's strength limit. The dotted line shows the extremal temperatures for various materials of the aircraft structure.

The *static ceiling* H_{st} is the greatest height for horizontal sustained flight of an aerodynamic vehicle in which the condition determined by the energy equation (3.14) is fulfilled.

Minimum allowable speed is the lowest speed V_{min} of sustained flight at a given altitude excluding the stalling of an aerodynamic vehicle:

$$V_{min\ all} = \sqrt{\frac{2G}{\rho S C_{y \cdot all}}}\ . \tag{3.22}$$

Maximum allowable speed is the greatest speed V_{max} of sustained flight at a given altitude under the maximum or after-burner engine operating conditions ensuring safe flight of the aerodynamic vehicle:

$$V_{max\ all} = \sqrt{\frac{2q_{all}}{\rho}}\ . \tag{3.23}$$

where q_{all}--extremal amount of velocity head for given type of aircraft.

Qualitative characteristics of $V_{min\ all}$ and $V_{max\ all}$ for aerodynamic vehicles are shown in Fig. 3.14.

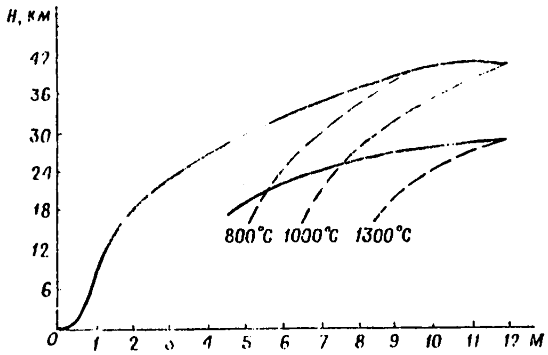


Fig. 3.13. Constraints on aircraft flight conditions

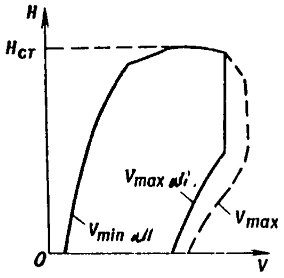


Fig. 3.14. Allowable values for flight speeds of aerodynamic vehicles

Principle of Jet Propulsion for Aeroballistic and Ballistic Missiles

In jet propulsion a jet reaction is employed as the propulsive force. The theory of jet propulsion for a point of variable mass moving rectilinearly in an air-free space in the absence of external forces was worked out by K. E. Tsiolkovskiy in the form of a first problem and for upwards vertical motion as a second problem.

The first Tsiolkovskiy problem is the speed of point V_1 at the end of the combustion process with an initial velocity V_0:

$$V_1 = 2{,}3 V_r \lg\left(1 + \frac{m}{M_s}\right). \tag{3.24}$$

where V_r--relative partical exhaust velocity;
M--ejected mass of fuel;
M_S--mass of point at end of jettisoning process.

The second Tsiolkovskiy problem. The total height H for the lift of the point will consist of the active leg S_a covered during time t_1 and the inactive leg S_i covered by the point with a fixed mass $M_S = M_0 - M$ and with a velocity equal to the velocity V_1 at the end of the active leg:

$$H = S_a + S_i = V_0 t_1 - \frac{g t_1^2}{2} + \alpha \frac{V_2 t_1^2}{2} + \frac{V_1^2}{2g}. \qquad (3.25)$$

where α--specific fuel consumption;

$$V_1 = V_0 - g t_1 + \alpha V_r t_1.$$

Flight Characteristics of Aeroballistic and Ballistic Missiles

Aeroballistic missiles are jet aircraft traveling along a ballistic trajectory on the basis of the laws of aerodynamics.

The length of flight

$$L = \frac{V_1^2 \sin 2\theta}{g}; \qquad (3.26)$$

maximum trajectory altitude

$$H = H_0 + \frac{V_1^2 \sin^2 \theta}{g}; \qquad (3.27)$$

duration of flight

$$T = \frac{2 V_1 \sin \theta}{g}. \qquad (3.28)$$

where H_0--flight altitude of carrier (aircraft) at moment of launching missile;
V_1--speed of flight at the moment of shutting down engine;
θ--angle of departure;
g--acceleration of force of gravity.

The characteristics of the trajectory are shown in Fig. 3.15.

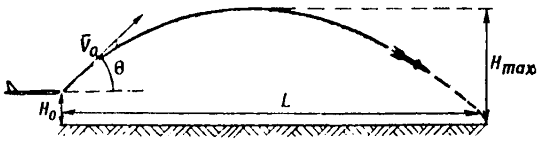


Fig. 3.15. Characteristics for trajectory of aeroballistic vehicle

Ballistic missiles (BM) are vehicles the trajectory of which consists of an active leg with a firing engine during which the device gains a reserve of kinetic (speed of flight) and potential (altitude of flight) energy and an inactive leg when motion occurs according to the law of a freely thrown body, that is, according to a ballistic curve.

The trajectory of a ballistic missile can be broken up into three characteristic legs (Fig. 3.16).

The active leg is the portion of the trajectory from the launch point A to the end of the engine's operation (point K) over which there is an increase in velocity V_k to the required amount and direction.

The free flight leg is the portion of the trajectory (from point K to point B) over which the vehicle flies along a ballistic curve.

The terminal leg is the portion of the trajectory (from B to point C) during which the vehicle moves in the dense layers of the atmosphere.

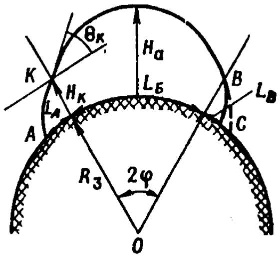


Fig. 3.16. Trajectory of ballistic missile's flight

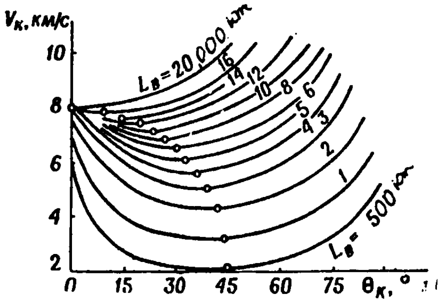


Fig. 3.17. Basic ratios characterizing ballistic missile flight

A projection of the total distance for the flight of a BM onto the earth's surface is:

$$L = L_A + L_B + L_C ,$$

where L_A, L_B, L_C--respectively, projections of the active, free-flight and terminal legs of the trajectory.

Since $L_B \gg L_A + L_C$, for a rough approximation it is possible to disregard the values L_A and L_C, that is,

$$L \simeq L_B = 2\phi R_e,$$

where ϕ--central angle, radian;
R_e--radius of earth, or $L \simeq 114.6\ R_e\phi°$;
($\phi°$--measured in degrees).

The dependence between the velocity V_k, the angle of its incline relative to the horizon θ_k, the altitude of the active leg H_k and the angular range of the flight 2ϕ is expressed by the formula

$$V_\kappa^2 = \frac{\mu}{r_\kappa}\,\frac{1-\cos 2\varphi}{\left[\frac{r_\kappa}{R_3}\cos^2\theta_\kappa - \cos(2\varphi-\theta_\kappa)\cos\theta_\kappa\right]}, \qquad (3.29)$$

where $\mu = \gamma M_e$ (γ--gravitation constant, M_e--mass of the earth);
$r_k = H_k + R_e$.

The connection between the projection of the range L_B of the BM flight on the earth's surface, the velocity V_k at the end of the active leg and the angle of departure θ_k is shown in Fig. 3.17 (in the diagram the points with the minimum angles of departure θ_k are circled).

3.1.3. Laws of Motion of Aircraft

Motion is any change encompassing all processes occurring in the universe. While the motion of matter as a whole is not restricted by anything, it is absolutely inevitable and indestructible, the motion of any individual body is limited in space and time and for this reason can be determined only by a relatively concrete system of reckoning (a system of coordinates).

To the degree that real motion always occurs simultaneously relative to a number of reckoning systems, a number of methods for assessing it are possible. The choice of the reckoning system is dictated solely by the conditions of expedience and simplicity of description.

The law of motion of an aircraft is an analytical or graphic dependence of the aircraft's coordinates upon time for the given reckoning system. The representation of the aircraft's motion is possible due to such physical phenomena as speed, acceleration and the other higher derivatives of speed.

For a spherical system of coordinates, in a general form an aircraft's laws of motion for distance and angular coordinates can be represented in the form of time series:

$$\left.\begin{aligned} D(t) &= D(0) + \dot{D}t + \frac{\ddot{D}t^2}{2} + \frac{\dddot{D}t^3}{3} + \ldots = \sum_{n=0}^{N} \frac{D^{(n)}t^n}{n!}; \\ \beta(t) &= \beta(0) + \dot{\beta}t + \frac{\ddot{\beta}t^2}{2} + \frac{\dddot{\beta}t^3}{3} + \ldots = \sum_{n=0}^{N} \frac{\beta^{(n)}t^n}{n!}; \\ \varepsilon(t) &= \varepsilon(0) + \dot{\varepsilon}t + \frac{\ddot{\varepsilon}t^2}{2} + \frac{\dddot{\varepsilon}t^3}{3} + \ldots = \sum_{n=0}^{N} \frac{\varepsilon^{(n)}t^n}{n!}. \end{aligned}\right\} \quad (3.30)$$

where $D^{(n)}$, $\beta^{(n)}$, $\varepsilon^{(n)}$--values (n-x) for the derivatives from the distance, azimuth and elevation, respectively,
N--the number of terms in the series.

The laws of motion for an aircraft in terms of distance, azimuth and elevation determine the operating conditions for the tracking range finder and angle-measuring systems, respectively. Here for the tracking systems with a known magnitude of astatism, the values of the derivatives from range and angular coordinates determine the amounts of the dynamic errors and, consequently, the accuracy of measuring the aircraft's coordinates.

An aircraft's law of motion for range is an analytical or graphic representation of the change in the aircraft's range coordinates relative to a specific reckoning system.

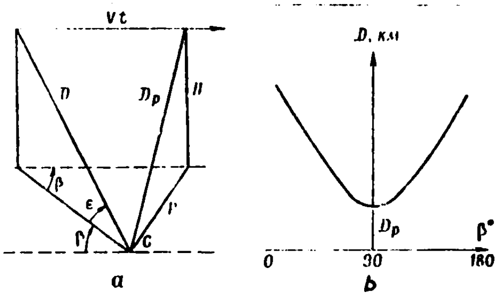


Fig. 3.18. Model of horizontal flight (a)
and law for change in distance (b) of an aircraft

For practical purposes it is advisable to represent the law of motion as a dependence upon the aircraft's azimuth.

A model of an aircraft's horizontal flight with a constant speed relative to a ground tracking system (point C) is shown in Fig. 3.18a. The law for the change in distance relative to the tracking system is shown in Fig. 3.18b.

The analytical expressions characterizing the law of change in range and its derivatives depending upon the aircraft's azimuth are given in Table 3.3.

Fig. 3.18 and Table 3.2 have employed the following symbols: V--aircraft speed; P--parameter relative to the start of the calculation; H--aircraft altitude; β, ε--azimuth and elevation of aircraft relative to start of reckoning.

Graphs for the change of $\dot{D}(\beta)$, $\ddot{D}(\beta)$ and $\dddot{D}(\beta)$ are shown in Fig. 3.19.

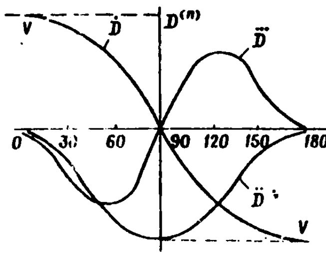


Fig. 3.19. Graphs for change in derivatives for range

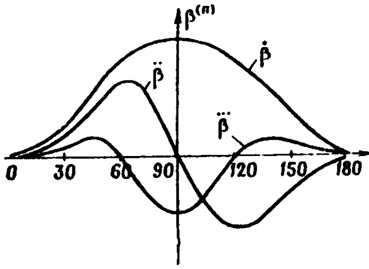


Fig. 3.20. Graphs for change in derivatives for azimuth

Table 3.2

1 Составляющая закона движения	2 Аналитическое представление дальности летательного аппарата и производных	3 Экстремальные значения	4 Азимут экстремума
Range, m	$D(\beta)=\frac{1}{\sin\beta}\sqrt{P^2+H^2\sin^2\beta}$	$\sqrt{P^2+H^2}$	$\beta=90°$
		$D\to\infty$	$\beta=0°$; $\beta=180°$
Radial velocity, m/s	$\dot{D}(\beta)=\frac{VP\cos\beta}{\sqrt{P^2+H^2\sin^2\beta}}$	V 0	$\beta=0°$; $\beta=180°$ $\beta=90°$
Acceleration m/s²	$\ddot{D}(\beta)=\frac{V^2(P^2+H^2)\sin^2\beta}{\sqrt{(P^2+H^2\sin^2\beta)^3}}$	$\frac{V^2}{\sqrt{P^2+H^2}}$	$\beta=90°$
		0	$\beta=0°$; $\beta=180°$

Key: 1--Component of law of motion; 2--Analytical representation of aircraft's range and derivatives; 3--Extremal values; 4--Extremum azimuth

An aircraft's log motion for azimuth is an analytical or graphic representation for the change in the aircraft's azimuth coordinates relative to the specific reckoning system.

The nature of the change in an aircraft's azimuth and the derivatives from the azimuth (Fig. 3.18a) is shown in Table 3.3.

Graphs for the change in $\dot{\beta}(\beta)$, $\ddot{\beta}(\beta)$, $\dddot{\beta}(\beta)$ are shown in Fig. 3.20.

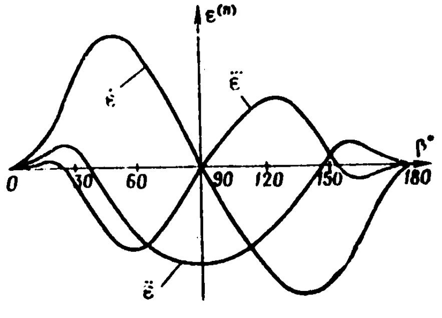


Fig. 3.21. Graphs for change in derivatives for elevation

An aircraft's law of motion for elevation is an analytical or graphic representation of the change in the aircraft's elevation coordinates relative to the specific reckoning system.

The nature of the change of the aircraft's elevation and the derivatives is shown in Table 3.4.

The graphs for the change of $\dot{\varepsilon}(\beta)$, $\ddot{\varepsilon}(\beta)$ and $\dddot{\varepsilon}(\beta)$ are shown in Fig. 3.21.

The ratios given in the tables and graphs make it possible to assess the amounts of the dynamic errors in tracking and guidance systems as well as determine the areas of space in the tracking and guidance (kill) zone where these errors are maximal and to take measures to compensate for them.

Table 3.3

1 Составляющая закона движения	2 Аналитическое представление азимута летательного аппарата и производных	3 Экстремальные значения	4 Азимут экстремума
Azimuth, rad.	$\beta(t) = \operatorname{arcctg} \frac{Vt}{\sqrt{P^2+H^2}}$	—	—
Angular velocity, 1/s	$\dot{\beta}(\beta) = \pm \frac{V \sin^2\beta}{P}$	0	$\beta = 0°$; $\beta = 180°$
		$\frac{V}{P}$	$\beta = 90°$
Angular acceleration, $1/s^2$	$\ddot{\beta}(\beta) = \frac{2V^2 \cos\beta \sin^3\beta}{P^2}$	$\pm 0{,}65 \frac{V^2}{P^2}$	$\beta = 60°$; $\beta = 120°$

Key: 1--Component of law of motion; 2--Analytical representation of aircraft's azimuth and derivatives; 3--Extremal values; 4--Azimuth of extremum

Table 3.4

1 Составляющая закона движения	2 Аналитическое представление угла места летательного аппарата и производных	3 Экстремальные значения	4 Азимут экстремума
Elevation, rad.	$\varepsilon(\beta) = \operatorname{arctg}\left(\frac{H}{P}\sin\beta\right)$	0 $\operatorname{arctg} H/P$	$\beta = 0°$; $\beta = 180°$ $\beta = 90°$
Angular velocity, 1/s	$\dot{\varepsilon}(\beta) = \frac{VH \cos\beta \cdot \sin^2\beta}{P^2 + H^2 \sin^2\beta}$	$\pm 0{,}38\, VH/P^2$ $\pm V/H$	$\beta = 55°, 125°$ $(P \gg H)$ $\beta = 0°, 180°$ $(P \ll H)$
Angular acceleration, $1/s^2$	$\ddot{\varepsilon}(\beta) = -\frac{V^2 H \sin^2\beta\left(2 - 3\sin^2\beta - \frac{H^2}{P^2}\sin^4\beta\right)}{P^2\left(1 + \frac{H^2}{P^2}\sin^2\beta\right)^2}$	$-V^2H^2/P^2$ $V^2/H\sqrt{P^2+H^2}$	$\beta = 90°$ $(P \gg H)$ $\beta = 90°$ $(P \ll H)$

Key: 1--Component of law of motion; 2--Analytical representation of aircraft's elevation and derivatives; 3--Extremal values; 4--Azimuth of extremum

3.2. Principles for the Designing of Detection Systems Against Enemy Air Weapons

3.2.1. Systems of Coordinates Employed to Solve the Problems of Detecting and Determining the Location of Aircraft

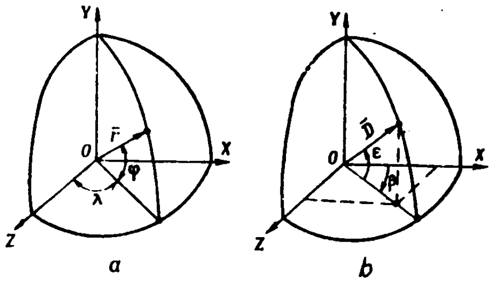
The position of an aircraft in space can be determined only in relation to certain other bodies which are termed reckoning or reference bodies.

As reckoning bodies it is possible to employ, the sun, the center of the earth, a certain point on the earth's surface, the center of mass of any aircraft and so forth. A certain system of coordinates is linked to the reckoning body.

For solving the problems of determining the location of aircraft, their guidance and hitting in circumterrestrial space it is possible to employ earth (stationary relative to the earth), body-axis and wind-body (moving relative to the earth) coordinate systems.

Earth Coordinate Systems

Geocentric rectangular (X, Y, Z) and spherical ($\bar{r}$, ϕ, λ) systems. As the origin of the coordinates O, the center of the earth's mass is employed while the OY axis of the rectangular system is directed along the earth's axis of rotation, the OX and OZ axes in such a manner as to form a right-handed system.



In a sperical system, the position of the aircraft is determined by the radius vector r and the geocentric latitude ϕ and λ (Fig. 3.22a).

The relation between the geocentric rectangular and spherical coordinates is:

$$\left.\begin{aligned} X &= r\cos\varphi\sin\lambda; \\ Y &= r\sin\varphi; \\ Z &= r\cos\varphi\cos\lambda. \end{aligned}\right\} \qquad (3.31)$$

Fig. 3.22. Geocentric (a) and surface (b) coordinate systems

Surface rectangular (x, y, z) and spherical ($\bar{D}$, β, ε) systems. As the origin of the coordinates o a certain point of the earth's surface is accepted, the oy axis of the rectalinear system goes vertically upwards, the ox axis runs to the north (or to a local object), and the oz axis in such a manner as to obtain a right-handed coordinate system.

In a spherical coordinate system, the aircraft's position is determined by the slant range D and by two angles β, ε determining the direction for the vector of the slant range D.

The angle ε between the vector and its projection to the horizontal plane is termed the elevation; the angle β determining in a horizontal plane the direction of the projection of D relative to the start of the readout (the ox axis) is called the azimuth (Fig. 3.22b).

The relation between the surface rectangular and spherical coordinate systems is:

$$\left.\begin{aligned} D &= \sqrt{x^2+y^2+z^2};\\ \beta &= \operatorname{arctg}\frac{z}{x};\\ \varepsilon &= \operatorname{arctg}\frac{y}{\sqrt{x^2+z^2}}. \end{aligned}\right\} \tag{3.32}$$

Moving (Relative to the Earth) Coordinate Systems

The body axis coordinate system (x_1, y_1, z_1). For the point of origin o (Fig. 3.23a), the aircraft's center of mass is employed; the ox_1 axis is directed along the aircraft's longitudinal axis, the oy_1 axis to the plane of the vertical axis and the oz_1 axis to the plane of the aircraft's horizontal section so as to obtain a right-handed coordinate system.

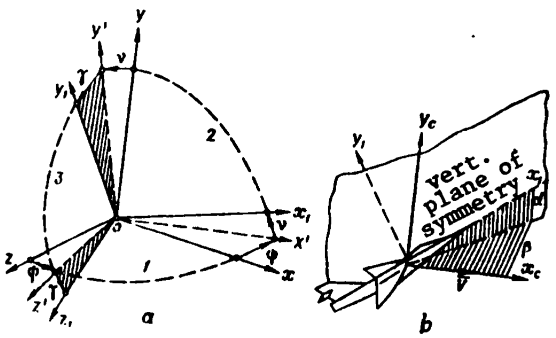


Fig. 3.23. Body axis (a) and wind body (b) coordinate systems

The angle between the aircraft's longitudinal axis and its projection to the horizontal plane is termed the pitch angle Θ.

The angle between the projection of the aircraft's longitudinal axis to the horizontal plane and the ox axis is termed the heading (yaw) angle ψ.

The angle between the vertical plane running through the ox_1 axis and connecting the oy_1 axis is called the bank angle γ.

Fig. 3.23a shows the reciprocal positioning of the body axis and earth coordinate system with the lining up of their center.

The angles ψ, θ and γ are formed by successive turns: 1--around the y angle to angle ψ; 2--around the z' axis to angle θ; 3--around the x_1 axis to angle γ.

The wind body coordinate system (x_c, y_c, z_c). The center of masses is taken as the point of origin o; the ox_c axis coincides with the velocity vector, with the oy_c and oz_c axes lying, respectively, in the aircraft's vertical and horizontal planes of symmetry (Fig. 3.23b).

The position of a wind body coordinate system relative to a body axis one is determined by the angles of attack and slip.

The angle of attack α is the angle between the projection of the velocity vector V to the aircraft's vertical plane of symmetry and the ox_1 axis.

The slip angle β is the angle between the velocity vector and the aircraft's vertical symmetry plane.

The choice of each specific coordinate system is determined by the conditions of the combat mission to be carried out by the given weapons system, by the requirement of design simplicity for the antennas and launchers, by the demands of reducing the dynamic errors, by the simplicity of the calculations made and by other factors.

In a general form, the transition from one system of rectangular coordinates to another is carried out using the formulas of analytical geometry and direction cosine tables.

An example of the transition from the system (x_1, y_1, z_1) to the system (x, y, z) and vice versa is given in Table 3.5, where for simplicity the cosine values have been replaced by letters.

The values of the direction cosines between the body axis and earth coordinate systems are given in Table 3.6.

The values of the direction cosines between the body axis and wind body coordinate systems are given in Table 3.7.

Table 3.5

coord.	x_1	y_1	z_1	coordinate recalculation formulas
x	a_1	a_2	a_3	$\left.\begin{array}{l} x = a_1x_1 + a_2y_1 + a_3z_1; \\ y = b_1x_1 + b_2y_1 + b_3z_1; \\ z = c_1x_1 + c_2y_1 + c_3z_1 \end{array}\right\}$ $\left.\begin{array}{l} x_1 = a_1x + b_1y + c_1z; \\ y_1 = a_2x + b_2y + c_2z; \\ z_1 = a_3x + b_3y + c_3z \end{array}\right\}$
y	b_1	b_2	b_3	
z	c_1	c_2	c_3	

Table 3.6

coord.	ox_1	oy_1	oz_1
ox	$\cos\vartheta\cdot\cos\psi$	$-\cos\psi\cdot\sin\vartheta\cdot\cos\gamma + \sin\psi\cdot\sin\gamma$	$\cos\psi\cdot\sin\vartheta\cdot\sin\gamma + \sin\psi\cdot\cos\gamma$
oy	$\sin\vartheta$	$\cos\vartheta\cdot\cos\gamma$	$-\cos\vartheta\cdot\sin\gamma$
oz	$-\sin\psi\cdot\cos\vartheta$	$\cos\psi\cdot\sin\gamma + \sin\psi\cdot\sin\vartheta\cdot\cos\gamma$	$\cos\psi\cdot\cos\gamma - \sin\psi\cdot\sin\vartheta\cdot\sin\gamma$

Table 3.7

coord.	ox_1	oy_1	oz_1
ox_c	$\cos\alpha\cdot\cos\beta$	$-\cos\beta\cdot\sin\alpha$	$\sin\beta$
oy_c	$\sin\alpha$	$\cos\alpha$	0
oz_c	$-\cos\alpha\cdot\sin\beta$	$\sin\alpha\cdot\sin\beta$	$\cos\beta$

Various modifications of the coordinate systems can be employed for solving individual specific problems.

3.2.2. Physical Principles Underlying the Obtaining of Information on Aircraft

The detection of aircraft in the process of their flight can be ensured only by receiving the energy returned from the aircraft's surface or emitted by the aircraft itself. It is also possible for a detection to be made by establishing changes in the surrounding medium and related to the process of the aircraft's motion in this medium.

Consequently, the physical phenomena comprising the objective basis of detection can be divided into three groups.

1. *The reflection of energy* is a physical phenomenon ensuring detection due to differences in the reflecting properties of the aircraft and the surrounding medium.

For this reason the active detection of an aircraft is possible if it can be radiated by a flow of electromagnetic energy, the energy of sound waves or by a flow of particles moving at a high speed and the return signals picked up. Here it is possible to use the solar energy reflected from the aircraft as well as energy from other space sources.

2. *The emission of energy* is a physical phenomenon ensuring detection by the various types of emission from the aircraft themselves in the flight process (the emission of inflight sources, thermal radiation in the heating of the aircraft body, the emission from the jet engine glow and sonic emission). These phenomena ensure the creation of passive inflight aircraft detection systems by radio and in the optic and sound wave bands. Carriers of nuclear weapons are sources of very weak nuclear radiation the detection of which is virtually possible only at very short distances.

3. *Perturbation of the medium* is the physical phenomena accompanied by changes in the surrounding medium during the process of the aircraft's flight (the change in the chemical composition, the ionization of the earth's gravitational field, the earth magnetism field and so forth). These phenomena can potentially be employed to solve the problems of aircraft detection under the condition of realizing methods to record these phenomena.

A classification of the physical phenomena which in principle can be realized for solving detection problems is shown in Fig. 3.24.

Of all the listed phenomena for detecting an aircraft in flight, the most widely used is the phenomenon of reflected energy employed in active and semiactive radar location and the radiation phenomenon which comprises the basis of passive location.

Secondary radiation. The wave falling on the aircraft's surface is termed the primary one while the reflected or scattered wave is the secondary and the phenomenon of reflection or dispersion is known as secondary radiation.

The radar cross-section (RCS) of targets. If on the surface of a point target which is the distance D away from the source of radiation a flow density is created with a power S_t for the primary wave, then as a result of omnidirectional secondary radiation of the target, at the receiving point combined with the emitter a signal will be received with a power

$$P = 4\pi D^2 S_{re},$$

where S_{re}--density of power flow at receiving point, watts/m^2.

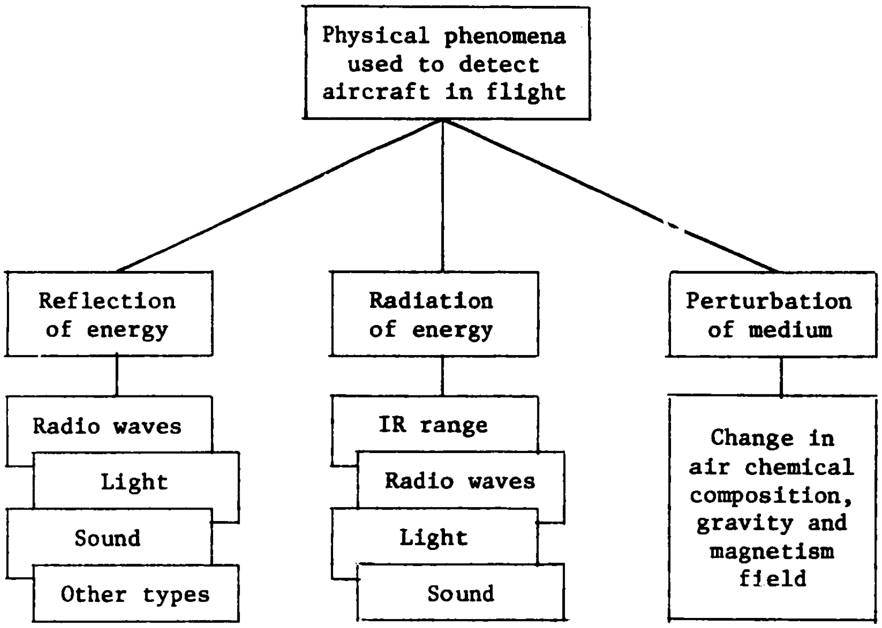


Fig. 3.24. Classification of physical phenomena used in detecting aircraft

The radio of this power to the density of the primary wave's flow is termed the radar cross-section of the target or echo area σ_t, m^2:

$$\sigma_t = \frac{P}{S_t} = 4\pi D^2 \frac{S_{re}}{S_t}. \tag{3.33}$$

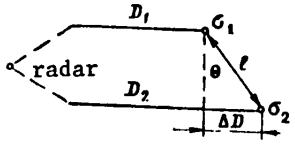


Fig. 3.25. Model of secondary radiation from two emitters

Real targets (or a group of targets) according to the patterns of secondary radiation can be reduced to a model of group emitters.

A model of two emitters. The total RCS of a model consisting of two emitters with the RCS of each of them σ_1 and σ_2 is (Fig. 3.25):

$$\sigma_t = \sigma_1 + \sigma_2 + 2\sqrt{\sigma_1\sigma_2}\cos\left(\frac{4\pi l}{\lambda}\sin\theta\right). \tag{3.34}$$

The phase shift between the signals returned from the emitters σ_1 and σ_2:

$$\varphi = \omega\Delta t = 2\pi f\frac{2\Delta D}{c} = \frac{4\pi l}{\lambda}\sin\theta,$$

where ℓ--distance between emitters;
 θ--angle between normal to the plane of the emitters' location and the direction of radiation.

The total RCS of a model of n emitters is

$$\sigma_t = \sum_{i=1}^{n}\sigma_i + 2\sum_{i\neq j}^{n}\sqrt{\sigma_i\sigma_j}\cos\varphi_{ij}. \qquad (3.35)$$

where ϕ_{ij}--phase shift between emitter i and j.

The RCS of bodies which are small in relation to the wave length ($\ell_t < \lambda$) is approximately expressed by the formula

$$\sigma_t = 4\pi^2\frac{l_t^3}{\lambda^4}. \qquad (3.36)$$

The RCS of bodies the dimensions of which are commensurate with the wave length ($\ell_t \simeq \lambda/2$) is:

$$\sigma_t \approx 0{,}17\,(2l_t)^2 \approx 0{,}17\lambda^2. \qquad (3.37)$$

(In all the designated instances as ℓ_t we have employed a certain equivalent to the dimensions of a real target.)

Of special interest are the methods for calculating the RCS of targets the dimensions of which significantly exceed the wave length ($\ell_t \gg \lambda$). In this instance the resulting RCS of the real targets, on the basis of the superimposition principle, is calculated as the total of the RCS of flat and convex surfaces.

An analysis of the adopted models indicates that the secondary radiation diagram for real targets is of a lob-shaped nature. A change in the aircraft's position in the process of flight relative to the receiving point leads to a change in the intensity of the returned signals. This phenomenon characterizes the RCS as a random value.

The density of the distribution of the RCS as a random value with single-frequency $f_1(\sigma_t)$ and two-frequency $f_2(\sigma_t)$ radiation of the targets is:

$$\left.\begin{aligned} f_1(\sigma_t) &= \frac{1}{\sigma_0}e^{-\frac{\sigma_t}{\sigma_0}};\\ f_2(\sigma_t) &= \frac{4\sigma_t}{\sigma_0}e^{-2\frac{\sigma_t}{\sigma_0}}. \end{aligned}\right\} \qquad (3.38)$$

where σ_0 and σ_t--mathematical expectation and current value of target RCS, respectively.

Fig. 3.26 shows the values of the RCS distribution densities for $f_1(\sigma_t)$ and $f_2(\sigma_t)$.

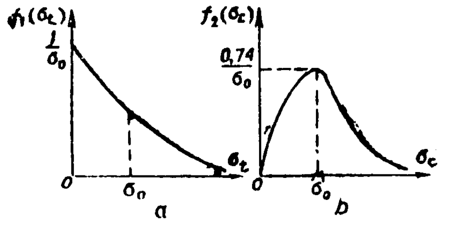


Fig. 3.26. Distribution density of radar cross-section with single-frequency (a) and two-frequency (b) radiation of target

The dispersion of the target's RCS with single-frequency radiation $D_1 = \sigma_0^2$ and with two-frequency $D_2 = \sigma_0^2/2$. Consequently, the use of two-frequency (multifrequency) radars leads to a reduction in the deviation of the RCS as a random value from the mathematical expectation σ_0. This corresponds to increased range and probability of detection.

Table 3.8 gives the values for the mathematical expectation of the RCS for bodies of varying configuration.

The mathematical expectations for the return surfaces of various aircraft are given in Table 3.9. The lower limit for the values of the RCS corresponds to a target below a zero aspect angle and the upper one below an aspect angle of 45°.

Table 3.8

Body design	Calculated ratios for determining RCS, m^2
Metal sphere with radius r	$\sigma_0 = \pi r^2$ (with $r \gg \lambda$)
Ellipsoid (paraboloid) with curve radii of r_1 and r_2	$\sigma_0 = \pi r_1 \cdot r_2$ (with r_1 and $r_2 \gg \lambda$)
Conducting reflection surface with side parameters a and b	$\sigma_0 = 4\pi \left(\frac{a \cdot b}{\lambda}\right)^2$ (with $a, b \gg \lambda$)
Metal cylinder with base radius r and generatrix ℓ	$\sigma_0 = \frac{2\pi r}{\lambda} \cdot \ell^2 \left(\text{with } \frac{2\pi r}{\lambda} \gg 1\right)$
Metal cone with base radius r and angle at apex α	$\sigma_0 = \pi r^2 tg^2 \frac{\alpha}{2}$ (with $r \gg \lambda$)

Table 3.9

Type of aircraft	α_0, m^2
Strategic bomber	10-20
Medium bomber	8-15
Fighter	1-2
Cruise missiles	0.1-1
BM warheads	0.001-0.01
Spacecraft	1-2

3.2.3. Radar Detection of Aircraft

Radar is a sector of radio electronics which determines the position of objects and obtains information on them by the receiving and analysis of radio waves.

Radar targets are radar objects, that is, physical bodies (for example, aircraft) information on which is of practical interest.

Depending upon the area of radar's application, targets can be: aerodynamic, ballistic and space, ground and surface or they can be targets of natural origin (ionized formations and trails, clouds, the accumulation of hydrometeors and so forth).

Radar information is the aggregate of information concerning the targets as obtained by radar methods.

Radar sets are technical devices used to obtain radar information.

The unified process of obtaining radar information can be conditionally divided into the following stages: acquisition or detection, the measuring of the coordinates and parameters of motion, the clearance and identification of the targets.

Detection is the process of taking a decision on the presence or absence of a target in the given area of space by receiving and statistically processing the total value s(t) of radar signals and interference n(t), that is, $y(t) = s(t) + n(t)$.

The taking of a decision occurs with two mutually exclusive conditions.

Conditions	A_1--target present; A_0--no target.	Decisions	A_1^*--target present; A_0^*--no target.

Consequently, there are four possible situations for the coinciding of the events of the "condition" and "decision" which are expressed by the conditional probabilities:

$$A_1^*/A_1; \quad A_0^*/A_1; \quad A_1^*/A_0 \text{ and } A_0^*/A_0.$$

The possibilities for the occurrence of these situations are characterized by the probabilities of the correct and incorrect decisions (P_{cd}--the probability of correct detection, P_{cn}--the probability of a correct nondetection, P_{fa}--the probability of a false alarm and P_{mi}--the probability of missing the target).

The total of P_{cd} and P_{mi} forms the total group of incompatible events, that is $P_{cd} + P_{mi} = 1$ ($P_{cd} = 1 - P_{mi}$). Analogously $P_{fa} + P_{cn} = 1$ ($P_{fa} = 1 - P_{cn}$). These ratios indicate that among the probabilities P_{cd}, P_{mi}, P_{fa} and P_{cn}, only two are independent and for this reason the probabilities P_{cd} and P_{fa} are used for describing the detection devices (and the radar as a whole).

The statistical nature of signal detection is determined by the values for the densities of interference distribution P_i and the mixture of signal and interference P_{si} which for a normal law have the appearance:

$$\left.\begin{aligned} P_{i}(y) &= \frac{1}{\sqrt{2\pi}\,\sigma} e^{-\frac{y^2}{2\sigma^2}};\\ P_{si}(y) &= \frac{1}{\sqrt{2\pi}\,\sigma} e^{-\frac{(y-s)^2}{2\sigma^2}}. \end{aligned}\right\} \qquad (3.39)$$

where σ--mean square deviation.

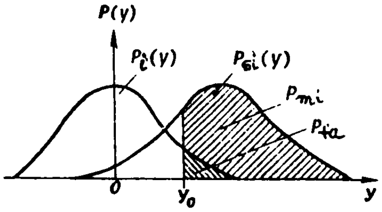


Fig. 3.27. Graphic representation of probabilities of correct detection and false alarm

With a known threshold value y_0 for the receiver

$$\left.\begin{aligned} P_{cd} &= \int_{y_0}^{\infty} P_{si}(y)\,dy;\\ P_{fa} &= \int_{y_0}^{\infty} P_{t}(y)\,dy. \end{aligned}\right\},$$

Graphically the values of P_{cd} and P_{fa} are shown in Fig. 3.27 (shaded areas).

The probability of correct detection P_{cd} is the probability of taking a decision on the presence of a target by isolating the signal against the background of interference under the condition that the target is actually present in the given volume of space, that is $P_{cd} = P(A_1^*/A_1)$. Of practical significance is:

$$P_{cd} = \frac{1}{2}\left[1 + \Phi\left(\frac{y - y_0}{\sigma}\right)\right] = 0.5 \div 0.99, \qquad (3.40)$$

where $\Phi(x) = \frac{2}{\sqrt{2\pi}} \int_0^x e^{-\frac{s^2}{2}}\,ds$ --error function the graph of which is shown in Fig. 3.28.

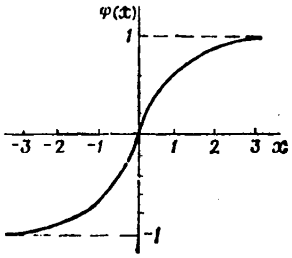


Fig. 3.28. Graph of error function

With $y = 0 P_{cd} = P_{fa}$; with $y = y_0 P_{cd} = 0.5$; with $y \gg y_0, P_{cd} \rightarrow 1$.

Probability of false alarm P_{fa} is the probability of taking a decision on the presence of a target under the condition that a target is absent in the given volume of space. Of practical significance is:

$$P_{fa} = \frac{1}{2}\left[1 - \Phi\left(\frac{y_0}{\sigma}\right)\right] = 10^{-4} \div 10^{-8}. \qquad (3.41)$$

The threshold value y_0 is determined by the value of optimization and the task being carried out by the detector.

Detection optimization are the regular solving rules for taking a decision on the presence or absence of a target under interference conditions.

In detection theory the following criteria are employed: Minimum average risk, a maximum of the liklihood ratio, the ideal observer, Neyman-Pearson, successive observer and others.

The most general optimization criterion for a detection system is the minimum average risk criterion which can be reduced to a so-called weighted criterion:

$$P_{cd} - \ell_0 P_{fa} = \max, \qquad (3.42)$$

where ℓ_0--a weighted multiplier determining the amount of the observer's threshold whereby a maximum value for the ratio of (3.43) is obtained.

The maximum liklihood ratio criterion is the corollary of the minimum average risk criterion

$$l(y) = \frac{P_{si.}(y)}{P_{l}(y)} = e^{-\frac{(s^2-2ys)}{2\sigma^2}}. \qquad (3.43)$$

The dependence of the liklihood ratio upon the amount of the total signal is shown in Fig. 3.29 where the value $\ell(y) > \ell_0$ is equivalent to the value $y > y_0$.

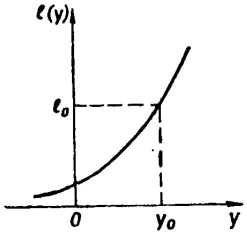


Fig. 3.29. Dependence of liklihood ratio upon amount of total signal

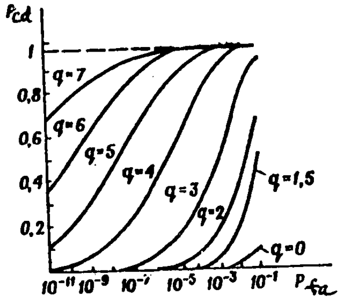


Fig. 3.30. Detection curves

If it is necessary to choose the threshold value directly for the set level of P_{fa}, then the Neyman-Pearson test is employed.

The detection parameter q is a dimensionless ratio of the energy E from the effective signal to the spectral density N_0 of the noise:

$$q = \frac{2E}{N_0}. \qquad (3.44)$$

The value of the detection parameter determines all the basic tactical characteristics of radars such as range and detection probability, the false alarm probability, the accuracy of measuring the coordinates and so forth.

The relationship between the values P_{cd} and P_{fa} is determined by the ratio

$$P_{cd} = P_{fa}^{\frac{2}{2+q}}. \qquad (3.45)$$

A graphic representation of this dependence is called the detection curves (Fig. 3.30).

An analysis of the detection curves indicates that an increase in the correct detection probability can be obtained either by increasing P_{fa} with q = const., or by increasing q with P_{fa} = const., and this corresponds to increasing the radar's potential.

An optimum receiver is a receiver which, with other conditions being equal, ensures a maximum value for the ratio of the effective signal energy to the noise spectral density q_{max}.

The total signal on the output of an optimum receiver is described by:

$$y_{out}(t) = \int_{-\infty}^{\infty} y(t)\, s(t-\tau)\, dt, \qquad (3.46)$$

where y(t)--the received signal;
s(t-τ)--expected signal;
τ--time shift between received and expected signals.

The physical sense of an optimum detection operation is that the multiplying of the receivable signal y(t) by the expected one s(t-τ) ensures the suppression of the noise not coinciding with the expected signal in time or in frequency.

The right-hand side of formula (3.46) is called the correlation integral. The correlation integral is solved by the constructing of either a correlation receiver or a receiver with an optimum filter.

A correlation receiver is a receiver which ensures the receiving of the correlation integral of (3.46) using a correlator, integrator and threshold device (Fig. 3.31a).

A receiver with an optimum filter is a receiver ensuring the receiving of the correlation integral of (3.46) using an optimum filter, a detector and threshold device (Fig. 3.31b).

Here s(t-τ) is the filter's response to the incoming effect in the form of a short pulse (the δ function) representing the mirror image of the probe pulse shifted by the arbitrary time τ. The advantage of the correlators is their flexibility and the possibility of rapidly shifting to various signal shapes and for this it is merely necessary to alter the s(t) function received by the multiplier's input.

An optimum filter is matched only with a certain shape signal and requires a substantial change in the circuitry for matching with another signal. However, the energy capabilities of these receivers (from the viewpoint of obtaining q_{max}) are approximately the same.

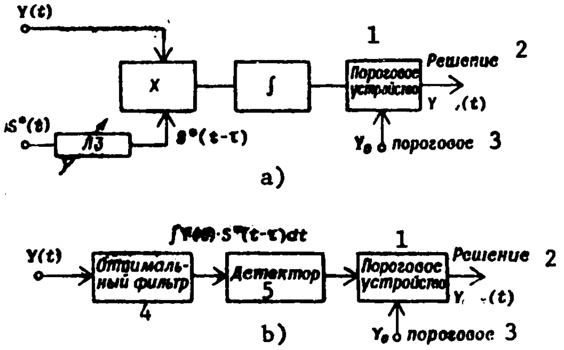


Fig. 3.31. Diagram of correlation receiver (a) and optimum filter receiver (b)

Key: 1--Threshold device; 2--Decision; 3--Threshold; 4--Optimum filter; 5--Detector

An automatic detector is a device ensuring the taking of a decision on the presence or absence of a target as a result of the corresponding processing of the signal and noise mix on the receiver output.

Automatic detectors are classified by their functional purpose.

Binary detectors are devices ensuring the taking of a decision on the presence or absence of a signal from the target.

Multiple alternative detectors are devices ensuring the taking of a decision on the presence or absence of signals from targets in each of the k clearance cells for the given volume of space.

In this instance the total number of possible decisions will equal 2^k.

Sequential detectors are devices ensuring the obtaining of the set probability of a correct decision with the least mean number of observations by introducing two thresholds: y_0 and y_1. The threshold levels are chosen in relation to a likelihood maximum:

$$\left.\begin{aligned} y_0 &= \frac{1-P_{cd}}{1-P_{fa}}; \\ y_1 &= \frac{P_{cd}}{P_{fa}}. \end{aligned}\right\} \qquad (3.47)$$

If the signal level lies between the limits between y_0 and y_1, a retesting is made.

Discrete Processes in Signal Detection

In practice, particularly with the use of electronic computers, often discrete processes are employed which can be divided into two categories: the formation of discrete samples and quantizing.

The forming of discrete samples is the selecting of discrete values of a continuous process with a limited spectrum making it possible to represent this process in the form of an expansion into a series for the nonrandom functions $\psi_k(t)$ with random coefficients y_k (the Kotel'nikov theorem):

$$y(t) = \sum_{k} y_k \psi_k(t), \tag{3.48}$$

where $y_k = y(t_k)$--the values of $y(t)$ in discrete equidistant moments of time $t_k = k\Delta t$ (with $k = 0, \pm 1 \pm 2 \ldots$), Fig. 3.32a, b;

Δt--discretization interval, $\Delta t = 1/2f_{max}$;

$\psi_k(t)$--functions of the type sin x/x reciprocally shifted for time Δt, that is,

$$\psi_k(t) = \frac{\sin[2\pi f_{max}(t-t_k)]}{2\pi f_{max}(t-t_k)}. \tag{3.49}$$

The restoring of the initial process $y(t)$ using the discrete samples is achieved by the convoluting of the y_k values with the $\psi_k(t)$ function (Fig. 3.32c).

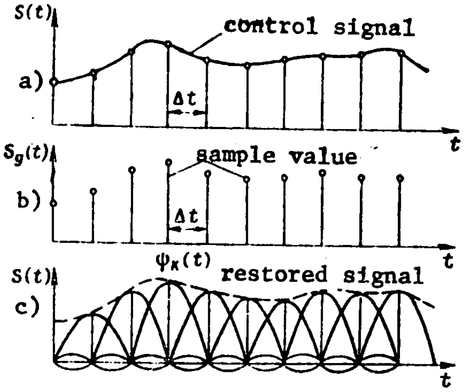


Fig. 3.32. Representation of continuous process in discrete form: a--control signal; b--characteristics of samples; c--restoring of signal

Thus, a discrete representation of continuous commands is provided for transmitting them to the aircraft and restoring these commands using the onboard equipment.

Quantization is the process of encoding the samples in a digital form. Quantization is carried out for the level (the size of the signals) and for time (for example, for the time of the signal delay, that is, for range). Moreover, special converters are introduced for the angular coordinates and these convert the shaft rotation angle into a figure.

In all instances the size of the signal, the time interval or the angular values are expressed in a discrete form, for example, as binary numbers and this makes it possible to calculate them on computers.

For carrying out a quantization operation, to the output of the receivers (Fig. 3.31) there are connected devices which transform the signal levels into a number and also a second threshold device which generates a decision on the presence of a target is the number of signals m exceeds a certain value m_0 determined by a certain criterion. Thus, a discrete detector performs the evaluation operation $m > m_0$.

Binary encoding is the process of converting individual samples or continuous signals into a binary code.

Any physical value expressed in fractions N can be converted into a binary code:

$$N = a_0 \cdot 2^0 + a_1 \cdot 2^1 + a_2 \cdot 2^2 + a_3 \cdot 2^3 + \ldots = \sum_{i=0}^{n} a_i \cdot 2^i, \tag{3.50}$$

where a_i--coefficients assuming the value 0 or 1 depending upon the amount of N, $i = 0, 1, 2, 3, \ldots, n$.

For example, $N = 10 = 0 \cdot 2^0 + 1 \cdot 2^1 + 0 \cdot 2^2 + 1 \cdot 2^3 = 0101$. Here $a_0 = 0$, $a_1 = 1$, $a_2 = 0$, $a_3 = 1$.

Consequently, the various physical values (aircraft coordinates, control commands, characteristics of an aircraft's motion and so forth) can be represented in a binary code and the various operations of the calculation can be done on a computer.

Radar Signals

The nature and quality of information received by a radar depends upon the structure and properties of the probe signals. Depending upon the radar's purpose, the probe signals provide: the required radiation energy for detecting aircraft at the set range with the subsequent measuring of their coordinates and parameters of motion, the required resolution of the aircraft and the corresponding neutralization of various interference.

The probe signals are characterized by a number of energy parameters, including:

Instantaneous active power $P(t)$ or the current power reading (watts) averaged over a period of time T_0 for the emitted oscillations $P(t) = u(t)i(t)$, where $u(t)$ and $i(t)$ are the instantaneous values of voltage and current averaged for the high frequency period T_0:

$$P(t) = \frac{1}{T_0} \int_0^{T_0} P(t)\,dt. \tag{3.51}$$

The greatest value of instantaneous capacity is termed the peak, that is, $P_{max}(t) = P_{pk}$.

Pulse power is the power averaged over the duration of a pulse τ_i:

$$P_i = \frac{1}{\tau_i} \int_0^{\tau_i} P(t)\,dt < P_{pk}. \tag{3.52}$$

For rectangularly-shaped pulses, the values of the pulse and peak powers coincide, that is $P_i = P_{pk}$.

Pulse energy E_i in joules:

$$E_i = \int_0^{\tau_i} p(t)\,dt = P_i \tau_i. \qquad (3.53)$$

Average power--the power averaged for the pulse repetition period T_p:

$$P_{av} = \frac{E_i}{T_p} = \frac{P_i}{Q}, \qquad (3.54)$$

where $Q = T_p/\tau_i$--relative pulse duration.

All the basic characteristics of radars related to the structure of the probe signals are generalized by the ambiguity function of these signals and this determines the capability of the radar to resolve [identify] an aircraft as well as for the accuracy and uniformity of measuring aircraft coordinates.

The ambiguity function (AF) of probe signals is a two-dimensional autocorrelation function $\rho(\tau, f)$ of the signals, simultaneously representing their structure both in terms of the time and spectral areas (Fig. 3.33).

$$\rho(\tau, f) = \frac{1}{E}\left| \int_{-\infty}^{\infty} s(t)\, s(t-\tau)\, e^{j2\pi f t}\, dt \right|. \qquad (3.55)$$

The narrower (sharper) the relief of the ambiguity function in the corresponding direction the greater the accuracy and resolution for range or speed. The cross-section of the AF along the frequency axis is the spectrum of a single pulse while the cross-section along the τ axis is its correlation function.

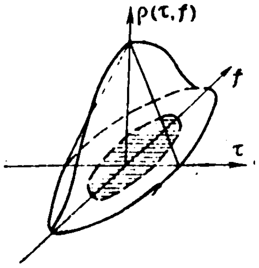


Fig. 3.33. Two-dimensional autocorrelation function of radar signal

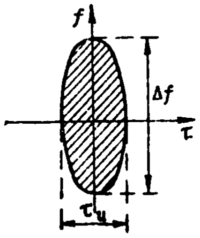


Fig. 3.34. Cross-section of two-dimensional autocorrelation function of pulse signal

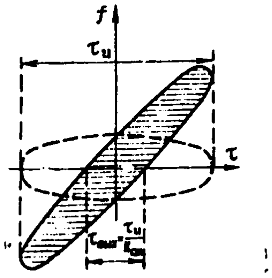


Fig. 3.35. Cross-section of two-dimensional autocorrelation function of LFM signal

Simple signals are radar probe signals the product of the length τ_i of which by the width of their spectrum Δf approximately equals one, that is, $\tau_i \Delta f \approx 1$.

Consequently, an increase in the duration of such signals leads to a reduction in their spectrum in an inversely proportionate dependence and vice versa. A drawback of such signals is the fact that an increase in radar range, in requiring an increase in τ_i (for increasing energy) worsens the range resolution.

Moreover, such signals do not ensure (without the taking of special measures) the speed resolution of an aircraft.

A cross-section of a two-dimensional correlation function for a rectalinear pulse signal in the form of an ellipse is shown in Fig. 3.34. It can conditionally be accepted that the differences in the range and speed of two or several aircraft can not be detected if the signals returned from them hit within the ellipse.

The principle of ambiguity in radar is a principle asserting that there is a certain ambiguity in the simultaneous determining of range and speed, that is, a gain in range resolution and accuracy is achieved at the expense of a worsening of these characteristics for speed and vice versa.

In altering the signal parameters it is only possible to redistribute this ambiguity, that is, to alter the shape of the ellipse without reducing its area.

Complex signals are radar probe signals the product of the duration $_i$ of which by the width of their spectrum Δf can be significantly greater than 1, that is, $\tau_i \Delta f \gg 1$.

This is achieved by introducing in-pulse modulation of frequency (frequency modulated signals) or phase (phase modulated signals).

A merit of these signals is that with a long duration of τ_i chosen to ensure great detection range, it is possible to provide the required range resolution by "compressing" the signal on the detector's output by the amount determined by the compression coefficient $K_{cm} \approx \tau_i \Delta f$.

Linearly frequency modulated (LFM) signals are signals the frequency of which during the pulse duration changes according to a linear law, that is,

$$f(t) = f_0 + \Delta f \frac{t}{\tau_i}.$$

The analytical expression of the signal is:

$$s(t) = s_0 \sin\left[\omega_0 t + \frac{\pi \Delta f}{\tau_i} t^2\right]. \qquad (3.56)$$

where f_0--initial frequency;
Δf--frequency deviation over signal's duration.

The signal compression coefficient $K_{cm} = \tau_i \Delta f$.

Consequently, the energy of a probe signal with a pulse power P_i equals $E = P_i \tau_i$, joules, while the signal's duration on the output of an optimum receiver is:

$$\tau_{out} = \frac{\tau_i}{K_{cm}} \approx \frac{1}{\Delta f}. \qquad (3.57)$$

Fig. 3.35 shows the cross-section of an ambiguity function for a LFM signal the boundaries of which on the time axis determine the size of the "compression" signal τ_{out}.

Phase-code manipulated (PCM) signals--signals for which a broadening of the spectrum is achieved by manipulating the phase according to a certain rule.

A PCM signal consists of N rectangular discretes with a duration $_d$ combined into a single signal with a duration of τ_i and having an analytical expression

$$s(t) = \sum_{K=0}^{N-1} (-1)^K \cos \omega t = f(t - K\tau_d)\, e^{j2\pi f_0 t}, \tag{3.58}$$

where the numbers K = 0, 1, 2,..., N - 1 form a sequence of zeroes and ones and this determines the phase alternation sequence.

The structure of a PCM signal, the form of recording the phase code and the cross-section of the AF are shown in Fig. 3.36.

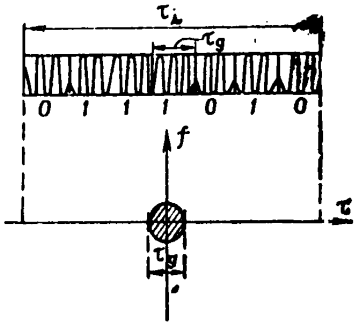


Fig. 3.36. Cross-section of two-dimensional autocorrelation function for a FCM signal

Here for a PCM signal, the following equalities are valid:

$$\tau_i = N\tau_d; \quad \tau_d = \frac{1}{\Delta f}; \quad \tau_i \Delta f = N = K_{cж}.$$

As a result of optimum processing on the filter output an output signal is obtained equal to $\tau_{out} = \tau_d$ (Fig. 3.36).

The phase of a PCM signal can be altered by skipping either $\phi = 0$ (code 0) or $\phi = \pi$ (code 1). However, a maximum value $q_{max} = 2E/N_0$ is achieved if an optimum code is employed and the phase is altered from zero to ϕ_0 equal to

$$\varphi_0 = \pi - \arccos\left(\frac{N-1}{N+1}\right). \tag{3.59}$$

If one takes an arbitrary initial number of n binary signs, then the total number of discretes of a PCM signal equals $2^n - 1 = N$ (with n = 3N = 7; with n = 4N = 15 and so forth).

The rule for obtaining an optimum code is:

$$K_i = K_{i-n} \oplus K_{i-1}, \tag{3.60}$$

where K_i--code of phase n + 1, n + 2,..., N discrete of PCM signal;
$\oplus$--the logical total of binary signs whereby $0 \oplus 0 = 0$; $0 \oplus 1 = 1$; $1 \oplus 1 = 0$.
For example, n = 011, that is, three signs, we obtain $2^3 - 1 = N = 0111010$, and this corresponds to the signal shown in Fig. 3.36. The signal has N = 7 discretes and a phase shift according to the law 0111010.

In the interests of increasing detection range, it is possible to provide the continuous emitting of a sequence of PCM signals whereby it is essential to solve the problem of eliminating the ambiguity in a certain range.

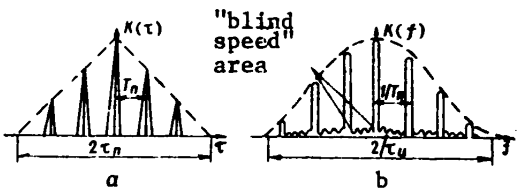


Fig. 3.37. Time (a) and spectral (b) representation of pulse sequence

A pulse sequence (cluster) is the basic type of space probing in pulse radar. Periodic pulse modulation by the frequency of the train of pulses F_s alters the structure of the spectrum and the type of correlation function the values of which are shown in Fig. 3.37 where the following symbols have been used: τ_c--duration of pulse cluster; t_i--duration of individual pulse; T_s--period of train of pulses equal to $T_s = 1/F_s$.

Fig. 3.37b shows the physical sense of "blind speeds" and which means that the Doppler frequency coinciding with the signal's intrinsic spectrum lines cannot be isolated at these points. It can be isolated in the intervals between the spectrum lines and this is the basis for designing coherent-pulse radars with selection of moving targets equipment.

3.2.4. Operating Range and Basic Characteristics of Ground and Onboard Radar Systems

Ground and airborne radars which solve the problems of detecting and measuring the coordinates of aircraft comprise a single class of radioelectronic systems, variations of which are shown in Fig. 3.38.

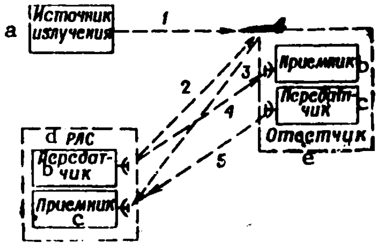


Fig. 3.38. Ground and airborne radar systems

Key: a--Radiation source; b--Transmitter; c--Receiver; d--Radar; e--Responder

With a certain combination of these devices together with their lines, we will obtain systems for various purposes: an active radar system with the second and third communications lines; a passive radar system with the third communications line; a semi-active radar system with the first and third communications lines; a response radar system with the fourth and fifth communications lines; remote control system with the fourth communications line.

Radar range is one of the most important tactical characteristics ensuring the carrying out of the combat mission to detect, track and measure the coordinates of aircraft.

Range in free space for pulse radars with modern receiving and transmitting antennas in meters is:

$$D_0 = \sqrt[4]{\frac{P_t G_0^2 \lambda^2 \sigma_t}{(4\pi)^3 P_{re\,min} q K}}. \tag{3.61}$$

where P_i--pulse power, watts;
G_0--antenna gain;
λ--wave length, meters;
σ_t--radar cross-section of target, m^2;
$P_{re\ min}$--receiver sensitivity, watts;
q--detection parameter;
K--resulting loss coefficient.

The system's loss coefficient. The loss coefficient K takes into account various losses in the radar transmitting and receiving channels. In a general form the resulting loss coefficient can be represented as the product of $K = \prod_{t=1} K_t$, where K_i--partial coefficients describing losses in various radar elements.

Calculating the loss coefficients of K_i is a specific task which takes into account the particular features of each specific radar set.

However, for practical purposes it is possible to make an approximate quantitative assessment of these coefficients:

K_1--loss coefficient considering the mismatching of the radar receiver pass band with the spectrum of the probe signal; approximately $K_1 \approx 0.9$ decibel ($K_1 \simeq 1.23$);
K_2--coefficient considering fluctuation losses related to a fluctuation in the return signals $K_2 \simeq 1.5$ decibel ($K_2 \simeq 1.44$) under the condition of providing a correct detection probability $P_{cd} = 0.5$;
K_3--coefficient considering losses of postdetector integration (noncoherent integration):

$$K_3 = 10(1-\gamma) \log n,$$

where γ--coefficient characterizing integration quality;
n--number of integrated pulses.

Under the condition that $\gamma \simeq 0.8$, $K_3 = 2 \log n$. If the number of integrated pulses $n = 10$, then $K_3 = 2$ decibels ($K_3 \simeq 1.58$).

The detection coefficient q_n obtained by postdetector integration of n pulses is expressed by the coefficient for detecting a single signal q_1:

$$q_n = q_1 n^{0.8}.$$

K_4--a coefficient considering losses due to the accumulation of noise on the indicator screen; $K_4 = f(\rho)$, where $\rho = \frac{m+n}{n}$ (m, n--the numbers of noise and signal samples, respectively).

With $m = n = 10$, $K_4 = 0.5$ decibel ($K_4 \simeq 1.22$).

Thus, considering the listed factors the total decay coefficient, decibels:

$$K = K_1 + K_2 + K_3 + K_4 \approx 4.9,$$

and this coincides to a resulting value for the loss coefficient $K = K_1 K_2 K_3 K_4 \approx 3.14$.

In substituting the value of the resulting loss coefficient K in equation (3.61) we obtain a calculation formula making it possible to determine radar range considering the probability of detection $q > 1$ (see Fig. 3.30). With $q = 1$, equation (3.61) provides an opportunity to determine the maximum detection range with a correct detection probability $P_{cd} \approx 0.5$.

All the given ratios are valid under the condition that the losses in the transmitting path are considered by substituting into equation (3.61) the values of the emitted power on the antenna output, that is $P_i P_{out}$. Here $P_{out} = P_g \eta$, where P_g--the power on the output of the radio-frequency generator; η--efficiency of antenna-feeder path ($\eta < 1$). The method of calculating the losses by incorporating the resulting coefficient K can be employed with various modifications of the range equation (3.62), (3.63).

Considering the decay coefficient of the electromagnetic waves in the atmosphere α (decibel/km) in the interval of passing through an absorbing medium ℓ (km), formula (3.8) assumes the form

$$D = \sqrt[4]{\frac{P_g \eta G_0^2 \lambda^2 \sigma_t}{(4\pi)^3 P_{re,\,min} q K}} \cdot 10^{-0,005\alpha\ell}. \tag{3.62}$$

The operating range of a continuous wave radar is:

$$D_c = \sqrt[4]{\frac{E G_{tr} G_{re} \lambda^2 \sigma_t}{(4\pi)^3 N_0 q K}} \cdot 10^{-0,005\alpha\ell}. \tag{3.63}$$

where $E = P_{av}\tau = P_{av}/\Delta f_p$--the amount of energy emitted into space, joules;
Δf_p--receiver pass band, hertz;
P_{av}--average radiating power, watts;
N_0--noise spectral density, watts/hertz;
G_{tr}, G_{re}--gains of transmitting and receiving antennas.

Operating range considering attenuation of EM waves in the ionosphere is determined by formulas (3.9), (3.62) and (3.63).

A diagram of the pulse and continuous-wave radars is shown in Fig. 3.39a and b.

Radar operating range considering probability of detection can be determined by the probability distribution function shown in Fig. 3.40:

$$P(D) = e^{-\left(\frac{D}{D_0}\right)^4}.$$

where D--current range value changing from zero to D_{max};
D_o--determined by formulas (3.62) and (3.63).

In Fig. 3.40, curve 1 corresponds to the distribution function with single-frequency illumination and curve 2 with double-frequency illumination of the target.

The values of D_1 and D_2 describe the detection range for a certain type of aircraft with the probability $P_{cd} = 0.9$ for single- and double-frequency target illumination.

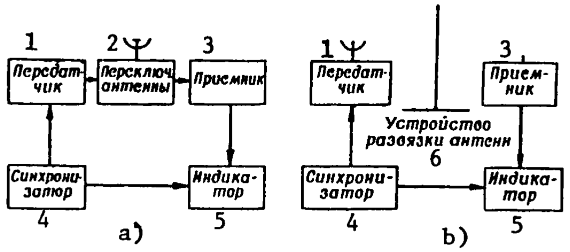


Fig. 3.39. Schematic diagram of pulse (a) and continuous-wave (b) radars

Key: 1--Transmitter; 2--Antenna switch;
3--Receiver; 4--Synchronizer; 5--Indicator;
6--Antenna duplexer

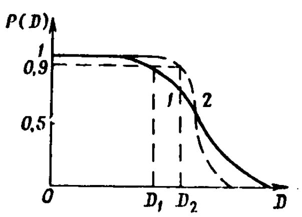


Fig. 3.40. Graph for radar operating range considering probability of detection with single-frequency (1) and double-frequency (2) illumination

The values of these ranges are determined by the threshold level (Fig. 3.40).

The radar operating range considering the earth's influence with low elevations is

$$D(\varepsilon) = 2\sqrt{\frac{\pi h H_t}{\lambda}}\,\sqrt[8]{\frac{P_i G_0^2 \lambda^2 \sigma_t}{(4\pi)^3 P_{re\,min}\, qK}}, \tag{3.64}$$

where h and H_t--height of radar antenna and target over earth's surface, meters [for remaining values, see formula (3.61)].

Line-of-sight range $D_{\ell s}$--the maximum distance for the detection of aircraft by ground radars considering the earth's curvature, km:

$$D_{\ell s} = 4.1(\sqrt{h} + \sqrt{H_t}), \tag{3.65}$$

where h--height of antenna, m;
H_t--target height, m.

Operating range of systems with response (radio communications equation):

$$D_a = \frac{\lambda}{4\pi}\sqrt{\frac{P_i G_{tr} G_{re}}{P_{re\,min} q K_a}}, \tag{3.66}$$

where P_i and G_{tr}--pulse power (watts) and gain of sending radar;
$P_{re\ min}$, q, G_{re}--receiver sensitivity (watts), detection parameter and antenna gain of receiving radar;
$K_a = K_1K_3K_4$--loss coefficient; $K_a \simeq 2.2$ with $K_2 = 1$.

Methods of Measuring Range to Noise Sources

The triangularion method is a method of range finding for noise sources consisting of two or more separated receiving points (Fig. 3.41) one of which is located at point 0 and the remainder in points A and B.

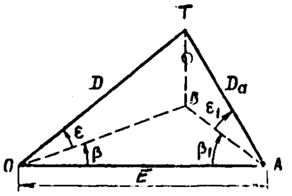


Fig. 3.41. Triangulation method for determining range

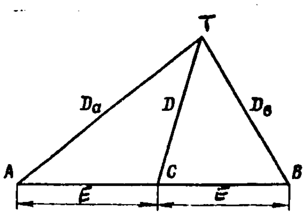


Fig. 3.42. The different range method for determining distance

The distance to the noise source is:

$$D = \frac{E}{\cos\varepsilon\,(\cos\beta - \sin\beta\,\mathrm{ctg}\,\beta_1)}. \qquad (3.67)$$

where E--the base between points 0 and A, m;
ε, β, β_1--elevations and azimuth of source measured relative to points 0 and A.

The angle and different range method is a method based upon measuring the angular directions to the noise source and the difference in the ranges between the target and point 0 and the target and point A (Fig. 3.41).

The distance is:

$$D = \frac{E^2 - \Delta D_a^2}{2(E\cos\beta\cos\varepsilon - \Delta D_a)}. \qquad (3.68)$$

where ΔD_a--the difference in determining distances to the noise source between points 0 and A, m.

The different range method is a method based on measuring the difference in the distances between the noise source and points 0 and A (Fig. 3.42).

The distance is:

$$D = \frac{2E^2 - \Delta D_a^2 - \Delta D_\text{в}^2}{2(\Delta D_a + \Delta D_\text{в})}. \qquad (3.69)$$

where E--the base between points O and A, m;
ΔD_a, ΔD_b--differences in distances to noise source between points located at points A and B, m.

For the second and third methods, the difference in the ranges ΔD_a and ΔD_b is determined by setting a special correlator at point O which considers the significance of the base (E) between the points and the time lag τ_d, that is, $\Delta D = \tau_d - E$.

Basic Radar Units and Performance

Transmitters are single- or multiple-stage devices which shape and generate high frequency probe signals with set values of shape and output power.

Transmitters are classified by the type of generating devices, including: tube, magnetron, amplitron, klystron, platinotron and others.

A diagram of single- and multiple-stage transmitters is shown in Fig. 3.43. In shaping the signals with in-pulse modulation, transmitters include elements for encoding and phase and frequency control.

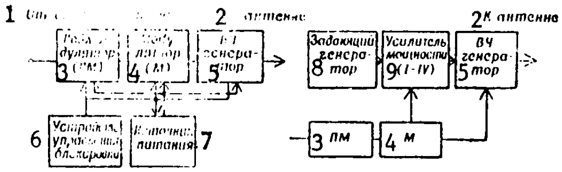


Fig. 3.43. Schematic diagram of single-stage (a) and multi-stage (b) transmitter

Key: 1--From synchronizer; 2--To antenna; 3--Driver device; 4--Modulator; 5--Radio-frequency generator; 6--Interlocking device; 7--Power source; 8--Master oscillator; 9--Power amplifier (I-IV)

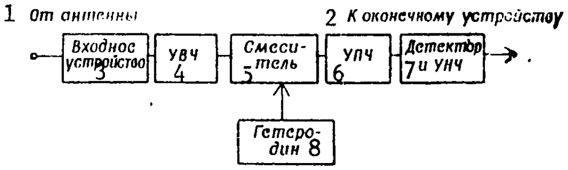


Fig. 3.44. Schematic diagram of super heterodyne-type receiver

Key: 1--From antenna; 2--To terminal; 3--Input; 4--High-frequency amplifier; 5--Mixer; 6--Intermediate-frequency amplifier; 7--Detector and low-frequency amplifier; 8--Heterodyne

Receivers are devices which separate signals of a certain frequency and shape with their subsequent amplification and transformation into a type required for the operation of the terminal.

A diagram of a super heterodyne-type receiver is shown in Fig. 3.44. Depending upon the purpose of the radar and the type of probe signal, optimum detection devices can be located on the receiver input or on the mixer's output.

Receiver sensitivity ($P_{re\ min}$)--the minimum value (watts) for the average signal power on the receiver input which ensures a ratio of signal strength to noise strength equal to one:

$$P_{re\ min} = KNT_0\Delta f_p, \tag{3.70}$$

where $K = 1.38 \cdot 10^{-23}$--the Boltzmann's constant, joules/degree;
N--receiver noise factor;
f_p--receiver pass band, hertz;
T_0--temperature.

In practice the concept of threshold sensitivity is used, that is, the sensitivity which ensures the receiving and detection of the returned signals with the desigated probability:

$$P_{thr} = P_{re\ min} \cdot q, \tag{3.71}$$

where q--detection parameter [see formula (3.44)].

The sensitivity $P^*_{re\ min}$ is usually expressed in decibels:

$$P^*_{re\ min} = 10 \log \frac{P_{r\ell}}{P_{re\ min}},$$

where $P_{r\ell}$--the value of the power corresponding to the read level, watts (for example, with $P_{r\ell} = 10^{-3}$ watts and $P_{re\ min} = 10^{-14}$ watts, $P^*_{re\ min} \approx 110$ decibels).

The recalculation formula is:

$$P_{re\ min} = P_{r\ell} \cdot 10^{-\frac{P^*_{re\ min}}{10}}. \tag{3.72}$$

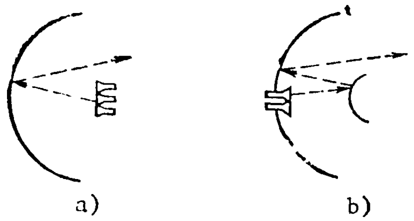
Antennas are devices providing directional radiation and the receiving of the electromagnetic waves. The antennas possess the property of reversibility and are classified in the following types: single-reflector, multiple reflector and antenna arrays.

Single-reflector antennas are a design consisting of a reflector and a feed (Fig. 3.45a). As a reflector it is possible to use a parabolic cylinder, a truncated paraboloid and so forth and as the feeds the individual elements or line arrays which consist of dipoles, slots and horns.

The position of the directional pattern (DP) is controlled by the mechanical turning of the entire antenna or within a limited sector by altering the position of the feed.

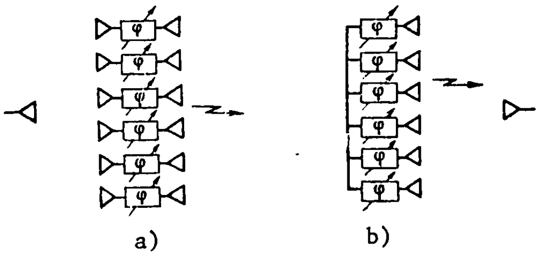
Multi-reflector antennas consist of large (parabolic) and small (hyperbolic) reflectors (Fig. 3.45b). Electromechanical scanning of the DP with a stationary antenna can be provided by turning the feed or the small reflector providing a scanning which surpasses by 2-2.5-fold the turning angles in a single reflector antenna.

The phased antenna arrays (PAA) are a system of feeds (elements) in which the DP is moved in space by introducing variable phase shifts between the signals emitted or received by the individual elements.



a) b)

Fig. 3.45. Single-reflector (a) and multi-reflector (b) antennas



a) b)

Fig. 3.46. Phased antenna arrays designed according to the pass-through (a) and return (b) systems

A distinction is made between three basic types of PAA: with passive elements, with active elements and of the matrix type. A PAA with passive elements can be constructed according to "pass-through" (Fig. 3.46a) and return (Fig. 3.46b) systems. A PAA with active elements includes a system of oscillators, phase shifters and feeds controlled by a computer.

Basic ratios in single-reflector and multi-reflector antennas. With a set wave length λ and antenna dimensions L, it is possible to determine:

The width of the directional pattern θ in the planes of the azimuth θ_β and elevation θ_ε, rad.:

$$\theta_\beta = K\frac{\lambda}{L_\beta},\ \theta_\varepsilon = K\frac{\lambda}{L_\varepsilon}, \qquad (3.73)$$

where L_β, L_ε--antenna dimensions in the azimuth and elevation planes;
K--proportionality factor ($K \approx 0.88$).

Antenna gain G_0

$$\left.\begin{aligned} G_0 &= \frac{4\pi S_{ef}}{\lambda^2}; \\ S_{ef} &= K_a S_{geom}, \end{aligned}\right\} \qquad (3.74)$$

where S_{ef}, S_{geom}, K_a--the effective and geometric areas and the utilization factor of the antenna's area, respectively.

For the various types of antennas $K_a = 0.5\text{-}0.7$.

The relationship of gain to the directional pattern:

$$G_a = \frac{4\pi}{\theta_\beta \theta_\varepsilon} \approx K_a \frac{40\,000}{\theta^\circ_\beta \theta^\circ_\varepsilon} \approx \frac{25\,000}{\theta^\circ_\beta \theta^\circ_\varepsilon}, \tag{3.75}$$

where θ_β, θ_ε--width of directional pattern, rad.;
θ°_β, θ°_ε--width of directional pattern, degrees;
K_a--accepted as equal to 0.6.

Basic ratios in phased antenna arrays. With the set width of the scanning sector in the azimuth β_{ck} and elevation ε_{ck} planes, it is possible to establish the basic dependences in the antenna arrays.

The distance between the array elements is usually chosen as equal to one-half the wave length: $d = \lambda/2$.

The total number of active (passive) elements in a flat array is:

$$N \approx \frac{\beta_{ck} \varepsilon_{ck}}{4 \theta_\beta \theta_\varepsilon}. \tag{3.76}$$

The width of the directional pattern in the corresponding plane is:

$$\theta = K \frac{\lambda}{L \cos \alpha}. \tag{3.77}$$

where α--the angle between the perpendicular to the array's plane and the position of the DP at the given moment.

If one assumes the possibility of broadening the DP with a 2-fold deviation from the perpendicular to the plane, then $1/\cos \alpha = 2$, that is, $\alpha = \pm 60^\circ$.

Consequently, the scanning sector $\theta_{ck} = 2\alpha = 120^\circ$.

For practical calculations the normed DP of an antenna, as a function of an angle in the corresponding plane, can be approximated by the ratios:

$$\left.\begin{aligned} F^2_{(\varepsilon)} &= e^{-\frac{2{,}78}{\theta^2_\varepsilon}\varepsilon^2} \text{ — for half-power level;} \\ F(\varepsilon) &= e^{-\frac{1{,}39}{\theta^2_\varepsilon}\varepsilon^2} \text{ — for field directivity.} \end{aligned}\right\} \tag{3.78}$$

Indicators (IU) are devices which provide the observance of the air situation, the detection and measuring of coordinates of an aircraft. The composition and type of indicator are determined by the radar's purpose.

The following types of indicators are recognized:

Plan position indicators (Fig. 3.47a, b);

Azimuth--range sector indicators (Fig. 3.48a);

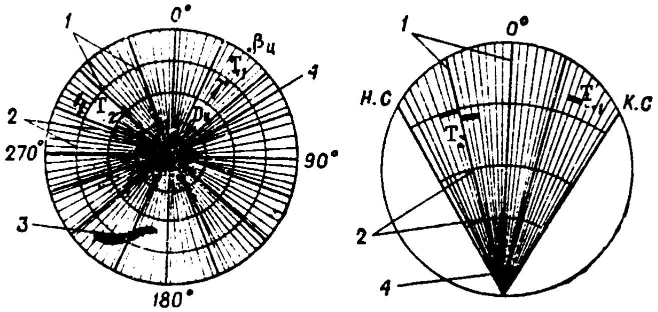
Range-speed indicators (Fig. 3.48c);

H--D and ε--D altitude measuring indicators (Fig. 3.48b);

Semiautomatic plotting indicators;

Indicators with linear and circular scanning (Fig. 3.49a, b);

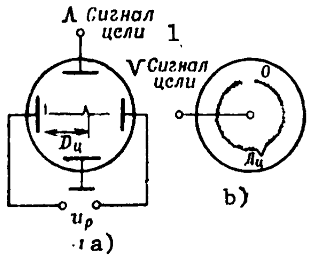
Digital indicators or displays.



a) b)

Fig. 3.47. Plan position indicators:

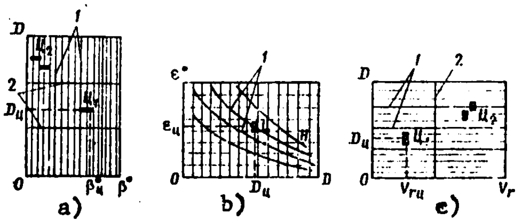
a--Circular mode; b--Sector mode (1, 2, 3, 4--respectively, the scale marks β, D and the blips from a group target and terrain features)



a) b)

Fig. 3.48. Sector indicators:

a--Azimuth--range (1, 2--correspondingly, the scale marks of β and D); b--Elevation--range (1--equal elevation lines); c--Range--speed (1, 2--respectively, the scale marks of D and V)



a) b) c)

Fig. 3.49. Indicators:

a--With linear scanning; b--With circular scanning; 1--Target signal

The effect of the indicators on detection range is determined by the value of the q coefficient which has been given the name for the particular case of the discrimination factor (formula 3.44).

For the normal operation of an indicator it is essential to provide a value of $q \approx 2\text{-}3.5$. The linear dimension of the target blip on the indicator is:

$$\ell = \frac{D_{sc}}{L_p} d_s, \qquad (3.79)$$

where D_{sc}--gradation of scale on screen;
L_p--linear dimension of scan;
d_s--diameter of spot on screen.

Radar resolution considering effect of indicators is the capacity to provide separate observation and measuring of coordinates for two nearby targets.

Range resolution is:

$$\delta D = \frac{c(\tau_i + \Delta\tau)}{2K_{cm}} + \frac{D_{sc}}{L_p} d_s, \qquad (3.80)$$

where c--EM wave propagation velocity;
τ_i, $\Delta\tau$--duration and amount of expansion of return signal;
K_{cm}--signal compression coefficient at output of optimum receiver (for pulse signals without in-pulse modulation $K_{cm} = 1$).

Resolution for angular coordinates (for azimuth and elevation):

$$\left.\begin{aligned} \delta\beta &= \theta_\beta + \frac{\beta_{sc}}{L_p} d_s; \\ \delta\varepsilon &= \theta_\varepsilon + \frac{\varepsilon_{sc}}{L_p} d_s, \end{aligned}\right\} \qquad (3.81)$$

where β_{sc}, ε_{sc}--the sector amounts for azimuth and elevation, degrees;
L_p--linear dimension of azimuth (elevation) scan.

Height resolution is the minimum measurable difference in the heights of two targets located at the same distance and under the same azimuth:

$$\delta H = \frac{\theta_\varepsilon D}{\cos\varepsilon} + \frac{\varepsilon_{sc}}{L_p} d_s. \qquad (3.82)$$

where ε_{sc}, ε--amount of elevation sector and current elevation value.

Radar resolvable volume--a part of space in the radar's view zone limited by distances equal to the resolutions for D, β, ε, that is,

$$\delta V = D^2 \delta D \delta\beta \delta\varepsilon. \qquad (3.83)$$

The principle of measuring target height. Considering the spherical earth, the height of an aircraft (target) over the earth's surface depending upon distance D is

$$H = D\sin\varepsilon + \frac{D^2}{2R_e}. \qquad (3.84)$$

where ε--target elevation;
$R_e \approx 8500$--effective radius of earth, km.

The second component increases with an increase in distance and for this reason for calculating height on the range--height indicators, nonlinear graphs are applied which reflect the dependence of (3.84).

The radar detection zone is an area of space on the boundary of which targets with a certain RCS are detected with a set probability.

The boundary of the detection zone is determined by the resulting directional pattern and the view limit (circular or sector).

The cross-section of the detection zone in a vertical plane not considering the earth's influence $D(\varepsilon) = DF(\varepsilon)$, where $F(\varepsilon)$--the antenna's directional pattern in plane ε.

Considering the earth's influence, a radar antenna receives signals returned from the target s_1 and from the earth's surface s_2, here:

$$\left.\begin{aligned} s_1 &= s_0F(\varepsilon-\varepsilon_0);\\ s_2 &= s_0\rho F(\varepsilon+\varepsilon_0), \end{aligned}\right\}$$

where ρ--modulus of reflection coefficient;
ε, ε_0--respectively the current value of the target's elevation and the slope angle for the maximum DP to the horizon.

According to the theorem of cosines, the total value of these two signals having the phase shift ϕ:

$$S = \sqrt{s_1^2 + s_2^2 + 2s_1s_2\cos\varphi} = s_0F_{\varepsilon}.$$

where $F_e = \sqrt{F^2(\varepsilon-\varepsilon_0) + \rho^2F^2(\varepsilon+\varepsilon_0) + 2\rho F(\varepsilon-\varepsilon_0)F(\varepsilon+\varepsilon_0)\cos\phi}$--the resulting DP for the receiving antenna in a vertical plane considering the earth's influence.

With $\varepsilon_0 = 0$ which corresponds to the condition of the positioning of the directional pattern maximum parallel to a horizontal surface whereby the influence of the earth is felt, we obtain

$$F_{\varepsilon} = F(\varepsilon)\sqrt{1 + \rho^2 + 2\rho\cos\varphi}. \qquad (3.85)$$

In the general instance, the phase shift is:

$$\phi = \phi_x + \phi_0,$$

where ϕ_x--phase shift due to difference in the path of the direct (from the target) signal and the signal returned from the earth;
ϕ_0--phase shift with the reflecting of EM waves from the earth.

For a meter-band radar with horizontal polarization with all angles of ε from zero to 90°, $\rho \approx 1$, $\phi_0 \approx \pi$, we obtain

$$F_\varepsilon = F(\varepsilon)\cdot 2\sin\frac{\varphi_x}{2}.$$

With a set antenna height h, the phase shift is:

$$\varphi_x = \frac{2\pi}{\lambda}\cdot 2h\sin\varepsilon.$$

Consequently, $F_e = F(\varepsilon)\phi(\varepsilon)$, where $\phi(\varepsilon) = 2\sin(2\pi/\lambda\ h\sin\varepsilon)$ is termed the earth multiplier.

For small angles of ε, the obtained value of the earth's multiplier is also valid for vertical polarization.

Formula (3.85) makes it possible to calculate the detection zones for the conditions of an even earth surface while consideration of the effect of an uneven surface is carried out using a special method or by a radar overflight.

Target identification is the putting of a detected target in a certain class (type) on the basis of analyzing the features inherent to the given target.

As the features it is possible to use the target's dimensions, configuration, the nature of the cross-section, the characteristics of the jet engine, the law of motion, the type of radiation from the onboard systems and so forth.

The listed features are assessed by analyzing the aggregate of the returned signals and the laws of motion of the aircraft.

Identification probability P_{id}. If it is necessary to solve the problem of identifying two detected aircraft from K features, each of which is measured n times, then the identification probability is:

$$P_{id} = \frac{1}{2}\left[1 + \Phi\left(\frac{m_2 - m_1}{2\sigma_1}\sqrt{nK}\right)\right]. \qquad (3.86)$$

where m_1, m_2--mathematical expectation for the value of the feature of the first and second targets;
σ_1--mean square error in assessing feature;
n--number of measurements of feature;
K--number of feature;
$\phi(x)$--error function (see Fig. 3.28).

The dependence of identification probability upon the number of features is shown in Fig. 3.50. There is an optimum number of specific features which ensures a maximum value of the identification probability.

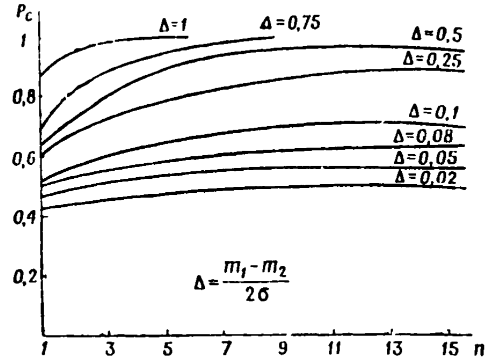


Fig. 3.50. Dependence of object identification probability upon number of features

3.2.5. Target Detection by Optoelectronic Equipment*

Optoelectronic equipment (OEE) is equipment utilizing the optical band of the EM wave spectrum for receiving and transmitting information and various electronic devices for converting the information.

The basic types of OEE are television (TV), infrared (IR), optovisual (OV) and laser (LS).

The detection of targets using OEE is based upon the principles of active radar location for lasers and passive location for the remaining types of the OEE. The operating range of the active and passive radar OEE depends upon their technical data, the characteristics of the returned or emitted properties of the targets and the conditions of optical band wave propagation.

Operating range of active OEE, meters:

$$D_n = \sqrt[4]{\frac{P_{rp} S_{re} \sigma_t}{\pi \theta_{dp}^2 P_b q}}\, e^{-\frac{1}{2}\gamma l}, \qquad (3.87)$$

where P_{rp}, θ_{dp}--emitted power (watts) and width of directional pattern, rad.;
S_{re}--area of receiving aperture, m^2;
σ_t--target radar cross-section, m^2;
P_b--power of background radiation, watts;
q--detection parameter;
γ--radiation attenuation factor in atmosphere, decibel/km;
ℓ--path traveled by beam in dense layers of atmosphere, km.

Thermal radiation of an aircraft in flight, in the infrared (IR) band, occurs as a consequence of the aerodynamic heating of the structure, the running of the jet engine and the effect of solar radiation.

The distribution of radiation intensity J_{ri} for an absolutely black body is determined using Planck's law, watts/cm^3:

$$J_{ri} = \frac{c_1}{\lambda^5} \frac{1}{e^{\left(\frac{c_2}{\lambda T}\right)} - 1}. \qquad (3.88)$$

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* From materials of the foreign press.

where the constants $c_1 = 3.74 \cdot 10^{-12}$ watts cm^2, $c_2 = 1.4$ cm•K; T--absolute temperature of heated body, K.

The radiation intensity of real bodies is:

$$J = \varepsilon J_{ri}, \tag{3.89}$$

where ε--spectral radiation coefficient ($\varepsilon \approx 0.7$ for a nickel alloy in the maximum radiation area).

The dependence of J upon wave length is shown in Fig. 3.51a.

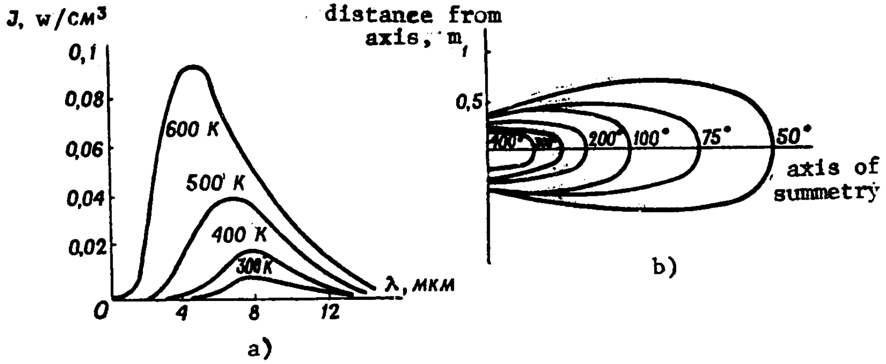


Fig. 3.51. Intensity (a) and indicatrices (b) of target thermal radiation

Radiation indicatrix is the geometric place of points in space characterizing the radiation levels of uniform intensity.

A vertical cross-section for the thermal radiation indicatrix of a jet aircraft is shown in Fig. 3.51b.

Operating range of passive IR systems:

$$D_{ir} = \sqrt{\frac{J_{ri} \varepsilon S_t}{\pi \theta_\lambda \omega_{re} q}} e^{-\frac{1}{2}\gamma l}. \tag{3.90}$$

where S_t--area of target's projection;
θ_λ--spectral density of background radiation, watts/m^2•Å av;
ω_{re}--receiver field of vision angle, av;
J_{ri}, ε, q have been determined in formulas (3.88), (3.89), (3.44).

Operating range of TV systems:

$$D_{tv} = \sqrt{\frac{B_\lambda S_t r_t S_{re} \Delta\lambda}{\pi P_b q}} e^{-\frac{1}{2}\gamma l}. \tag{3.91}$$

where B_λ--spectral density of target surface radiation S_t as a consequence of its illumination by the sun, watts/$m^2 \cdot Å$ av;
r_t--target reflection coefficient;
P_b--power of background radiation, watts.

The variables given in formulas (3.87)-(3.90) have the values:

$$P_b \approx 10^{-17} \text{ watts}, \; Q_\lambda = 3 \cdot 10^{-2} \text{ watts}/(\text{cm}^2 \cdot \text{mcm} \cdot \text{av})\text{--}$$

for a daytime sky;

$$Q_\lambda = 10^{-8} \text{ watts}/(\text{cm}^2 \cdot \text{mcm} \cdot \text{av})\text{--}$$

for a nighttime sky:

$$q = 2\text{-}3; \; B_\lambda = 10^{-2} \text{ watts}/(\text{cm}^2 \cdot \text{mcm} \cdot \text{av}); \; r_t = 0.2\text{-}0.8.$$

Range resolution. Only the active OEE operating in a pulse mode possess range resolution.

The value of range resolution, like for radar, is determined by the amount of the signal length τ_c which is considered in the estimate:

$$P_b = n_{av} h \nu \tau_c,$$

where n_{av}--average number of photons in the signal;
h--Planck's constant;
ν--radiation frequency.

Resolution for angular coordinates $\delta\theta$:

For active systems $\delta\theta_a = \theta_{dp}$;

For passive IR systems $\delta\theta_p = \omega_{re}$;

For TV systems $\delta\theta_{tv} = \frac{\Omega}{b} d_s$,

where Ω--field of vision angle for transmitting tube;
b--target width of transmitting tube;
d_s--diameter of scanning beam (spot);
θ_{rp}--half-angle of oscillator beam.

3.3. Methods of Determining Coordinates and Parameters of Motion for Air Attack Weapons

3.3.1. Distance Measuring Devices

Determining the distance and angular coordinates of objects is based upon the rectalinearity of radio wave propagation and their constant velocity. Distance to a target can be measured by radar and optical devices. For this the time is determined for the signal to pass from the source of radiation to the target and back:

$$D_t = \frac{ct_{pd}}{2}, \tag{3.92}$$

where c--propagation velocity of electromagnetic energy;
t_{pd}--time for signal to reach target and return (signal delay time).

The time t_{pd} can be measured from the delay in the pulse return from the target, from the amount of the change in transmitter frequency and from the amount of the change in the radar signal phase. Because of this, three methods of determining range are distinguished.

Measuring distance by radar means

The pulse method is a method whereby a radar sends toward the target a short-duration, high-frequency pulse. The moments of sending and receiving the pulse are recorded on the time scan of the indicator (Fig. 3.52a). During the time the pulse travels to the target and back, the beam of the CRT draws on the screen a line the length of which is proportional to the target's range and this can be read off from the mechanical or electronic scale of the indicator.

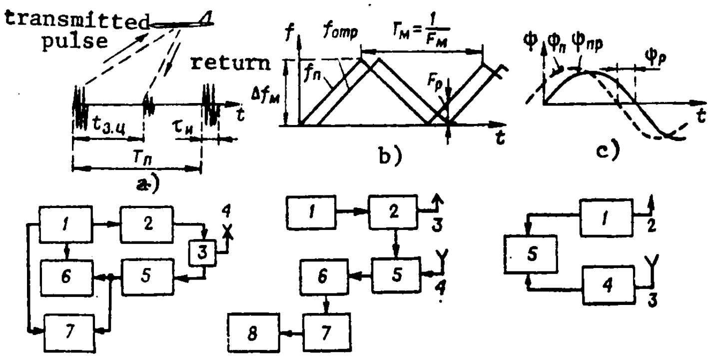


Fig. 3.52. Methods of measuring distance:

a--Pulse; b--Frequency; c--Phase

With the pulse method, radar range resolution is:

$$\Delta D = \frac{c\tau_i}{2} + M_D d_s, \tag{3.93}$$

where τ_i--duration of transmitter pulse;
M_D--scale of indicator range scan;
d_s--diameter of CRT electron spot.

The range of the uniform determination of distance $D_{t\ max} = cT_p/2$, where T_p--the transmitter pulse repetition period.

The minimum target distance measurable by a pulse radar is:

$$D_{t\ min} = \frac{c(\tau_i + t_r)}{2},$$

where t_r--the receiver sensitivity recovery time.

The merits of the method are: the possibility of measuring distance and identifying many targets, comparative simplicity; the shortcomings are: the impossibility of measuring short distances and the high radiation pulse power.

The frequency method is a method whereby the delay time of the signal returned from the target is measured by the amount of transmitter frequency change. The transmitter sends electromagnetic energy with a linearly changing frequency for the high-frequency oscillations (Fig. 3.52b). During the time the radio waves travel to the target and back to the receiver, the transmitter frequency will change by the amount:

$$\Delta f_t = \eta_p \frac{2D_t}{c}, \qquad (3.94)$$

where η_p--the rate of change in the frequency of emitted oscillations.

The signals received from the target and the high frequency transmitter oscillations go to the receiver mixer, where a difference frequency is isolated:

$$\Delta F_p = f_t - f_{re} = \frac{4\Delta F_m D_t}{cT_m}, \qquad (3.95)$$

where ΔF_m--frequency deviation of emitted oscillations;
T_m--repetition period of transmitter modulating frequency.

Target range is:

$$D_t = \frac{cF_p T_{\text{м}}}{4\Delta F_{\text{м}}}. \qquad (3.96)$$

Range resolution is:

$$\Delta D \geqslant \frac{\Delta F_f\ T_{\text{м}}}{4\Delta F_{\text{м}}}, \qquad (3.97)$$

where ΔF_f--the width of the receiver filter pass band.

The range of the uniform distance measurement is:

$$D_{c\ max} \leqslant \frac{1}{8} cT_{\text{м}}. \qquad (3.98)$$

The minimum distance determined by the radar is:

$$D_{t\ \min} > \frac{1}{4}\frac{c}{\Delta F_M}. \qquad (3.99)$$

The merits of the method include: the possibility of measuring short distances and the low radiation power; the drawback is the complexity of simultaneously measuring the range of numerous targets.

The phase method is a method whereby the delay time from the target signal is determined by the amount of change in the phase of modulating oscillations used to modulate the signals emitted by the transmitter (Fig. 3.52c). Over the signal delay time, the phase of these oscillations will change by the amount:

$$\Delta\psi = 2\pi F_m t_{pd}, \qquad (3.100)$$

where F_m--modulation frequency of high frequency oscillations.

The distance to the target is:

$$D_t = \frac{c}{4\pi F_M}\Delta\psi. \qquad (3.101)$$

The range for the uniform measurement of distance is:

$$D_{t\ \max} = \frac{1}{4}\frac{c}{F_M}. \qquad (3.102)$$

The merits of the method include the high accuracy of range measurement and the drawback is the nonuniformity of the measurement and the absence of resolution.

The structure of a device for measuring target range depends upon the adopted method of measurement. They can be analogue and digital.

A device for measuring range with a pulse method of measurement (a pulse range-finder) includes (Fig. 3.52a) a synchronizer 1, a transmitter 2, a receive-send switch 3, a send-receive antenna 4, a receiver 5, an indicator 6, and a range-measuring system 7.

The high frequency pulses from the transmitter through the receive-send switch go to the antenna and are sent toward the target. The return signals are picked up by the antenna and sent to the receiver. After amplification and conversion into video pulses, they go to the indicators and automatic tracking system.

An analogue-type automatic range-tracking system with the pulse method includes a time discriminator, a voltage amplifier of the error signal, an integrater, a variable delay circuit, and a range pulse oscillator (Fig. 3.53).

The target video pulses from the radar receiver are sent to the time discriminator (TD) which also receives the tracking strobes.

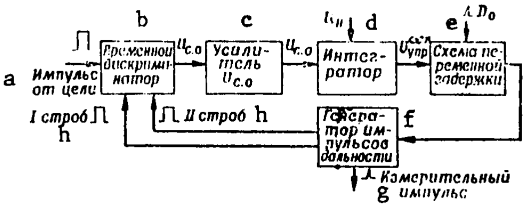


Fig. 3.53. Functional diagram of an automatic target range-tracking system

Key: a--Pulse from target; b--Time discriminator; c--Voltage amplifier of error signal; d--Integrator; e--Variable delay circuit; f--Range pulse oscillator; g--Metering pulse; h--Strobe

The time discriminator is a metering element and most often uses a coincidence circuit. As a result of comparing the time position of the target pulse and the tracking strobes, the TD generates an error signal voltage $u_{c.o} = K\ t$ (K--proportionality coefficient, t--the time mismatching between the energy center of the target pulse and the middle of the tracking strobes). The voltage polarity corresponds to the sign of the time mismatching. The graphic dependence of $u_{c.o} = f(\ t)$ is termed the discrimination characteristics (the characteristics of the discriminator). The steepness of the discrimination characteristics $S_g = \left.\frac{du_{c.o}}{dt}\right|_{\Delta t=0}$ determines the accuracy of range measurement. With an increase in the steepness, accuracy rises.

The voltage amplifier for the error signal is a linear element and is used for amplifying $u_{c.o}$ to a level which ensures the stable work of the integrator.

The integrator performs the role of a servoelement. It converts the voltage of $u_{c.o}$ into a control voltage u_{con} which is used to control the time position of the tracking strobes. The presence of an integrating element in the circuitry gives it the property of astatism.

A levice for measuring target distance with the frequency method (a frequency range finder) has (Fig. 3.52b) a modulator 1, a frequency modulatable generator 2, transmitting and receiving antennas 3, 4, a mixer 5, a low frequency amplifier 6, a frequency meter 7, and an indicator 8. The mixer, the LF amplifier and the frequency meter comprise the rangefinder receiver.

The modulator generates a modulating voltage and under the effect of this according to the set law (linear or sinusoidal) the frequency is changed in the generator's high-frequency oscillations.

The high-frequency signals are sent from the transmitter to the antenna and are sent out toward the target. The return signals through the receiving antenna are sent to the mixer where a small portion of the power from the transmitter's high frequency oscillations is delivered. As a result of the mixing of the oscillations of the f_t

and f_{re} frequencies, different frequency oscillations are generated and these pass through the amplifier and go to the frequency meter. For measuring the frequency F_p, it is possible to employ spectrum analyzers which are a set of filters tuned to the set frequency values. Target range is read off an arrow or digital indicator.

A device for measuring target distance with the phase method has (Fig. 3.52c) a transmitter 1, transmitting and receiving antennas 2, 3, a receiver 4, and a phase difference meter 5.

The high frequency signals from the transmitter are beamed out by the transmitting antenna. The signals returned from the target are picked up by the receiving antenna and then sent to the receiver. After amplification the received signals go to the phase meter where simultaneously high frequency oscillations from the transmitter are received. As a result of comparing the phases of these oscillations, a voltage is generated which is proportional to target distance.

Digital devices for measuring distance employ converters of the "time--digit" type making it possible to obtain range values in a digital code. In the device (Fig. 3.54), the signals returned from the target, after the receiver, are sent to the detection device and then to a flip-flop. Here also is received a start pulse which coincides in time with the moment of sending the transmitter's probe pulse. The flip-flop generates a rectangular pulse the length of which equals the time required for the probe pulse to travel to the target and back. This pulse is sent to an AND gate which also receives pulses from the standard repetition frequency of the pulse generator.

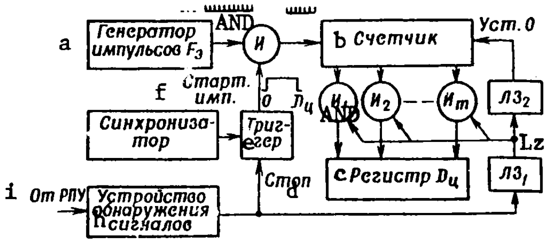


Fig. 3.54. Diagram of digital device for measuring target range

Key: a--Pulse generator; b--Counter; c--D_t register; d--Stop; e--Flip-flop; f--Start pulse; g--Synchronizer; h--Signal detection device; i--From receiver; j--AND

Under the effect of the range pulse and the frequency pulses F_e, the gate opens and through it passes a certain number of standard frequency pulses. Their number will equal

$$N_e = t_{pd}F_e = \frac{2D_t}{c} F_e.$$

For counting these pulses, an i-discharge flip-flop counter has been used on the output of which a number is given in a binary code. The number is read by the potential-pulse output circuit on gates AND_1, AND_2, ...AND_n in a special range register. The moment of reading is determined by pulses sent to the gates from the delay line Lzl.

The target's range is:

$$D_t = N_e \Delta D = N_e \frac{cT_e}{2}, \tag{3.103}$$

where $T_e = 1/F_2$--the pulse repetition period for the standard repetition rate.

Distance is measured discretely with an accuracy up to one pulse repetition period of the standard frequency. For increasing accuracy two-scale counting methods are employed.

With a variable repetition rate of the radar probe pulses, it is possible to employ a device for measuring range with the gating of the range sections (Fig. 3.55). In such devices the output signals and noise after the receiver are sent to a threshold amplifier--limiter and then to the gates AND_1, AND_2, ..., AND_k.

For gating the range sections, pulses of the time markers are formed and these are sent from the appropriate generator to a shift register where pulses are generated following with the range discretization frequency. The number of digits in the register equals the number of elementary range sections ΔD falling on $D_{t\ max}$.

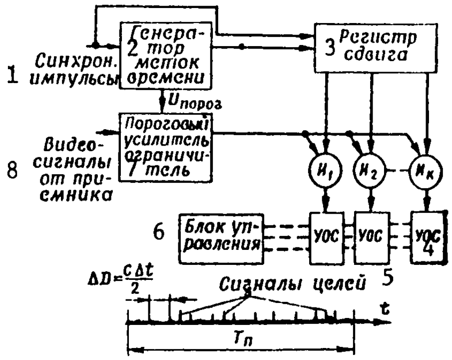


Fig. 3.55. Diagram of device for measuring target range with the gating of range sections

Key: 1--Synchronized pulses; 2--Time marker generator; 3--Shift register; 4--Signal detector; 5--Signals of targets; 6--Control unit; 7--Threshold amplifier--limiter; 8--Video signals from receiver

The pulses generated by each discharge of the shift register go to the corresponding elements of the coincidence circuit AND_1, AND_2 and so forth. Here also is received the output voltage from the threshold amplifier--limiter and containing the receiver noise and the target signals. When element AND_i is activated by a pulse from the i digit of the register and the receiver's output voltage, the element opens passing to the i signal detection device (YOC) the voltage from the receiver output corresponding to the given moment in time.

The YOC store the received information from the receiver over several (for example, ℓ) repetition periods T_p. With the receiving a signal--noise mix, the YOC performs the operation of detecting the target signal for all the ℓ periods. If in m periods a target signal is present in the mix (here $m < 1$ for the whole number of periods T_p), then the YOC puts out a target pulse. In detecting a target signal in a number of periods less than m, the target signal is not put out by the corresponding YOC as the YOC generates a target signal under the condition of not less than m observations of the signal from ℓ sample values.

Each signal of the YOC has its own number corresponding to a certain interval on the target range scale. This provides an opportunity to determine the range from the target signal generated by the YOC:

$$D_t = N_i \Delta D, \qquad (3.104)$$

where i--number of YOC;
ΔD--range section gated by i-m channel.

The signals from the outputs of the YOC can also be used to measure other target coordinates. For reducing the time for scanning maximum range, it is possible to employ systems of sequential and parallel-sequential search.

Measuring Range by Optical Devices

The measuring of target distance in the optical wave band is carried out by optical rangefinders. Distance is determined by the time lag of the signal emitted by the rangefinder generator and returned from the target. For this, the emitted oscillations of the generator are modulated for amplitude and phase. In accord with this a distinction is made between three methods of measuring range: pulse, phase and phase-pulse.

With the pulse method, the target is illiminated with short-duration pulses. The transmitter contains a laser, a modulator, and a radiation control generator (Fig. 3.56). At certain moments of time, the laser generates short pulses which are sent to a semi-transparent mirror. The basic portion of the pulse energy passes through the mirror into the transmitting optical system and is directed toward the target. A small portion of the pulse energy is diverted to the reference photoelectronic amplifier (PEA) and then is sent to the time lag measuring unit, in fixing the moment of emitting the probe pulse.

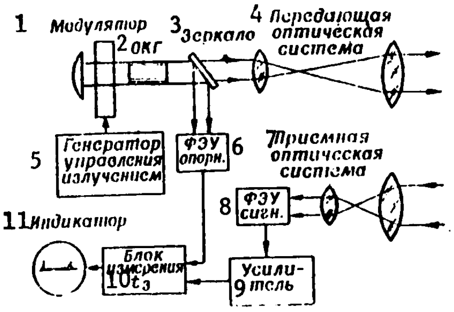


Fig. 3.56. Schematic diagram of pulse laser rangefinder

Key: 1--Modulator; 2--Laser; 3--Mirror; 4--Optical transmitting system; 5--Radiation control generator; 6--Reference PEA; 7--Receiving Optical System; 8--Signal PEA; 9--Amplifier; 10--t_3 measuring unit; 11--Indicator

The signal returned from the target passes through the receiving optical system and goes to the signal PEA and then to the signal amplifier. After amplification the received signal goes to the time lag measuring unit, in fixing the moment of its arrival. The direct and returned signals can be sent to a CRT indicator on which a range reading scale has been applied.

With the phase method, the laser generates a continuous signal which has been modulated for amplitude according to a sinusoidal law. In passing through the semitransparent mirror, the direct signal goes to the optical system and is directed toward the target. The return signal passes through an optical system and is sent to the PEA which also receives a portion of the direct signal's energy.

After passing through an amplifier, the direct and return signals are sent to a unit which measures the phase difference $\Delta\psi$ of the modulating oscillations and this makes it possible to measure target range. Moreover, this unit can also measure the rate of change of $\Delta\dot{\psi}$ and hence there is the possibility of also measuring target speed. In coming out of the unit measuring $\Delta\psi$ and $\Delta\dot{\psi}$, the corresponding signals are sent to the distance indicator and the target speed indicator.

In the foreign press it has been pointed out that the accuracy of measuring range with the designated system can be several centimeters.

With the phase-pulse method, the oscillations emitted by the rangefinder are modulated for amplitude and phase and this makes it possible to measure the target's distance and speed:

$$D_t = a\Delta\psi, \qquad (3.105)$$

where a--proportionality coefficient.

3.3.2. Devices for Tracking the Direction of Targets

The possibility of tracking objects in terms of heading is based on the use of the property of radio waves to propagate rectalinearly. Here there is the possibility of measuring the target's angular coordinates, that is, elevation and azimuth.

The following methods are recognized for determining angular coordinates (Fig. 3.57): maximum, minimum and equisignal zones (the integral method and the method of instantaneous equisignal zones).

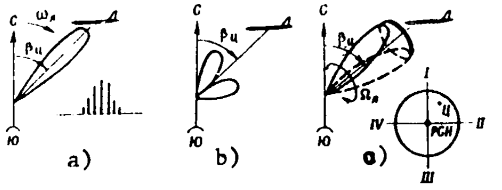


Fig. 3.57. Methods of determining target angular coordinates:
a--Maximum; b--Minimum; c--Equisignal integral zone (with conical beam scan)

The maximum method is a method whereby the direction to the target is determined from the direction of the antenna beam corresponding to the moment of receiving the maximum target signal (Fig. 3.57a).

The minimum method is a method whereby the direction to the target is determined from the minimum signal received by the antenna which forms two beams (Fig. 3.57b). The forms two beams (Fig. 3.57b). The beam maximums are displaced relative to one another by a certain angle.

The merits of the method are the high accuracy in determining the direction to the target while the drawback is the short range of target tracking. It is employed in radio navigation systems with direction finding employing powerful emitting sources.

The methods of equisignal zones--the direction to the target is determined from the equality of amplitudes (phases) of signals returned from the target and received by the antenna which forms two (four) overlapping beams. A distinction is drawn between methods with the amplitude total-difference processing of the signals and the phase method.

Methods involving the amplitude processing of the signals can have integral and instantaneous equisignal zones.

The method of an integral equisignal zone is one whereby the equisignal zone is created by switching or turning (scanning) the antenna beam (Fig. 3.57c). In beam switching devices the target signals are received by the antenna in positions I and II of the beam. If the target is not in an equisignal direction, then the signals will have different amplitudes. The operator or the tracking system rotates the antennas in such a manner that the signal amplitudes u_1 and u_2 are equal. The beam switching time should be such that the target does not go out of the antenna beams.

The method of instantaneous equisignal zones with amplitude total-difference signal processing. With this method the direction to the target is determined from the equality of signals received by an antenna which forms four overlapping beams (Fig. 3.58a).

A comparison of the signal amplitudes is made at the same moment of time and because of this the method has gained the name of instantaneous ESZ [equisignal zones]. In the event of the target's deviation from the RCH [equisignal direction] by the angle $\Delta\theta$, a difference occurs in the amplitudes of the received signals:

$$\Delta u = u_1 - u_2 = 2U_0 R(\psi_0) K_m \Delta\theta \sin \omega_0 t, \qquad (3.106)$$

where U_0--signal amplitude with the locating of target on RCH;
$R(\psi_0)$--antenna gain;
K_m--steepness of antenna rangefinder performance;
ω_0--signal cyclical frequency.

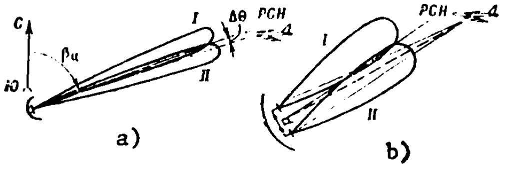


Fig. 3.58. Methods of instantaneous equisignal zones:
a--With amplitude total-difference signal processing; b--With signal phase processing

The voltage Δu is employed in the antenna position control system. Under the effect of the control voltage, the antennas are turned in a direction to reduce the amount of $\Delta\theta$ and as a result of this the target is in the RCH.

The total signal $u_\Sigma = u_1 + u_2$ does not carry information on the deviation of the target from the RCH and is used in devices for measuring target range and speed.

The merits of the method are the high accuracy of target tracking, the low values of fluctuation errors in measuring angular coordinates; the shortcomings are the lack of information on the targets outside the limits of the narrow antenna beams and the complexity of the "total--difference" unit. The method is employed in automatic target tracking radars.

The method of instantaneous equisignal zones with phase signal processing is a method whereby the direction to the target is determined from the equality of the phases of the signals received by two antennas located on a certain base d (Fig. 3.58b). With a deviation of the target from the RCH, the difference in the signal phases u_1 and u_2 is:

$$\Delta\varphi = \frac{2\pi d}{\lambda}\sin\Delta\theta \approx \frac{2\pi d}{\lambda}\Delta\theta; \qquad (3.107)$$

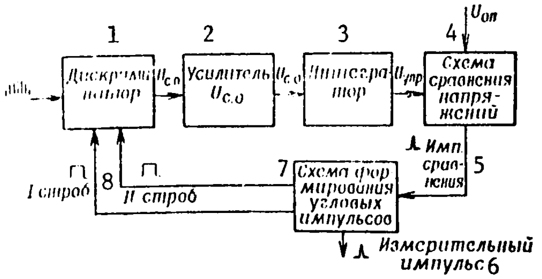
where λ--operating radar wave length.

For measuring the phase difference, waveguide ring bridges, phase detectors and so forth are employed. Voltage proportional to the amount of $\Delta\phi$ is employed for controlling antenna position with automatic target tracking for direction.

The merits of the method are the high accuracy of measurement; the drawbacks are the nonuniformity of determining the value of $\Delta\theta$ and the dependence of measurement accuracy upon the state of the radar waveguide transmission line.

Devices for the automatic tracking of targets for direction. The design of such devices depends upon the method employed for determining the angular coordinates.

With the maximum method and the linear displacement of the antenna beam, automatic target tracking devices are an analogue or digital tracking system. An analogue system consists of a discriminator, an error signal amplifier, an integrating element, a comparison circuit and a circuit for forming angular pulses (Fig. 3.59).



Key: 1--Discriminator; 2--False signal amplifier; 3--Integrator; 4--Voltage comparison circuit; 5--Comparison pulse; 6--Metering pulse; 7--Circuit for forming angular pulses; 8--Gate

Fig. 3.59. Functional diagram of a target tracking system with linear displacement of antenna beam

The antenna beam in moving in a certain sector for elevation (azimuth) forms clusters (bunches) of pulses returned from the target. The cluster maximum corresponds to the moment of coincidence of the antenna beam maximum with the direction to the target. After passing through the receiver and after rectification, the cluster pulses go to the discriminator where the tracking gates or strobes are also received.

The discriminator compares the time position for the energy center of the pulse cluster with the middle of the tracking strobes. As a result an error signal voltage $u_{c.o}$ is generated the amount and sign of which corresponds to the amount and sign of the time discrepancy t between the energy center of the cluster and the middle of the tracking strobes:

$$u_{c.o} = K_{\phi}\Delta t, \tag{3.108}$$

where K_{ϕ}--proportionality coefficient.

The error signal voltage after the discriminator goes to an integrating circuit which transforms this voltage into the control voltage u_{con}.

Tracking the direction of a target in one of the planes is carried out by the continuous alinement of the strobes with the target pulse cluster. The speed of the shift of the strobes in a system with one integrator is proportional to the voltage $u_{c.o}$. Thus, the tracking error increases with an increase in the rate of change of the target's angular coordinates and this is a drawback of the designated device.

With the method of an instantaneous equisignal zone with amplitude total-difference processing of the signals, the tracking device contains a target tracking system in the vertical plane and a tracking system in the horizontal plane. In accord with this the antenna forms four beams the maximums of which are displaced by a certain angle relative to the RCH.

The signals received by the antenna go to the "total--difference" device which can be a double hybrid circuit (Fig. 3.60). The different signal is taken off the output of the "E" leg and the total signal from the output of the "H" leg.

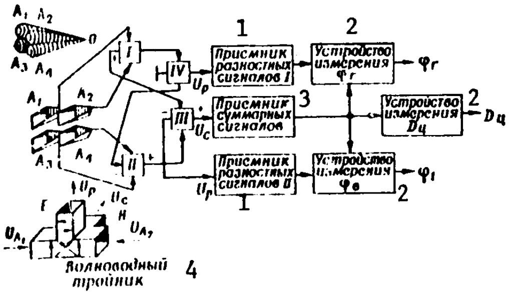


Fig. 3.60. Functional diagram of a target tracking device using the method of instantaneous equisignal zones with the amplitude total-difference processing of signals

Key: 1--Difference signals receiver; 2--Metering unit of; 3--Total signals receiver; 4--Hybrid circuit

The voltages of the difference and total signals are sent to the receiver where they are amplified and converted into intermediate frequency signals. After the receiver, the voltage of the different signal is used in the antenna position control

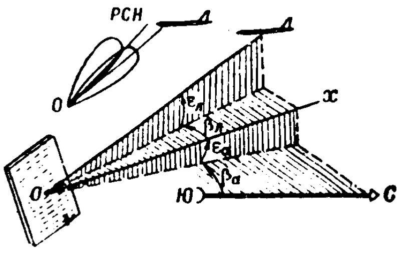


Fig. 3.61. Determining target angular coordinates in radar with PAA

circuit while the voltage of the total signal can be used to measure target range. The current values of the target angular coordinates are read by sensors placed in the appropriate planes on the antenna rotation axes.

A tracking device with the phase method is analogous to the one examined above. Its difference is in the principle of obtaining the difference signal which is proportional to the difference of the phases from the signals received by the antennas.

The measuring of angular coordinates in radars with phased antenna arrays [PAA] is carried out by determining the angular position of the antenna beam at the moment of receiving the signal returned from the target (Fig. 3.61):

$$\left.\begin{aligned} \varepsilon_t &= \varepsilon_a + \varepsilon_b; \\ \beta_t &= \beta_a + \beta_b, \end{aligned}\right\} \qquad (3.109)$$

where ε_a, β_a--elevation and azimuth of electric ox axis of antenna;
ε_b, β_b--elevation and azimuth of antenna beam relative to antenna axis.

The current values of ε_a, β_a are provided by the antenna rotation angle sensors while ε_b and β_b are calculated through the phase ratios provided by the phase converters of the PAA. Since their values are proportional to the control currents of the phase converters, the phase ratios are calculated from their values provided in a digital form. Digital computers are employed for determining the angular coordinates.

Determining the direction to a target is carried out by the method of instantaneous equisignal zones. The time for determining the coordinates of one target is fractions of a second and for this reason by using one radar it is possible to determine the coordinates of a large number of targets with a sufficiently short period of information updating.

The measuring of angular coordinates using optical devices (television and optical sights) is carried out by automatic or manual tracking of a target observed through an optical sight or on the screen of a television-optical sight indicator. The angular coordinates are read by sensors mounted on the sight's rotation axes. Their values can be produced in an analogue or digital form.

3.3.3. Devices for Tracking Target Speeds

The high frequency signals returned (emitted) by moving objects produce an increment in the Doppler frequency F_d the amount of which is proportional to the radial component V_r of their speed of motion:

$$F_d = \frac{2V_r}{\lambda}, \qquad (3.110)$$

where λ--radar wave length.

Hence,

$$V_r = \frac{F_d \lambda}{2}. \qquad (3.111)$$

The measuring of the radial component of target speed comes down to measuring the Doppler increment in the frequency of the received signals. For this it is possible to employ analogue or digital meters.

An analogue-type device for measuring speed has a system of Doppler filters, a multiplexing switch, a speed scan voltage generator and an indicator (Fig. 3.62). The target signals are received from the antenna by the receiver and after conversion go to resonance filters each of which is tuned to a certain value of the Doppler frequency. As a result a signal having a frequency of F_{d1} passes through filter Φ_1, a signal with a frequency F_{d2} goes through filter Φ_2 and so forth. With the known number of filters and their resonance frequencies it is possible to determine target speed V_r as

$$V_{rt} = N_f \frac{F_d \lambda}{2}, \qquad (3.112)$$

where N_f--filter number.

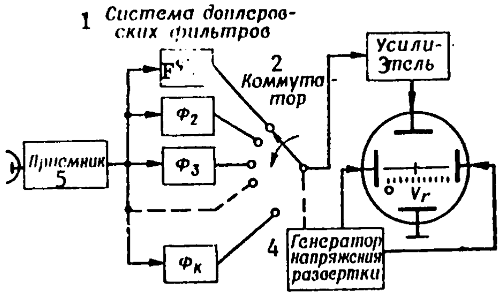


Fig. 3.62. Diagram of device for measuring target speed

Key: 1--System of Doppler filters; 2--Multiplexing switch; 3--Amplifier; 4--Scan voltage generator; 5--Receiver

Automatic devices for the tracking of target speed are based on the principle of tracking the Doppler frequency of the signals. The target signals, after passing through the receiver, go to a mixer where also there is delivered a voltage of an AC frequency F_{din} (F_{din}--instrument Doppler frequency). As a result of mixing the oscillations of F_{dt} and F_{din}, a difference frequency signal is produced:

$$\Delta F_d = F_{dt} - F_{din}. \qquad (3.113)$$

The voltage of the frequency ΔF_d goes to the signal voltage forming unit which produces $u_{c.o} = K_d \Delta F_d$. The voltage $u_{c.o}$ is then converted into the control voltage which is used for controlling the frequency of the generator F_{din}. As a result, the frequency of this generator is changed toward a reduced difference frequency. Thus, in the tracking process the condition for the equality of frequencies $F_{din} = F_d$ is met. The speed V_{rt} is read off a digital or arrow indicator which receives a voltage proportional to the current value of the instrument Doppler frequency.

The obtained values for the speed V_{rt} can be used for solving the problems of guiding missiles and fighters to air targets.

3.4. Principles for the Control of Antiaircraft and Air-Launched Missiles

3.4.1. Information from Aerodynamics

Aerodynamics is a science concerned with studying the laws of motion of bodies in the atmosphere. The outstanding Soviet scientists N. Ye. Zhukovskiy, I. V. Meshcherskiy and K. E. Tsiokovskiy contributed greatly to the development of aerodynamics.

The flight of air-launched and antiaircraft guided missiles occurs in the earth's atmosphere (in the air) which is a mixture of gases characterized by their regular laws.

Gas Laws

The Boyle-Mariotte's Law. With a fixed temperature and mass of the gas, the product of the numerical pressure and volume values is a constant amount:

$$PV = \text{const.} \tag{3.114}$$

Consequently, with a reduction in gas pressure by a certain number of times volume will increase by an equal number of times.

The Gay-Lussac's Law. With constant pressure the volume of a given mass of gas is directly proportional to its absolute temperature:

$$V = \alpha V_0 T_0 - V_0 \frac{1}{T_0}. \tag{3.115}$$

where V--gas volume at temperature $T_0 = 273.15$ K,
$\alpha = 1/T_0$--volumetric expansion coefficient.

The given law states that the ratio of a certain gas volume to gas temperature is a constant amount with fixed gas pressure and mass:

$$\frac{V}{T} = \text{const.} \tag{3.116}$$

On the basis of these two laws, a general gas law has been deduced or the equation for the state of a gas· for a given mass of gas, the product of its volume by the pressure divided by the corresponding absolute temperature is a constant amount:

$$R = \frac{PV}{T} \quad \text{or} \quad PV = RT, \tag{3.117}$$

where R--gas constant the numerical value of which for the air equals 29.26 kg per meter/kg per degree.

The gas constant is viewed as the work of pressure forces applied to 1 kg of gas with a change in its temperature by 1°.

The Mendeleyev-Clapeyron equation:

$$PV = \frac{M}{\mu} BT, \tag{3.118}$$

where M--arbitrary gas mass;
$B = R/\mu$--specific gas constant depending upon molecular weight of gas.

Basic Laws of Aerodynamics

In studying the laws of motion of bodies in the air, the principle of reversibility is employed, that is, the motion of a solid relative to the medium and the motion of the medium relative to the solid will create an equal force effect if the velocity of the body's motion relative to the air in either instance is the same.

The motion of air can be steady or unsteady. Motion whereby velocities at fixed points of space do not depend upon time is termed steady. But if air speed in fixed points of space changes over time then motion is termed unsteady. These definitions also apply to other parameters of air flow (to pressure, density and temperature).

In aerodynamics, in studying the laws of motion of air, a flow is considered steady and concepts of airstream and stream flow are employed.

Here, airstream is the name given to a line the tangent at each point of which coincides with the direction of the speed at this point at a given moment of time. Air flowing inside a tube the surface of which is formed by airstreams is called the stream flow. Through the side walls of the stream flow there is no air current and the stream flow can narrow, widen or adapt itself to the form of the body being flowed around. The air current is represented as consisting of individual stream flows.

The equation of the constancy of consumption (the continuity equation). The flow rate of an incompressible fluid (gas) in a stream flow is inversely proportional to the area of the cross-section of the stream flow (Fig. 3.63):

$$\frac{V_1}{V_2} = \frac{S_2}{S_1} \tag{3.119}$$

or

$$V_1S_1 = V_2S_2 = VS = \text{const}. \tag{3.120}$$

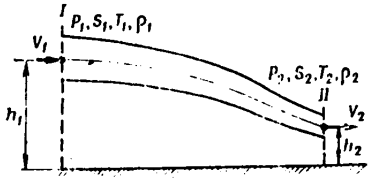


Fig. 3.63. On the deriving of Bernoulli's equation

The equation (3.120) is termed the equation for the constancy of mass consumption or the continuity equation expressing the law of the conservation of mass as formulated by M. V. Lomonosov.

The energy equation (Bernoulli's equation) expresses the law of the conservation of energy for a moving ideal fluid medium.

A flow of gas is examined with arbitrary cross-sections S_1 and S_2, with the corresponding parameters in these sections (P_1, T_1, ρ_1; P_2, T_2, ρ_2) and velocities V_1, V_2. The total energy os the gas having a weight m consists of the potential energy of position [?state], the intrinsic energy and the kinetic energy.

The potential energy of position characterizes the ability of the gas to perform work with a change in the position of the center of gravity of gas weight relative to a hypothetical level

$$E_p = m_1 g h_1.$$

The potential pressure energy is the work of the pressure forces $P_1 S_1$ on a path over a unit of time equal to the velocity V_1:

$$E_p = P_1 S_1 V_1 = P_1 \frac{m_1}{\rho_1}.$$

The intrinsic energy characterizes the capacity of the gas to perform work with a change in temperature:

$$E_{in} = C_V T_1 m_1 g_1,$$

where C_V--specific heat of gas with constant volume:
T_1--absolute gas temperature.

The kinetic energy describes the capacity of a moving gas to perform work:

$$E_k = \frac{m_1 V_1^2}{2}.$$

The total specific energy possessed by a unit of gas weight in section I and II is:

$$E_\Sigma = g h_1 + \frac{P_1}{\rho_1} + C_V T_1 g + \frac{V_1^2}{2} = g h_2 + \frac{P_2}{\rho_2} + C_V T_2 g + \frac{V_2^2}{2}. \qquad (3.121)$$

The expression (3.121) is termed Bernoulli's equation or the equation of the conservation of energy.

In accepting $h_1 = h_2$ (compressibility of the gas is absent: $\rho_1 = \rho_2 = \rho$; $C_V T_1 = C_V T_2 = C_V T$), we obtain

$$\frac{\rho V_1^2}{2} + P_1 = \frac{\rho V_2^2}{2} + P_2 \quad \text{or} \quad \frac{\rho V^2}{2} + P = \text{const}, \qquad (3.122)$$

where $\rho V^2/2$--velocity head or dynamic pressure.

For an imcompressible gas, the total of the static and dynamic pressures in any cross-section of a steady flow is a constant amount. In practical terms this means that any increase in the flow rate leads to a drop of pressure in the flow and vice versa.

The equation of motion. The product of a body's weight by its acceleration equals the force applied to it:

$$mg = F \tag{3.123}$$

or

$$F = m_{\text{в}}V_2 - m_{\text{в}}V_1 = m_{\text{в}}(V_2 - V_1). \tag{3.124}$$

where m_B--the weight of the air repelled by the body in 1 second;
V--velocity of air flow.

If the flow velocity V_1 prior to impacting with the body was greater than after the interaction with it, then the force F checks the body's motion.

With the compressibility of a gas, a change in the speed of motion leads to a change in the intrinsic energy of the gas. Compressibility is also characterized by the speed of sound. With flow velocities more than 0.5-0.6 the speed of sound, gas compressibility increases. As the criterion for assessing the compressibility of a gas, the ratio of the rate of flow to the speed of sound is used (the Mach--Mayevskiy number M):

$$M = \frac{V}{a}. \tag{3.125}$$

With the motion of a body in an air medium at a speed equal to the speed of sound, leading-edge shockwaves arise and as a result of this the nature of the flow of the body through the current is abruptly changed.

The flow is called subsonic if $M < 1$ and with $M > 1$ the flow is called supersonic. Correspondingly a distinction is made between subsonic and supersonic speeds of flight.

Air Flow Around Bodies

The flowing of air around bodies is accompanied by the introduction of disturbances into the flow and these are transmitted in all directions as small changes in the density and pressure in the designated medium. The rate of propagation of the minor disturbances equals the speed of sound.

With $V < a$ (Fig. 3.64a), the sound wave is able to escape forward from the body and at a certain distance from it causes a deformation in the jet stream. If $V = a$, the disturbances will not be propagated ahead of the body and the flow ahead of the body's motion is undisturbed.

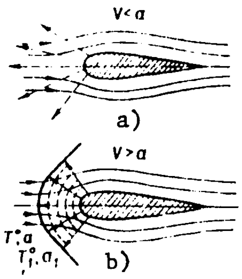


Fig. 3.64. Air flow around bodies:
a--With speed < speed of sound;
b--With speed > speed of sound

With V > a (Fig. 3.64b), a cone of small disturbances is formed and this is an envelope of sound waves. Inside the shock cone there are changes in pressure and density but beyond it the flow remains undisturbed. The angle at the apex of the shock cone depends upon the flow velocity and the speed of sound:

$$\varphi = \arcsin\frac{a}{V} = \arcsin\frac{1}{M}. \qquad (3.126)$$

With the flowing of a supersonic flow around bodies, in representing an infinitely large quantity of material points, shock waves occur.

A shock wave is a concentration of sound waves a short distance away from a body. Ahead of the body an area of increased temperature is formed in which the local velocity of sound is greater than in the undisturbed flow. As one moves away from the body the concentration of sound waves is reduced and the shock wave turns into a boundary wave of small disturbances. The thickness of the shock wave is around 10^{-5}mm. In the wave, velocity is reduced while density and pressure grow. The change in the parameters of the wave leads to the rise of an area of compressed air behind it (a shock wave). The form and position of the shock wave depend upon the shape of the head of the body (Fig. 3.65).

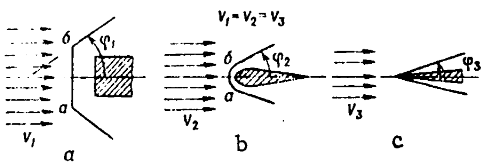


Fig. 3.65. Dependence of shape of shock wave upon shape of head of body:
a--Normal shock wave; b, c--Oblique shock wave

In terms of shape, a distinction is made between normal (lines a, b) and oblique shock waves. A normal shock wave is positioned perpendicular to the flow. The flow velocity V_1 ahead of the shock and behind the shock V_2 is related by the dependence:

$$V_1V_2 = a_{cr}^2, \qquad (3.127)$$

where a_{cr}--critical velocity of sound.

Beyond a normal shock wave $V < a$, for an oblique shock wave $V_k' < a_{cr}$ (V_k'--normal velocity component of oblique shock wave).

The speed of flight at which local shock waves arise is termed the critical speed and the M number of flight M_{cr}. The occurrence of shock waves leads to an abrupt increase in drag and to vibration in the aircraft.

Forces Effecting a Missile in Flight

In analyzing the forces effecting a missile in flight, wind-body and body-axis coordinate systems are used (Fig. 3.66). Here it is assumed

$$\nu = \theta + a, \qquad (3.128)$$

where ν--missile pitch angle;
θ--slant angle of velocity vector;
a--angle of attack;

$$\psi = \beta + \phi, \qquad (3.129)$$

where ψ--yaw angle;
β--slip angle;
ϕ--heading angle.

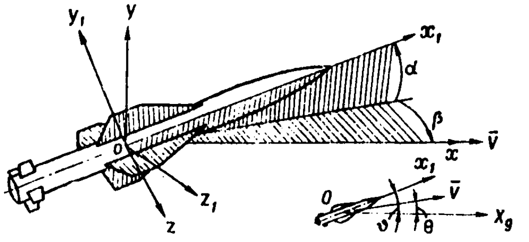


Fig. 3.66. Missile wind-body and body-axis coordinate systems

A missile during flight experiences longitudinal acceleration

$$W_x = \frac{dV}{dt} \qquad (3.130)$$

and normal acceleration

$$W_n = \dot{\theta} V. \qquad (3.131)$$

where $\dot{\theta} = d\theta/dt$.

With normal acceleration, the missile's trajectory will have a curve radius of:

$$\rho_T = \frac{V}{\dot{\theta}} = \frac{V'}{W_n} \qquad (3.132)$$

or a trajectory curve

$$S_\rho = \frac{W_n}{V'}. \qquad (3.133)$$

A missile's translatory motion occurs under the effect of force $\bar{P}$ created by the rocket engine. This force is called the reactive force or the thrust of the rocket engine. It is directed along the longitudinal axis ox of the missile (Fig. 3.67).

Thrust is the reaction (counteraction) of the gases escaping from the nozzle of the jet engine to its walls and is manifested in the form of pressure forces. Its amount is determined by the resultant of out-of-balance forces on the surface of the combustion chamber. The dependence of thrust upon the properties of the rocket engine and the external conditions is:

$$P = \frac{G}{g} V_g + (p_c + p_h / s_c), \qquad (3.134)$$

where G--second gas consumption;
V_g--velocity of gas exhaust on cross-section of engine nozzle;
g--acceleration of free-falling body;
p_c--gas pressure in nozzle cross-section;
p_h--atmospheric pressure at altitude H;
s_c--are of nozzle outlet section.

The amount of thrust determines the range and speed of the missile's flight. The desire to control the range and speed of flight leads to the controlling of thrust and this represents certain technical difficulties.

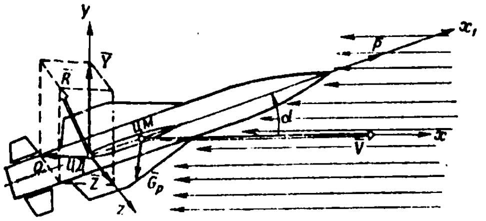


Fig. 3.67. Forces effecting missile in flight: $\bar{P}$--thrust; $\bar{G}_p$--gravity; $\bar{R}$--total aerodynamic force; $\bar{Q}$--drag; $\bar{Y}$--lift; $\bar{Z}$--cross-wind force

Specific thrust is the ratio of the rocket engine's thrust to the fuel flow rate:

$$\mathcal{P}_{эр} = \frac{P}{G_c}. \tag{3.135}$$

Specific thrust indicates the effective use of fuel in the given rocket engine (an indicator of fuel quality and the advanced engine design).

Engines which operate during short time intervals, instead of specific thrust are characterized by a specific impulse of thrust equal to the product of the thrust by the engine operating time. The thrust is considered as the average over the fuel combustion time.

The force of gravity is the force of the rocket's attraction for the earth. This equals the product of the rocket's weight by the acceleration of a free-falling body:

$$G_p = m_p g. \tag{3.136}$$

For the range of altitudes of air-launched and antiaircraft missiles, the amount of g can be accepted as constant and equal to 9.81 m/sec^2. Then, at any moment of time,

$$G_p = G_{p.o} - \int_0^t G_c(t)\,dt, \tag{3.137}$$

where $G_{p.o}$--the initial missile weight (the missile's weight at launching);
t--operating time of missile engine.

The direction of the force $\bar{G}_p$ coincides with the direction of the earth's radius drawn to a given point while the force of gravity operates in a vertical plane.

Thrust and force of gravity are applied to the missile's center of mass (CM [in the diagrams ЦМ]).

The motion of the missile through the air causes the appearance of an aerodynamic force which depends upon the parameters of the medium, the speed of flight and the missile design features. The appearance of an aerodynamic force is caused by the resistance which the air medium puts up to the missile's motion.

The total aerodynamic force $\bar{R}$ is the resultant of all the aerodynamic forces effecting each element of the body's (missile's) surface. It is applied to a point called the center of pressure (CP) [in the diagrams]:

$$R = C_R \frac{\rho V^2}{2} S, \qquad (3.138)$$

where ρ--air mass density;
V--speed of body's motion relative to the air;
S--area of body's surface;
C_R--dimensionless (aerodynamic) coefficient depending upon angle α and other factors.

The direction of R depends upon the shape of the body and the α and β angles.

With the motion of the rocket at a certain angle to an incoming flow (with the presence of the angle of attack α and the slip angle β), the total aerodynamic force can be broken down into three components which are directed along the axes of the missile's body-axes coordinate system.

Drag is a component of the total aerodynamic force operating in an opposite direction to the ox axis:

$$Q = C_x \cdot \rho V^2/2 \cdot S, \qquad (3.139)$$

where C_x--drag coefficient (a dimensionless value which depends upon the missile's shape and its speed of flight);
S--the area of the greatest cross-section perpendicular to the incoming flow of air;
$\rho V^2/2$--velocity head.

From formula (3.139) it follows that drag changes with a change in the velocity head. With V = const., the amount of Q changes with the altitude of the missile's flight.

The coefficient C_x depends basically upon the M number, the angle of attack and the slip angle. The greatest change in C_x occurs in the range of M = 1.

Lift is a component of the total aerodynamic force and is perpendicular to the missile's velocity vector and is directed along the ox axis:

$$Y = C_y \cdot \rho V^2/2 \cdot S. \qquad (3.140)$$

where C_y--lift coefficient.

The amount of the C_y coefficient is a function of the M number, the angle of attack and the missile's control-surface angle δ_p. With $\alpha = 0$, the coefficient $C_y = 0$. An increase in α causes increased lift. This occurs until a critical value of the angle of attack α_{cr} is reached and after this there is a flow breakaway and the above-indicated dependences are disrupted. In the area of flight angles of attack the dependence Cy(α) can be considered as linear. Then:

$$C_y = \alpha \operatorname{tg} \eta,$$

where $\operatorname{tg} \eta$--the steepness of the change in the amount of C_y with a change in angle α. Having designated $\operatorname{tg} \eta = C_y^\alpha$, expression (3.140) can be written:

$$Y = C_y^\alpha \frac{\rho V^2}{2} S\alpha. \qquad (3.141)$$

The presence of lift causes the flight of an aerodynamic vehicle in the air and determines its maneuvering properties. The amount of lift is controlled by changing the angle of attack. With $\alpha = 0$, lift $= 0$. The minimum amount α_{min} whereby horizontal flight of the missile is possible is:

$$\alpha_{min} = \frac{2G_p}{V^2 \rho S C_y^\alpha}. \qquad (3.142)$$

With the maximum possible angle of attack for horizontal flight, a missile should have a velocity:

$$V_{min} \geqslant \sqrt{\frac{2G_p}{S\rho C_y^\alpha \alpha}}$$

In practical terms the flight of air-launched and particularly antiaircraft missiles occurs with a climb in altitude and this requires that $\alpha > \alpha_{min}$.

The cross-wind force is a component of the total aerodynamic force directed perpendicular to the missile's velocity vector V along the oz axis:

$$Z = C_z \frac{\rho V^2}{2} S, \qquad (3.143)$$

where C_z--the coefficient of the cross-wind force.

For axisymmetrical missiles, Z is determined by factors analogous to lift. The cross-wind force changes with a change in the heading angle.

From Fig. 3.67 we can see that the center of mass (CM) is located closer to the missile's nose than is the center of pressure (CP). Such a position of these points creates the missile's stable equilibrium. With a change in the angle of attack, the position of the center of pressure changes. With an increase in α, the center of pressure comes closer to the center of mass and this makes stability worse.

The forces effecting a missile in flight create conditions for controlling its movement for heading and pitch. For controlling a missile's motion along a curvalinear trajectory, it is essential to apply to the missile a certain control force which creates an acceleration $\overline{W}_{clo}$ directed toward the missile's closing with the kinematic trajectory (Fig. 3.68). The components of this acceleration are the normal $\overline{W}_n$ and tangential $\overline{W}_\tau$ accelerations:

$$\overline{W}_{clo} = \overline{W}_n + \overline{W}_\tau.$$

The component $\overline{W}_\tau$ is directed along the velocity vector $\overline{V}$ and does not cause a change in the direction of the missile's motion. The component $\overline{W}_n$ operates normally (perpendicularly) to the velocity vector. Being applied to the missile's center of mass, it causes a change in the direction of motion. The control of the missile's flight comes down to controlling the amount of $\overline{W}_n$:

$$\overline{W}_n = V\dot{\theta} ,$$

where $\dot{\theta} = d\theta/dt$--the angular rotation rate of the missile's velocity vector. Since $\dot{\theta} = V/R_\tau$ (R_τ--the curve radius of the kinematic trajectory), then for moving along the set trajectory the missile should have:

$$W_{n\ req} = \frac{V^2}{R_\tau}. \tag{3.144}$$

Over a certain time of motion, the missile will cover a distance:

$$\overline{L}_p = \int_0^t\int_0^t \overline{W}_{clo}\, dtdt,$$

$$L_n = \int_0^t\int_0^t W_n\, dtdt.$$

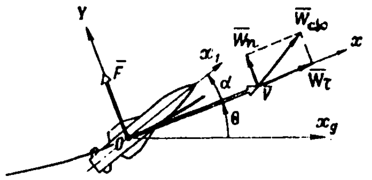


Fig. 3.68. Components of closure acceleration

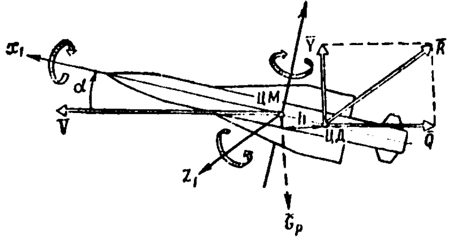


Fig. 3.69. On determining the total aerodynamic moment and its components

In knowing the required normal accelerations, we can determine the required normal g-loads:

$$n_{p.req} = \frac{\overline{W}_{n.req}}{g}.$$

The values of the required g-loads depend upon the adopted guidance method and the nature of the target's motion. They are the greatest (for the adopted guidance method) with rapid rates for a change in the target motion coordinates. It has been established that for guiding a missile to a maneuvering target, the normal g-loads should exceed the target g-loads by at least double. A missile develops the maximum possible g-loads at a maximum speed and the maximum possible control-surface angles. These g-loads are called the available g-loads. Control of the missile's flight is possible under the condition that $n_{n.av} \geqslant n_{n.req}$.

Aerodynamic Moments

Forces effecting a missile in flight and applied at points not coinciding with the center of mass (CM) cause the appearance of moments. In investigating the laws of motion of a missile, the movement of its CM and rotation relative to the CM are examined (Fig. 3.69). For this the total aerodynamic force R is assumed applied to the point of the CM and its action causing the rotation of the missile relative to the CM is called the moment:

$$M = Rh = C_R \frac{\rho V^2}{2} Sh, \qquad (3.145)$$

where h--the arm of applying force R the amount of which depends upon the M number, the angle of attack and other factors.

Total aerodynamic moment is a moment created by the total aerodynamic force. In considering that $C_R h/\ell = m$ and there is a coefficient of total aerodynamic moment, while ℓ--a certain constant characteristic line to which the m coefficient is related, it is possible to write:

$$M = m \frac{\rho V^2}{2} l.$$

The total aerodynamic moment can be represented by the components

$$\bar{M} = \bar{M}_{x_1} + \bar{M}_{y_1} + \bar{M}_{z_1}.$$

where M_{x_1}, M_{y_1}, M_{z_1}--the moments of roll, yaw and pitch, respectively.

The moments are considered positive if the direction of the moment vector coincides with the direction of the axis of the coordinate system and negative with the opposite direction.

Each of the components of total aerodynamic moment is represented by the total of the stabilizing, damping and control moments

$$\left.\begin{aligned} M_{x_1} &= M_{x_1}^{\mathrm{ct}} + M_{x_1}^{\mathrm{dam}} + M_{x_1}^{\mathrm{con}} + M_{x_1}^{\mathrm{к.п.}} \\ M_{y_1} &= M_{y_1}^{\mathrm{ct}} + M_{y_1}^{\mathrm{dam}} + M_{y_1}^{\mathrm{con}}, \\ M_{z_1} &= M_{z_1}^{\mathrm{ct}} + M_{z_1}^{\mathrm{dam}} + M_{z_1}^{\mathrm{con}}. \end{aligned}\right\} \qquad (3.146)$$

The stabilizing (righting) moment is the name given to the moment working to turn the missile toward a reduction in the angle of attack (slip, roll) caused by external disturbances.

The damping (extinguishing) moments are dynamic moments arising with the appearance of an angular missile rotation rate. Their amount depends upon the conditions of the missile's flowing through the external air stream and the conditions for the flowing of fluid and gases inside the missile, in accord with which a distinction is made between the external and internal moments.

Skewed airflow moment is a moment arising with the nonsymmetrical flow of the missile through the air stream. The basic reasons for its appearance are various conditions of wing flow, flow wash on the control surfaces, the blanketing of one of the wings and so forth:

$$M_{x_1}^{\text{к.о}} = m_{x_1\text{к.о}} \frac{\rho V^2}{2} Sl, \qquad (3.147)$$

where m_{x_1}k.o--aerodynamic coefficient for skewed airflow moment.

Control moments are moments created by the missile controls relative to its center of mass. On air-launched and antiaircraft missiles, aerodynamic control surfaces serve as the controls. In the moving of the controls from the neutral position by a certain angle δ_p, a control surface lift Y_p arises (Fig. 3.70) which with the presence of the arm ℓ_p creates a control moment:

$$M_z^{\text{con}} = Y_p \ell_p.$$

Since

$$Y_p = C_{y.p} \frac{\rho V^2}{2} S_в = -C_y^{\delta} \delta_в \frac{\rho V^2}{2} S_в,$$

where C_y^{δ}--aerodynamic coefficient for control surface lift;
S_{β}--control surface area, hence,

$$M_{z_1}^{\text{con}} = C_y^{\delta} \delta_в \frac{\rho V^2}{2} S_в l_p. \qquad (3.148)$$

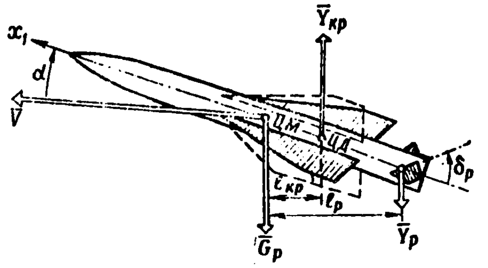


Fig. 3.70. For determining control moment

Control moments can also be created by interceptors [spoilers], by pivoted chambers and control nozzles.

Stability and Controllability of Missiles

A missile steady flight mode is characterized by a static equilibrium whereby the total of the moments effecting the missile equals zero. Here the angles of attack, slip and roll have fixed values.

Static stability is the missile's ability to recover a disrupted equilibrium after the halting of the effects of disturbances.

A distinction is made between pitch stability (longitudinal stability), heading stability (directional stability) and roll stability. The degree of stability depends largely upon the reciprocal position of the CM and CP.

The condition of stability is:

$$\frac{\partial m_{z_1}}{\partial C_y} = m_{z_1}^{C_y} \leqslant 0 \quad \text{or} \quad \frac{\partial m_{z_1}}{\partial \alpha} = m_{z_1}^{\alpha} \leqslant 0. \qquad (3.149)$$

A missile is stable if with the effect of disturbances the increment in the angle of attack and the increment in the coefficient of stabilizing moment have opposite signs.

Controllability of a missile is the ability of a missile to respond to a deviation of the controls from a neutral position. By a missile's controllability one sometimes understands the ability of a missile to travel along a kinematic trajectory.

In controlling a missile there is a change in the control surface angle and this leads to the appearance of the control moment

$$M_{z_1}^{con} = M_{z_1}^{\delta} S_{\beta}.$$

As a result the missile turns by a certain angle whereby it comes into equilibrium so that:

$$M_{z_1}^{CT} + M_{z_1}^{con} = 0.$$

The angle of attack whereby the missile is in a state of equilibrium is called the balanced angle of attack α_{δ}, while the dependence α_{δ} and α_{β} is the balance dependence.

An increase in controllability is achieved by an increase in the control moment and a reduction in the stabilizing moment. For this the various aerodynamic systems of the missiles and the corresponding controls are employed.

3.4.2. Missile Guidance Methods and Control Systems

The guidance of a guided missile to a moving target is a continuous process of the automatic control of its flight. As a result the missile is brought to the target impact area and destroys it. Control is provided by the guidance (control) system.

In controlling a flight, a certain condition (law) is set which determines the trajectory for the missile's motion. As such a condition, for example, it is possible to use the equality of the missile's angular coordinates to the target's angular coordinates; the absence of angular rotation on the missile--target line and so forth.

The condition or law for the closing of the missile with the target is generally termed the guidance method. The guidance method imposes certain demands on the nature of the missile's motion or, in other words, establishes a connection between the law of motion of the missile and target. The trajectory along which the missile moves in carrying out the requirements of the guidance method is called the kinematic trajectory.

In the process of the missile's flight, under the effect of a large number of factors and with a change in the airborne target's position in space, there is a disruption of the given law of closing and the missile moves off the kinematic trajectory.

The disruption in the relationships imposed by the guidance method on the law of the missile's motion is called the mismatch parameter (the control parameter). In accord with the given definition, the mismatch parameter is:

$$\Delta(t) = A(t) - B(t), \tag{3.150}$$

where $A(t)$, $B(t)$--the set and actual laws of the missile's motion.

The guidance system measures the mismatch parameter and generates control commands for the missile's flight. Under the effect of the control commands the control surfaces of the missile are moved and as a result the missile changes direction to reduce the mismatch parameter.

The type of the mismatch parameter depends upon the adopted guidance method. With certain methods the mismatch parameter is the difference in the angular coordinates of the missile and target, and in others the linear deviation of the missile from the target's line of sight. It can also be the angular rotation rate of the missile--target line and so forth.

If the requirements of the guidance method are met in guiding the missile to the target, the mismatch parameter equals zero and the missile moves along the kinematic (calculated) trajectory. With the nonfulfillment of these requirements, a guidance error occurs which reduces the probability of a target hit.

The mismatch parameter is the input action of the guidance system. The mismatch parameter is measured by the ground or onboard devices. As a result of measuring it, a mismatch signal is generated in an analogue or digital form and this comprises the basis of the control commands

$$u_{\Delta}(t) = KB(t), \tag{3.151}$$

where K--proportionality factor.

The adopted guidance method and, as a consequence of this, the mismatch parameter determine the structure of the guidance system.

The best is considered to be a guidance method whereby the trajectory of the missile's motion has the smallest curve and the instrumentation for the guidance system is the simplest; the required range of fire is provided with the given accuracy.

Depending upon the conditions imposed by the guidance method on the missile's position in space, a distinction is made between two- and three-point guidance methods (Fig. 3.71).

Two-Point Guidance Methods

Two-point is the name given to guidance methods whereby the reciprocal position in space is determined for two points, the missile and the target. These methods are applied in homing systems. They include: the direct guidance method, the stern chase method and the methods of parallel and proportional approach.

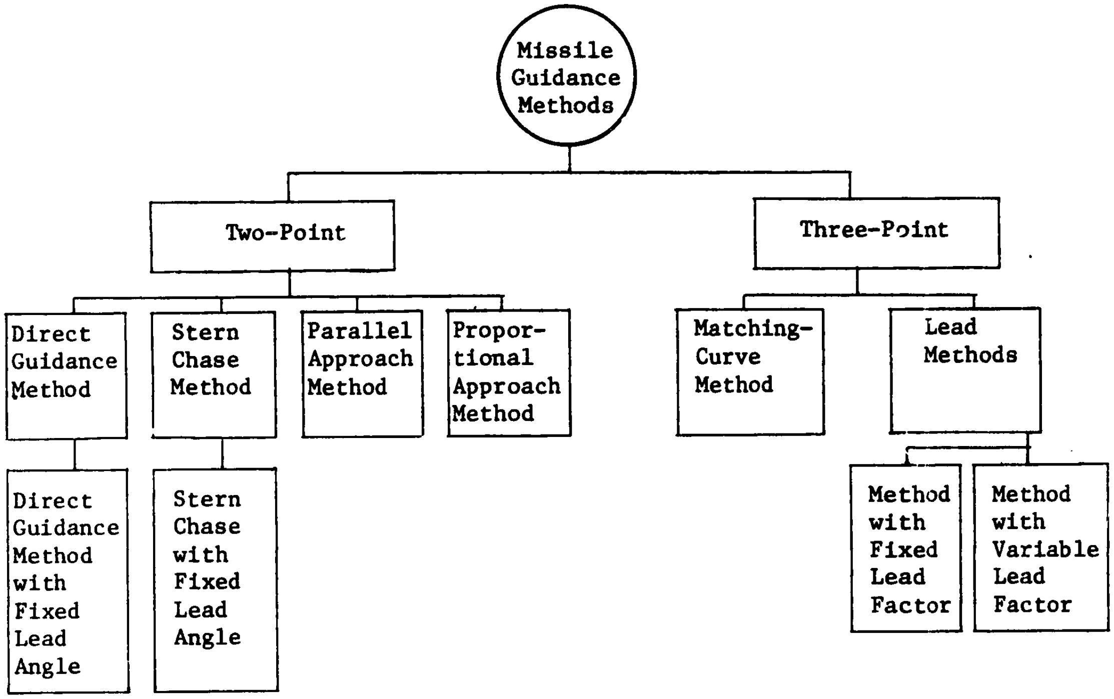


Fig. 3.71. Classification of guidance methods

The direct guidance method is a method whereby in the process of the motion of the missile to the target, the condition is met that the missile's longitudinal axis is constantly directly toward the target. This condition requires an equality of the missile's pitch angle ν to the slope angle ε of the missile--target line:

$$\nu = \varepsilon. \quad (3.152)$$

From formula (3.152) and Fig. 3.72 it follows that the mismatch parameter with this method is:

$$\Delta_\nu = \varepsilon - \nu. \quad (3.153)$$

In the process of missile guidance there must be a constant change in the amount of the angle Δ_ν, that is, the angle between the direction of the missile's ox_1 axis and the P--T (missile--target) line. For this it is possible to employ an onboard meter (seeker) which generates the mismatch voltage

$$u_\Delta = K_\Delta \Delta_\nu, \quad (3.154)$$

where K --proportionality coefficient.

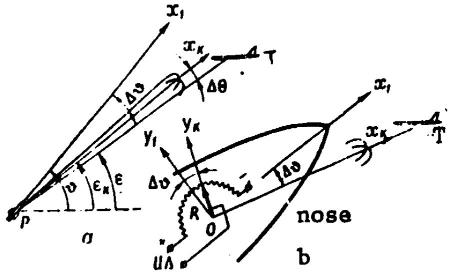


Fig. 3.72. The obtaining of the mismatch parameter with the direct guidance method (a) and a diagram of its measuring design (b)

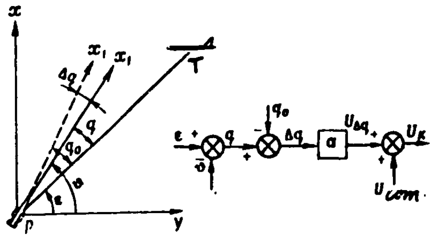


Fig. 3.73. The mismatch parameter with the direct guidance method with a fixed lead angle

For guidance using this method on the missile a tracking seeker is employed and its ox$_k$ axis is lined up with the P-T line. The the appearance of a tracking error Δ_ν in the seeker's tracking system a voltage is generated which is sent to the device controlling the position of the sensitive element (the antenna or optical system of the seeker) causing the ox$_k$ axis to line up with the P-T line. In this manner the direction to the target relative to the ox$_1$ axis of the missile is determined.

A voltage proportional to the Δ_ν angle can be taken from the moving contact of a potentiometer located on the missile's housing (Fig. 3.72). The moving contact is mechanically connected to the sensor of the Δ_ν angle located on the rotation axis of the seeker's metering element.

The voltage $u\Delta_\nu$ is sent to a computer where it is employed in generating the missile control commands. Under the effect of the control commands, the control surfaces turn to a certain angle and as a result of this the missile alters course so that its longitudinal axis coincides with the direction of the missile--target line.

With the direct guidance method, with the approach of the missile to the target, the reguired g-loads increase greatly. After reaching the maximum possible angle of attack the missile goes off the kinematic trajectory. As a result there is a significant error.

The method of direct guidance with a fixed lead angle requires a fixed lead angle for the missile's longitudinal ox axis and the missile--target line (Fig. 3.73). The given condition can be written thus:

$$q = q_0. \tag{3.155}$$

where q--the current value of the angle between the missile's longitudinal axis and the missile--target line;
q_0--the set lead angle.

With a disruption of the equality of (3.155) there is a mismatch parameter

$$\Delta_q = q_0 - q. \tag{3.156}$$

Its value can be measured by the tracking coordinator which lines up the ox_k axis with the missile--target range line. The voltage u_q which is proportional to the value of this angle is taken off the moveable contact of the potentiometer mounted on the missile housing. For obtaining the voltage $u_\Delta(t)$ it is possible to employ a voltage level comparison circuit which receives the voltage $u_{q_0} = aq$ and the voltage $u_q(t)$. As is seen from formula (3.156), the mismatch voltage is:

$$u_{\Delta q}(t) = aq_0 - aq(t) = a[q_0 - q(t)]. \tag{3.157}$$

where a--proportionality coefficient.

The voltage obtained in accord with formula (3.157) can be sent to a computer for obtaining the control commands. Under their effect the missile's control surfaces are moved to certain angles and as a result of this the missile develops normal accelerations and comes out on the kinematic trajectory. Here an equality of the angles $q(t) = q_0$ is established.

The direct guidance method with a fixed lead angle ensures the missile's moving along a trajectory having the smallest curve.

The stern chase (pure pursuit) method is a method of guiding a missile to a target whereby in the process of the missile's flight its velocity vector coincides with the direction of the missile--target line $\theta = \varepsilon$ (Fig. 3.74). From a definition of the method it follows that the angular deviation of the missile's velocity vector $\bar{V}$ from the direction to the target represents the mismatch parameter:

$$q_p = \varepsilon - \theta, \tag{3.158}$$

where θ--slant angle of missile velocity vector.

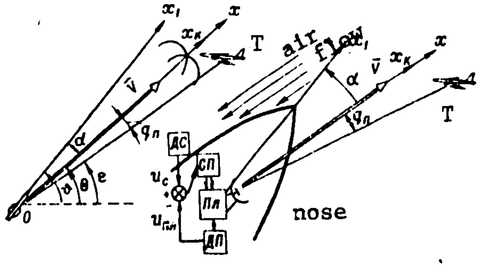


Fig. 3.74. Mismatch parameter with stern chase method

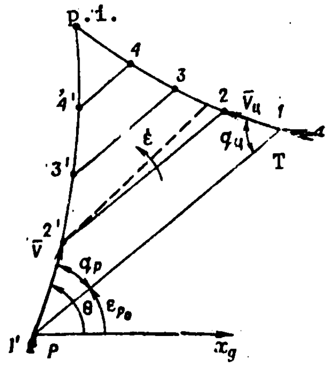


Fig. 3.75. Mismatch parameter with parallel approach method

As is seen from Fig. 3.74, for guiding a missile using this method it is essential to measure the current value of the q_p angle. Its measurement requires a knowledge of the direction of the $\bar{V}$ vector which can be determined by the power featherer which orients the ox_k axis of the coordinator for the incoming flow (for the vector of the missile's air speed). The coordinator forms an equisignal zone where the direction of the equisignals is the ox_k axis.

In the missile's flight, the coordinator measures the target deviation angle from the equisignal direction and generates a voltage

$$u_\Delta = u_{q_p} = a\frac{E_1 - E_2}{2}. \qquad (3.159)$$

Under the effect of the commands, the missile moves in such a manner that the mismatch angle equals zero and the condition of ideal contact is satisfied.

The stern chase method with a fixed lead angle requires a motion of the missile whereby its velocity vector anticipates the missile--target line by a set constant angle (a lead angle q_{p_0}). The equation of ideal contacts is:

$$q_{p_0} = \varepsilon - \theta. \qquad (3.160)$$

For realizing the method, like the stern chase method, it is essential to determine the position of the missile's velocity vector.

With guidance using this method, the missile develops smaller normal accelerations and this increases dynamic accuracy. However, inherent to this method are the same drawbacks as for the stern chase method.

The method of parallel approach is the name given to one where the missile--target line in the process of the flight of the missile toward the target moves parallel to the initial position. In other words, the method requires a missile position where the angular rate of rotation of the missile--target line should equal zero, that is,

$$\dot{\varepsilon} = 0 \quad \text{or} \quad \dot{\phi}_D = 0. \qquad (3.161)$$

The expression (3.161) is an ideal contact equation. From Fig. 3.75 it can be seen that the given method is a lead method. In the process of the target's movement toward the target, its velocity vector anticipates the missile--target line by the angle

$$q_\ell = \arcsin\left(\frac{V_t}{V}\sin q_t\right), \qquad (3.162)$$

where q_t--the angle between the target velocity vector and the direction of the P-T line.

The mismatch parameter can be:

$$\left.\begin{aligned} \Delta_{\dot{\varepsilon}} &= \dot{\varepsilon}; \\ \Delta &= \varepsilon - \varepsilon_{D_0}; \\ \Delta_q &= q_l - \arcsin\left(\frac{V_t}{V}\sin q_t\right). \end{aligned}\right\} \qquad (3.163)$$

The simplest for instrumentation would be a variation whereby the mismatch parameter is the angular rate of rotation of the missile--target line. For measuring the amount of ε the missile carries a tracking coordinator which constantly lines up the coordinator's ox_k axis with the direction to the target. With the appearance of an angular rate of rotation of the P-T line, the coordinator generates a mismatch voltage:

$$u_{\dot{\varepsilon}} = K_{\dot{\varepsilon}}\dot{\varepsilon}, \tag{3.164}$$

where $K_{\dot{\varepsilon}}$--proportionality coefficient.

The voltage $u_{\dot{\varepsilon}}$ is sent to a computer for generating the control commands.

The method of proportional approach (proportional navigation) is a method where the angular rate of rotation of the missile velocity vector θ should be proportional to the angular rate of rotation $\dot{\varepsilon}$ of the missile--target line:

$$\dot{\theta} = K\dot{\varepsilon}, \tag{3.165}$$

where K--proportionality coefficient (navigation constant).

The nonfulfillment of condition (3.165) leads to the rise of a mismatch parameter:

$$\Delta_{\dot{\theta}} = K\dot{\varepsilon} - \dot{\theta}. \tag{3.166}$$

Realizing the method (Fig. 3.76) requires measuring the values of $\dot{\varepsilon}$ and $\dot{\theta}$. The first of these can be measured by the missile's onboard tracking coordinator which in the process of tracking the target generates a voltage $u_{\dot{\varepsilon}} = a\dot{\varepsilon}$ (a--proportionality coefficient). The measuring of the amount of θ directly necessitates the carrying of a featherer and this leads to large mistakes in measuring the angular rotation rate of the missile velocity vector. The amount $\dot{\theta}$ can be measured indirectly. Since

$$W_n = \dot{\theta}V, \quad \text{hence} \quad \dot{\theta} = \frac{W_n}{V}. \tag{3.167}$$

Thus, for obtaining the value of $\dot{\theta}$, one measures the amount of the missile's normal acceleration and with the known value of missile speed this makes it possible to obtain the voltage:

$$u_{\dot{\theta}} = \beta\frac{W_n}{V}. \tag{3.168}$$

where β--proportionality coefficient.

The amount of W_n is measured by the linear acceleration transducer (LAT).

The mismatch voltage is:

$$u_{\Delta\dot{\theta}} = Ku_{\dot{\varepsilon}} - u_{\dot{\theta}}. \tag{3.169}$$

This voltage is part of the control command in moving the missile control surfaces in such a manner that with the appearance of a rate of turning in the missile--target line, the missile changes direction whereby the velocity vector is turned at a rate $\dot{\theta} = K\dot{\varepsilon}$.

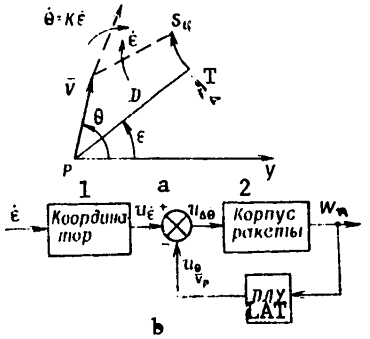


Fig. 3.76. Mismatch parameter with the proportional approach method (a) and a diagram of the device used to generate the control commands (b)

Key: 1--Coordinator; 2--Missile housing

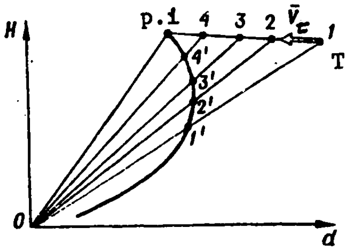


Fig. 3.77. Kinematic trajectory with matching-curve method

In guiding the missile by the given method, guidance errors occur caused by the influence of the missile's weight, the nose cone and the longitudinal accelerations. For compensating for them the voltage u' incorporates the appropriate components.

The normal required g-loads of a missile are:

$$n_n \approx \frac{KV}{g}\dot{\varepsilon}. \tag{3.170}$$

The proportionality coefficient K is considered equal to several units. Its amount changes depending upon the direction of the attack. With a head-on attack the amount is the greatest and with an attack in the rear hemisphere, the least.

From (3.165) it follows that with K = 1, the method of proportional approach corresponds to the stern chase method and with K = ∞ to the parallel approach method.

Three-Point Guidance Methods

Three-point guidance methods are those where the reciprocal position of three points (the guidance point, the missile and the target) is determined in space. Among these methods are the matching curve method and the lead methods.

The matching curve method (the line-of-sight method) requires a movement of the missile whereby the missile at any moment of time should be on the line between the guidance point and the target (on the target's line of sight). From Fig. 3.77 and the definition of the method, it follows that the coordinates for the points of the kinematic trajectory ε_k, β_k for any moment of time should be:

$$\left.\begin{aligned} \varepsilon_k &= \varepsilon_c \\ \beta_k &= \beta_t, \end{aligned}\right\} \tag{3.171}$$

where ε_t, β_t--target elevation and azimuth.

With the deviating of the missile from the OT line, a mismatch parameter arises:

$$\Delta\varepsilon = \varepsilon_t - \varepsilon_p; \qquad \Delta\beta = \beta_t - \beta_p. \tag{3.172}$$

For determining the mismatch parameter, it is essential to measure the current values of the target and missile angular coordinates. This problem is solved by the elevation and azimuth target and missile tracking devices as which radars and optical sights (including television-optical ones) can be employed.

The measured values for the coordinates ε_t, ε_p, β_t and β_p can be put into a deduction device as a result of which the mismatch voltages are obtained:

$$u_{\Delta\varepsilon} = K_\varepsilon \Delta\varepsilon; \qquad u_{\Delta\beta} = K_\beta \Delta\beta. \tag{3.173}$$

Under the effect of the voltages $u_{\Delta\varepsilon}$, $u_{\Delta\beta}$ there is a moving of the pitch and heading surfaces and the missile comes back to the guidance point--target line. However, as is seen from Fig. 3.77, this does not ensure equal precision of aiming the SAM [surface-to-air missile] with various firing ranges. With an increase in missile range with the same value of $\Delta\varepsilon$ ($\Delta\beta$), the significance of the missile's linear deviation from the OT line increases, that is, guidance accuracy deteriorates.

For obtaining equal firing accuracy regardless of range, the mismatch parameter is represented as the missile's linear deviation from the guidance point--target line:

$$h_{\Delta\varepsilon} = D_p \sin \Delta\varepsilon; \qquad h_{\Delta\beta} = D_p \sin \Delta\beta. \tag{3.174}$$

Since $\Delta\varepsilon$, $\Delta\beta$ are very small, the expression (3.175) can be written as:

$$h_{\Delta\varepsilon} \simeq D_p \Delta\varepsilon; \qquad h_{\Delta\beta} \simeq D_p \Delta\beta. \tag{3.175}$$

In accord with formula (3.175), the mismatch voltages are formed and these comprise the basis for the control commands of the SAM flight.

The control commands incorporate components to compensate for the guidance errors caused by the influence of the missile's weight, by the inertia of the control system and so forth.

Moreover, sometimes a damping signal is a command component as this improves the process of bringing the missile back to the kinematic trajectory.

As follows from formula (3.174), missile guidance using the matching-curve method does not require the measuring of target range and this is a plus for it.

Lead methods are methods where the current point of the kinematic trajectory is ahead of the guidance point--target line by a certain angle. The amount of the lead is proportional to the rate of change of the target angular coordinates. In controlling the missile's flight in two reciprocally perpendicular planes, the lead angles are (in a polar coordinate system):

$$\begin{aligned} \varepsilon_{\ell} &= \dot{\varepsilon}_t t_{clo}; \\ \beta_{\ell} &= (\dot{\beta}_t \cos \varepsilon_t) t_{clo}, \end{aligned} \qquad (3.176)$$

where t_{clo}--the missile-target closing time.

Considering that $t_{clo} = \frac{D_t - D_p}{\Delta \dot{D}} = \frac{\Delta D}{\Delta \dot{D}}$($\Delta \dot{D}$--the rate of change of the missile--target distance), we can write:

$$\left.\begin{aligned} h_{\varepsilon_1} &= \frac{\dot{\varepsilon}_t}{\Delta \dot{D}} \Delta D\, D_p; \\ h_{\beta_1} &= \frac{\dot{\beta}_t \cos \varepsilon_t}{\Delta \dot{D}} \Delta D\, D_p. \end{aligned}\right\}$$

In a linear form, the amount of the lead equals:

$$\left.\begin{aligned} \varepsilon_1 &= \frac{\dot{\varepsilon}_K}{\Delta \dot{D}}; \\ \beta_1 &= \frac{\dot{\beta}_t \cos \varepsilon_t}{\Delta \dot{D}} \Delta D. \end{aligned}\right\} \qquad (3.177)$$

From formula (3.177) it follows that the amount of the lead is proportional to the missile--target distance and with $\Delta D = 0$ it equals zero. Thus, the kinematic trajectory with the lead method runs through the target's location point.

The multipliers $\frac{\dot{\varepsilon}}{\Delta \dot{D}} = C_{\varepsilon}; \frac{\dot{\beta}_t \cos \varepsilon_t}{\Delta \dot{D}} = C_{\beta}$ in expression (3.177) are called the lead coefficients. A distinction is drawn between methods for leads with variable and fixed coefficients.

The lead methods can be realized by using ground (onboard aircraft) radar and optical range finder devices (sights) as with the matching-curve method. The values of $\dot{\varepsilon}_t$, $\dot{\beta}_t$ and $\Delta \dot{D}$ can be obtained by the differentiating of the corresponding amounts.

With missile guidance using the given methods, the trajectory curve is reduced and this increases range and accuracy of firing.

Control Systems

The control systems for air-launched and antiaircraft missiles are an aggregate of elements ensuring the preparation, launch and guidance of the missiles to the target. The guidance system which controls the missile's flight is a part of the control system. A distinction made between the following systems is recognized: command telecontrol, teleguidance, homing and hybrid (Fig. 3.78).

Command telecontrol systems are those in which control of the missile's flight is carried out by commands generated at the control point and transmitted to the missile over the command radio line.

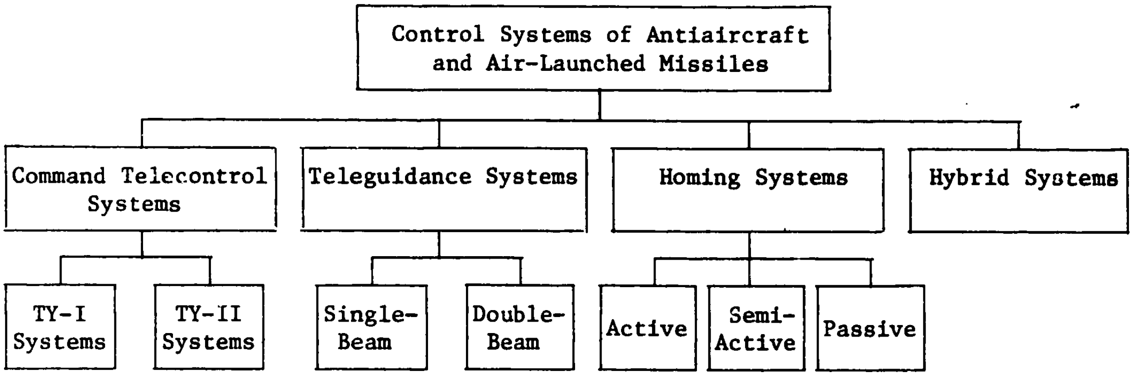


Fig. 3.78. Control systems for antiaircraft and air-launched missiles

Depending upon the method of obtaining information about the target, a distinction is made between the command telecontrol systems of types I and II (TY-I, TY-II). In the TY-I system, the target coordinates are metered by devices located at the control post and in the TY-II system, onboard the missile (Fig. 3.79).

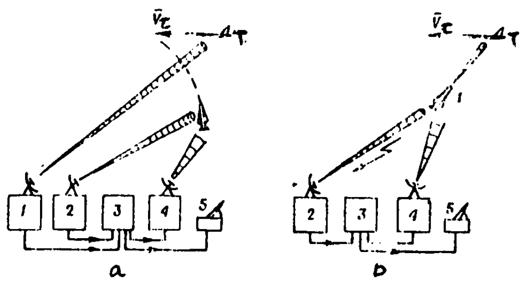


Fig. 3.79. Diagrams of command systems type I (a) and type II (b):

1--Target tracking unit; 2--Missile tracking unit; 3--CGU; 4--KPY; 5--Launchers

The TY-I command system. The equipment of the control post using target designation data or independently detect the targets. In the process of automatic or manual tracking, the target coordinates are measured (more often in a spherical coordinate system). The metered coordinate values are sent to the command generating unit (CGU). Using these data the moment of the missile's launching can be determined. The missile locks on to automatic tracking and as a result its current coordinates are calculated the values of which are sent to the CGU.

The CGU is an analogue or digital type computer. Its task is to determine the moment of the missile launch and to generate the control commands and single commands.

The command radio link (KPY) is a multichannel communications link used to convert the commands into radio signals and transmit them to the missiles being guided to the target. In simultaneously transmitting a large number of commands in the radio link there can be the converting of the command voltages and encoding. As a result each of the transmitted commands has an identification digit (safety digit). The equipment for converting and encoding the commands is located at the control post (the transmitting line) while the decoding equipment is onboard the missile (the receiving path).

The operating range of the KPY depends upon the technical parameters of the equipment in the transmitting and receiving paths:

$$D_{\text{кру}} = \sqrt{\frac{P_{\text{т. кру}} G_1 G_2 \lambda^2_{\text{кру}}}{(4\pi)^2 P_{\text{re min}}}} \geqslant D_{\text{стр max}}. \qquad (3.178)$$

where $P_{t.kpy}$--power of KPY transmitters;
G_1, G_2--directivity factors for antennas of KPY transmitter and receiver;
λ_{kpy}--operating wave length of KPY;
$P_{re\ min}$--sensitivity of onboard receiver of command transmission link;
$D_{ctp\ max}$--maximum firing range.

After decoding in the onboard equipment, the control commands go to the missile autopilot and control surfaces, controlling their position.

The merits of the TY-I command system are the possibility of realizing the matching-curve method and the lead methods, the sufficient guidance accuracy in firing at short and medium ranges, the possibility of guiding several missiles to a single target and the comparative simplicity of the onboard equipment; the drawbacks are the poor guidance accuracy with an increase in firing range and the large amount of equipment at the control center.

The TY-II command system differs from TY-I in the fact that the device for obtaining information on the parameters of the target's motion (the coordinator) is located on the missile. The target data after preliminary transformation and processing by the onboard equipment are transmitted over the radio link to the control center and are fed into the CGU. Here also are received the missile coordinates measured by the control center sights. The further process is analogous to control in the TY-1 system.

The merits of the TY-II system are the high accuracy of guidance which does not depend upon firing range, the process of target selection and identification and the possibility of guiding several missiles simultaneously to one target; the drawback is the more complicated missile-carried equipment.

Teleguidance systems are missile control systems in which the missile control commands are formed on the missile. Their amount is proportional to the deviation of the missile from the equisignal direction created by the radar sights of the control center (Fig. 3.80). Such systems are sometimes called radio-beam guidance systems. They may be single- or double-beam.

Homing systems are systems in which control over the missile's flight is carried out by control commands generated onboard the missiles. Here the information needed for generating them is produced by the onboard equipment (coordinator). Such systems employ homing missiles where the control center is not involved in controlling their flight.

In terms of the type of energy utilized to obtain information on the parameters of the target's motion, active, semi-active and passive homing systems are recognized.

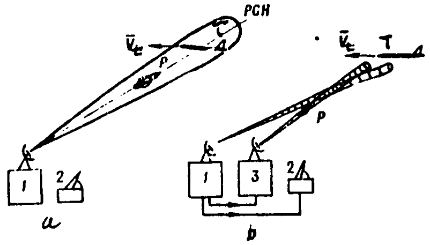


Fig. 3.80. Diagrams of teleguidance systems:
a--Single-beam; b--Double-beam; 1--Unit for tracking target and guiding missile; 2--Launchers; 3--Missile guidance unit

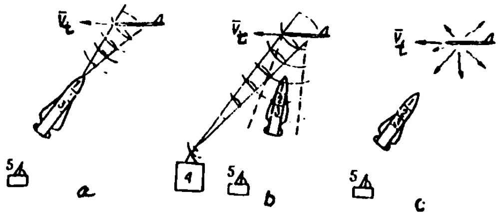


Fig. 3.81. Diagrams of homing systems:
a--Active; b--Semi-active; c--Passive; 1--Onboard coordinator; 2--Computer; 3--Autopilot; 4--Target illuminating radar; 5--Launchers

Homing systems are termed active when the source of target illumination is located on the missile. The signals returned from the target are picked up by the onboard coordinator and are used to meter the parameters of the target's motion (the mismatch parameter), Fig. 3.81a.

In the semi-active homing systems, the source of target illumination is located at the control center (Fig. 3.81b). The signals returned from the target are used by the onboard coordinator for measuring the mismatch parameter.

Homing systems are termed passive when the energy radiated by the target is employed for metering the parameters of the target's motion. This can be thermal (radiant), light or radio thermal energy.

The homing systems include devices which meter the mismatch parameter, a computer, an autopilot and a steering system. The operating principle of the homing system comes down to the following (Fig. 3.81c).

When the missile is on the launcher, the coordinator is aimed at the target designated for destruction. As a result the target is automatically locked on for automatic tracking. Here the target coordinates or the mismatch parameter directly are measured and this depends upon the adopted guidance method. After the launch, the coordinator continuously meters the amount of Δ and generates a mismatch voltage u_Δ which goes to the computer for generating missile flight control commands. The control over the quality of guidance can be visual or by radar and TV-optical equipment located at the control center.

Hybrid control systems are system in which the missile is guided to the target sequentially by several systems. These can be employed in long-range complexes. This can be a combination of a command telecontrol system on the initial leg of the missile's trajectory and homing on the terminal; or radio-beam guidance on the initial leg and homing on the terminal one. Such a combination of control systems ensures the guidance of the missiles to the target with sufficient accuracy with long firing ranges.

3.4.3. Elements of Missile Control Systems

The component elements of a standard control system for air-launched and antiaircraft missiles are: the guided missile as the object of control, the ground (aircraft) equipment for metering the target and missile coordinates, units for generating control commands, the command radio links for transmitting the commands to the missiles, the onboard coordinators [seekers] of homing missiles, the launchers and the missile fighting equipment.

The Guided Missile

A guided missile is an unmanned aircraft with a jet engine used to hit airborne targets. All the onboard equipment is carried on the missile's airframe.

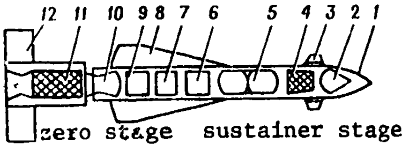


Fig. 3.82. Diagram of design of hypothetical guided missile:
1--Missile housing; 2--Proximity fuze; 3--Control surfaces; 4--Warhead; 5--Tanks for fuel components; 6--Autopilot; 7--Control equipment; 8--Wings; 9--In-flight electric power sources; 10--Sustainer-stage rocket engine; 11--Zero-stage rocket engine; 12--Stabilizer fins

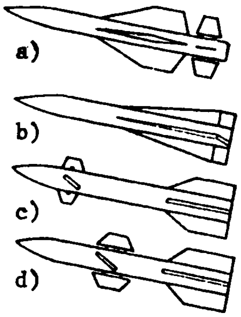


Fig. 3.83. Aerodynamic diagrams of guided missiles:
a--Normal; b--"Tailless"; c--"Canard"; d--"Tilting wing"

The airframe is the bearing structure of the missile and consists of the housing, fixed and moveable aerodynamic surfaces. The housing of the airframe is usually of cylindrical shape with a conical (spherical or ogival) nose. A possible version for the design of a guided missile is shown in Fig. 3.82.

The aerodynamic surfaces of the airframe are used to create the lift and control forces. These include the wings, the stabilizer fins (fixed surfaces) and control surfaces. In terms of the reciprocal position of the control surfaces and fixed aerodynamic surfaces, the aerodynamic designs of the missiles can be: normal, "tailless," "canard" and "tilting wing" (Fig. 3.83).

The engines of guided missiles are divided into two groups: rocket and air-breathing jet.

A rocket engine is one which employs fuel which is completely carried on the missile. For its operation oxygen need not be taken in from the surrounding medium. In terms of the type of fuel, rocket engines are divided into solid propellent rocket engines (SPRE) and liquid propellent rocket engines (LPRE).

As the fuel in the SPRE rocket powders and mixed solid fuels are employed as these can be filled and packed directly in the engine combustion chamber.

The advantages of the SPRE are the simplicity of design, constant readiness for immediate launching, high operating reliability and simplicity, high specific weight and the possibility of obtaining strong thrust with a small engine weight; the drawbacks are the dependence of the thrust and the pressure in the combustion chamber upon the temperature of the charge (the temperature of the surrounding medium), the smaller specific thrust in comparison with the LPRE and the difficulty of regulating the thrust.

The SPRE are employed as boosters in launching the missiles as well as in the sustainer stages.

In the liquid propellent rocket engines, a single- or double-component fuel is employed and this includes an oxidizer and the fuel. The fuel is stored in tanks outside the combustion chamber. The LPRE include fuel tanks, a combustion chamber, a fuel supply system, and units for controlling and regulating the firing. Fuel is delivered to the combustion chamber under pressure which exceeds the pressure in the chamber. In accord with this, a distinction is drawn between the LPRE with expulsion and turbopump-feed systems.

The expulsion system creates in the fuel propellent tanks a pressure that exceeds the pressure in the chamber and as a result the fuel is expelled. For this compressed air (gas) containers (CAC) are employed. The air (gas) is contained in tanks under a pressure of 250-300 kg per cm^2 (2,450-2,940 N). Sometimes for expelling the fuel from the tanks use is made of the burning combustion products in the gas generators operating on a solid or liquid propellant.

The turbopump system creates a pressure using pumps driven by a high-speed gas turbine. The gas generator, turbine and pumps form the turbopump unit (TPA).

The liquid monopropellent fuels are a nonhypergolic mix of an oxidizer and fuel in the necessary ratio for combustion. Monopropellants have gained limited use.

Liquid bipropellants are a combination of fuel and oxidizer in a ratio ensuring combustion. These fuels can be hypergolic and nonignitable. The former are ignited in combining the fuel and oxidizer in the engine combustion chamber and the latter in employing additional igniting agents. The advantages of liquid fuels are that they create a greater specific engine thrust than do the solid fuels, they provide thrust control with simpler means and make it possible to shut down and restart the engine. The drawbacks include the need to store and keep the fuel and oxidizer in separate containers and to observe safety measures in transporting and loading the fuel and oxidizer.

The fuel for the liquid bipropellants can be substances in which carbon and hydrogen are the oxidizable chemical elements. Wider use is made of hydrocarbons (kerosene, amines, hydrazines and others). Liquid oxygen, nitric acid, hydrogen peroxide, florine and others can be employed as the oxidizers.

Air-breathing engines (ABE) are engines in which oxygen collected from the surrounding air serves as the oxidizer. As a result the aircraft carries only fuel and this makes it possible to increase the fuel range. The drawback of an ABE is the impossibility of operating it in the rarified layers of the atmosphere. These engines can be employed on aircraft operating at altitudes up to 35-40 km.

In terms of design features, the ABE are divided into compressor and compressorless. In the compressor engines, the air entering the combustion chamber is compressed by compressors (turbocompressors, turbofans). In the compressorless ABE the air is compressed solely by the velocity head of the incoming air flow.

As a fuel the ABE can employ liquid mixes of hydrocarbons obtained in oil refining.

The operating principle of a jet engine. The basic part of a jet engine operating on a chemical fuel is the combustion chamber with its nozzle. In a SPRE the solid fuel is carried in the combustion chamber while in a LPRE the fuel components are kept in separate tanks and introduced into the combustion chamber under a pressure exceeding the gas pressure in the chamber (Fig. 3.84).

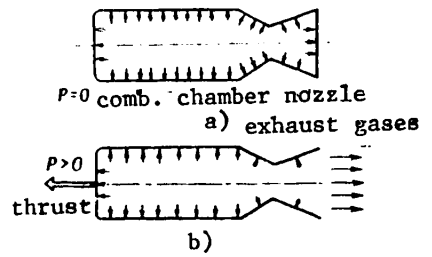


Fig. 3.84. Diagram of the operation of a jet engine:
a--Combustion chamber closed;
b--Combustion chamber with nozzle

When operating the fuel is burned and as a result gases are formed which represent the engine's working medium. If the combustion chamber was closed, then the combustion products would create a certain pressure equally distributed over all the chamber walls, and as a result of this no thrust would occur. With a nozzle, the gases which are pressurized in the chamber rush out through the nozzle at a high speed the amount of which increases as the gases approach the nozzle cross-section. As a result of this, the pressure along the combustion chamber and the nozzle will change. In the nozzle cross-section it will be minimal, while at the head wall inside the combustion chamber opposite the nozzle cross-section it will be at a maximum. A portion of the pressure forces is out of balance and this creates the engine thrust.

An autopilot (AP) is employed to stabilize the angular motions of the missile relative to the center of mass. Moreover, the AP is a component of the missile flight control system and controls the position of the very center of mass in space in accord with the control commands. In the first instance the AP performs the role of a missile stabilization system and in the latter instance the role of a control system element.

For stabilizing the missile in the longitudinal, azimuthal planes and in motion relative to the missile's longitudinal axis (for roll), three independent stabilization channels are employed: for pitch, heading and roll.

The sensing elements of the AP measure the missile's angular deviations α, ν, γ, its velocity V and velocity head $\rho V^2/2$. Thus, with the effect of external disturbances (under the effect of wind and changes in air density, missile asymmetry and so forth), there is, for example, the turning of the missile to a certain angle γ around the longitudinal ox_1 axis, that is, roll occurs. The presence of missile roll with certain control systems can lead to a situation where the rudders will alter the missile's pitch position while the elevators will alter the heading, and this will lead to a disruption of the control system.

With the appearance of the angle γ, the sensing element in the missile's roll stabilizing channel measures the amount of the angle and generates a signal proportional to the amount. After amplification and conversion into the required form, this signal is sent to the controls which turn, for example, the ailerons to a certain angle. As a result, the rolling of the missile is halted and the roll angle will be eliminated. After this the ailerons assume a neutral position. Missile stabilization for the oy_1 and oz_1 axes is carried out in a similar manner.

The missile stabilization systems can employ as sensing elements gyroscopic meters, linear acceleration transducers (accelerometers) and ram air-pressure sensors.

A gyroscopic meter is based on a gyroscope, a rapidly spinning flywheel (rotor) held at the ends of the rotation axis in a frame called the gyroscope gimbal. The rotor is driven by an electric motor.

Linear acceleration transducers (LAT) are a solid of a certain weight (an inertia body) suspended on springs the ends of which are fastened to the transducer's body and weight. A damper is used to eliminate oscillations of the body. The moving contact (slide) of a potentiometer has been fastened to the weight's axis of movement.

With missile acceleration equal to zero, the weight stays in the middle position. With the appearance of missile acceleration, the weight moves along the axis by an amount proportional to the amount of acceleration. As a result a voltage proportional to the amount of acceleration is taken off the potentiometer's moving contact. The LAT can be employed for measuring longitudinal and lateral (normal) acceleration. In the first instance the LAT is placed so that its axis is parallel (lined up) with the missile's longitudinal axis ox_1, while in the latter one the LAT axis should be directed along the oy_1 or oz_1 axis.

For measuring the velocity head, sensors are employed which meter air pressure in running into the air stream. As a result, an electric signal is produced proportional to the amount of ρV^2.

The converter and amplifier units of AP are usually electronic current and voltage converters. For this magnetic and transistorized amplifier-converters are employed as these possess high operating stability and dependability under the conditions of the missile's vibration and g-loads.

The AP servomechanisms are used to move the missile's control surfaces. They can be pneumatic, hydraulic and electric motor. Their purpose is to convert the electric energy of the control commands into an angle of the missile control surfaces. Often these devices are called actuators.

Preset devices are devices for controlling the missile's flight on the autonomous leg of the trajectory. Their task includes altering the operating conditions of the onboard equipment according to a preset program.

The onboard missile flight control equipment is a component part of the control system. Its design is determined by the adopted control system employed in the antiaircraft and air-launched missile control complex.

In command telecontrol systems, the missiles carry devices which comprise the receiving path of the command radio link (KPY). They consist of an antenna and a receiver for the command radio signals, a command selector and a demodulator. As a result, the received command signals are amplified, detected in the receiver and after passing through the selector go to the demodulator. The demodulator converts the command signals as presented by the adopted code into slowly changing voltages which are sent to the controls of the missile control surfaces. The single commands used to control the operating conditions of the onboard equipment follow an analogous path.

In the second type of telecontrol command systems, the missiles carry a coordinator which measures the parameters of the target's movement and a transmitter for transmitting them in the appropriate code to the control center located on the ground (in controlling antiaircraft missiles) or on an aircraft.

In the teleguidance and homing systems, the onboard control equipment includes a target coordinator and a computer. The coordinator measures the mismatch parameter and sends to the computer a mismatch voltage of the corresponding amount and sign. The computer generates the control commands which include the components to compensate for the guidance errors. In coming out of the computer, the control commands go to the AP for controlling the missile's control surfaces.

The coordinators employed in homing systems can be radar and optical (light and infrared).

A radar coordinator contains an antenna, transmitter (in active type coordinators), a receiver, an autoselector, a terminal, a mismatch processor, a receiver and an antenna for the synchronization signals channel. The coordinator shown in Fig. 3.85a is a tracking one. The coordinator's ox_k axis, in being the electrical axis of the antenna, continuously lines up with the direction to the target. In tracking a target, its position relative to the ox_k axis can be determined by the coordinates: by the mismatch angles ϕ_y, ϕ_z in the longitudinal and transverse planes; by the mismatch angle ϕ and the phase angle Φ; by the phase angle and by the target's linear deviation Δ from line ox_k; by the target's linear deviations Δ_y, Δ_z from the coordinator's axis (Fig. 3.85b). With accurate tracking of the target, the values of these coordinates should be close to zero and the target should be on the direction of the ox_k axis.

The target is locked on to automatic tracking by the coordinator before or after the launching of the missile and for this it is first aimed at the target by the original setting commands (KHY) which are received from the control center. Here the switch S1 is in position 1 and switch S2 is open. The command voltage passes through the amplifier to the gyrodrive of the mismatch processor which controls the antenna position. As a result the ox_k axis is lined up with the target and the target is in the antenna's beam. The signals returned from the target are caught by the antenna and pass through the duplexer to the receiver.

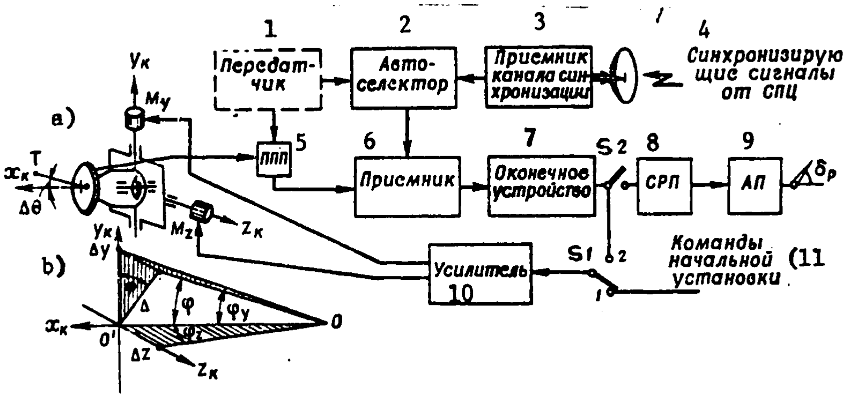


Fig. 3.85. Diagram of a radar coordinator (a) and its coordinate system (b)

Key: 1--Transmitter; 2--Autoselector; 3--Receiver of synchronizing channel; 4--Synchronizing signals from moving target selector; 5--Duplexer; 6--Receiver; 7--Terminal; 8--Computer; 9--Autopilot; 10--Amplifier; 11--Original setting commands

With sufficient power of the return signals, on the terminal output a control voltage appears the amount and sign of which correspond to the amount and sign of the target's deviation from the ox_k axis. After this switch S2 moves to position 2, closing the feedback in the target course tracking system. The coordinator shifts to the automatic course and range (feed) tracking mode. After this switch S2 closes and a mismatch voltage proportional to the mismatch parameter goes to the computer for generating the control instructions.

For the internal synchronizing of the autoselector's work it is possible to use synchronization signals received from the control center. In individual instances such signals can be generated also onboard the missile.

Course tracking of a target can be done using the method of integral and instantaneous equisignal zones. The latter is considered most preferred as it ensures a higher tracking accuracy. With the method of instantaneous equisignal zones, it is possible to employ both amplitude total-difference and phase processing of the radar signals.

With amplitude total-difference processing the signals (see Fig. 3.60) received by the antenna beams are sent to the "total--difference" device and as a result a difference u_Δ and total u_Σ signals are formed:

$$\left.\begin{aligned} u_\Delta &= 2KU_0\varphi_y K_м \cos\omega_0 t; \\ u_\Sigma &= 2KU_0 \cos\omega_0 t. \end{aligned}\right\} \qquad (3.179)$$

where U_0--signal voltage corresponding to the direction of the antenna beam maximum to the target;
K_m--steepness of rangefinder characteristics;
K--conversion coefficient;
ω--signal carrier frequency.

With phase processing of radar signals, there is a comparison of the phases of the high frequency oscillations from the signals returned from the target and received by the antennas. As a result a voltage is formed which is proportional to the phase difference $\Delta\psi$:

$$u_\Delta = K_\text{p} \Delta\psi = \frac{2\pi d}{\lambda} \Delta R = \frac{2\pi d}{\lambda} \sin \varphi_y, \tag{3.180}$$

where d--distance between phase centers of antenna (base);
λ--operating wave length of coordinator;
ΔR--difference in path of radio waves reflected from target and received by coordinator's antennas;
K_ϕ--conversion coefficient.

The mismatch voltage passes through switch S1 and the amplifier (see Fig. 3.85) to the torque motors of the gyro-stabilized platform, in controlling the antennas' position.

As a result the target is lined up with the ox_k axis of the coordinator.

The mismatch processing devices of the coordinators are the servomechanisms of the tracking system. They are in the form of a gyrodrive which stabilizes the antenna and controls its position.

Optical coordinators are mounted on short-range missiles. They are more compact and weigh less. Such a coordinator includes an optical system located beneath a transparent nose cone, an analyzer of the target image field, a radiant energy receiver, a photocurrent amplifier, a terminal and a mismatch processing device (Fig. 3.86). In terms of the principle for measuring target coordinates, optical coordinators are divided into frequency, amplitude, time-pulse and others.

In a frequency coordinator, the analyzer of the image field is a spinning disc divided into transparent and nontransparent areas. Here the number of such areas on the external ring is less than on the inner one. The disc is so placed that the point of origin of the coordinate axes is lined up with the division line of the wheels.

The target's flux of radiant (light) energy passes through the optical system and is focused at a certain point on the disc in accord with the target's position relative to the coordinator's axis. With the spinning of the disc there is a modulating of the flux and as a result on the output of the photoreceiver photocurrent pulses are produced the repetition rate of which will be determined by the position of the target's image on the disc surface. With the deviation of the target to the left of the ox_k axis, the pulse frequency increases and with a deviation to the right, it declines. Thus, after amplification of the photocurrent there is an

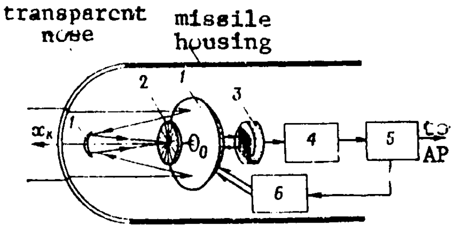


Fig. 3.86. Diagram of optical coordinator:

1--Reflector optical system; 2--Image field analyzer; 3--Photoreceiver; 4--Photocurrent amplifier; 5--Terminal; 6--Mismatch processor

alternating current of a certain frequency corresponding to the position of the target's image relative to the ox_k axis.

The terminal contains electrical filters tuned to certain frequencies. After separation and conversion of the photocurrent, a mismatch voltage is formed which goes to the mismatch processor. As a result there is a change in the position of the optical system and the target is lined up with the coordinator's axis.

Other types of coordinators differ in the pattern of the modulating discs and terminal design. A majority of the optical coordinators are tracking ones. In the process of target tracking they generate a voltage proportional to the angular rotation rate of the missile--target line and this is essential in employing the method of parallel and proportional approach.

As sensing elements in the photoreceivers of optical coordinators it is possible to employ photoelectric cells with an intrinsic photoeffect. Their merit is the short time constant (10^{-} -10^{-} sec.). For increasing integral and threshold sensitivity, the photoresistors undergo profound cooling.

The fighting equipment of antiaircraft and air-launch missiles is a combination of the warhead and fuze.

The warhead has the explosive charge, a detonator and a housing. In principle the warheads can be fragmentation and fragmentation-HE. According to data in the foreign press, certain types of SAM can also be equipped with nuclear warheads (for example, the Nike-Hercules SAM).

The damaging elements of a warhead can be the shrapnel as well as the prefabricated elements located on the housing surface. As explosive charges high explosives are employed (trotyl, mixtures of trotyl, hexogen and others).

Missile fuzes can be proximity and contact. Proximity fuzes, depending upon the location of the source of energy employed for activating it, are divided into active, semiactive and passive. Moreover, proximity fuzes are divided into electrostatic, optical, acoustical and radar fuzes. In foreign missile models, most frequently the radar and optical fuzes are employed. In individual instances, an optical and radar fuze operate in parallel and this increases the reliability of detonating the warhead under the conditions of electronic neutralization.

Radar principles underlie the operation of a radar fuze. For this reason such a fuze is a miniature radar which generates a detonate signal with a certain position of the target in the fuze antenna beam.

In terms of design and operating principles, fuzes can be pulse, Doppler and frequency.

In a pulse fuze, the transmitter generates high frequency short-duration pulses which are emitted by the antenna in the direction of the target. The antenna beam is matched in space with the warhead fragmentation area. When the target is in the beam, the return signals are received by the antenna, they go through the receiver and reach coincidence stages where a gate pulse is also received. With their coinciding a signal is given to explode the warhead detonator. The duration of the gate pulse determines the range of the possible fuze activation distances. The minimum activation distance is:

$$D_{min} = \frac{c\tau_i}{2} . \qquad (3.181)$$

The Doppler fuzes are most often used in a continuous transmitting mode. The signals returned from the target and received by the antenna go to a mixer and as a result the Doppler frequency is isolated:

$$F_d = \frac{2V_r}{\lambda} , \qquad (3.182)$$

where V_r--the radial component of the missile and target approach rate;
λ--operating wave length of radar fuze.

With the preset values of V_r, the signals of the F_d frequency pass through the filter and go to an amplifier. With a certain amplitude of oscillations for this frequency, a detonate signal is given.

Contact fuzes can be electrical and percussion. They are employed on short-range missiles with a high firing accuracy and this ensures the detonating of the warhead with the direct hit of the missile.

For increasing the probability of target kill with warhead fragments, measures are taken to coordinate the areas of fuze activation and fragmentation pattern. With good coordination, the fragmentation pattern area, as a rule, coincides in space with the target area.

Ground (Aircraft) Units for Measuring Target and Missile Coordinates

The given devices ensure the measuring of current, routine coordinates. They are employed in telecontrol systems. As such radar, optical and television-optical sights are employed.

A radar sight is a target course and distance tracking radar. As a result the current coordinates of a target are measured in the adopted coordinate system (more often spherical). The principle of their operation has been examined earlier. Analogous radar sights are used for tracking targets and measuring their current coordinates.

An optical sight is made in the form of hairline columns or an optical sight making it possible to visually observe the target and track it manually. Such sights are employed in short-range antiaircraft missile complexes. Their range is within limits of 10-15 km.

A television-optical sight is a television system consisting of a television transmitting camera and a video monitor. The target image in the television transmitting camera is transformed into electrical television signals which are sent over cable to the video monitor, creating an image of the target on the TV screen. As a result there is the possibility of manually tracking the target and measuring the current values of the angular coordinates.

In the television-optical sights provision is also made for automatic tracking, including for targets aimed at the missile. For obtaining dependable tracking, the missiles carry tracers which are sources of light and infrared radiation.

Devices for Generating Control Commands

These units are designed to obtain electric voltages the amount and sign of which correspond to the amount and sign of the missile's deviation from the kinematic trajectory. The structure of a CGU [control command generating unit] depends upon the adopted missile guidance method and the method for compensating for guidance errors. Thus, in generating control commands with the matching-curve methods, the CGU should have a unit for generating the voltages $U_{h\Delta\varepsilon}$, $U_{h\Delta\beta}$ which are linearly proportional to the mismatch parameter as well as devices for obtaining the voltages of the damping signal and the voltages of dynamic error compensation. In representing the expression of the voltage of the control command in the form of:

$$u_k = u_{h\Delta} + u_{c.d} + u_{k.d}, \tag{3.183}$$

where $u_{h\Delta} = a_\Delta h_\Delta$;

$u_{c.d}$--damping signal;

$u_{k.d}$--dynamic error compensation signal, we will have a structure of the CGU (Fig. 3.87).

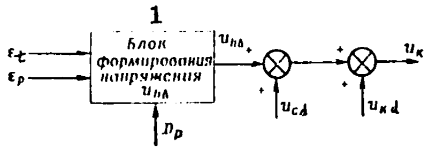


Fig. 3.87. Standard diagram of a CGU in realizing the matching-curve method

Key: 1--Voltage generating unit

In guiding a missile using lead methods the CGU should incorporate a unit for generating a lead signal $u_{h\ell}$. The structure of this signal should correspond to the expression (3.177). This device should carry out multiplication and division operations and for this reason can be called a divide and multiply unit.

In addition to the designated tasks, a CGU also performs other ones: it determines the missile launch moment, it generates control signals for the launchers, it provides instructions for controlling the operating modes of the onboard equipment and so forth.

The Control Command Radiolink

The control command radiolink [KPY] is a multichannel communications line designed for the conversion and transmission of control commands. The number of line channels corresponds to the number of commands to be transmitted with the simultaneous control of several missiles.

The converting of the control commands into radio signals is carried out, as a rule, in three stages. In the first of them the slowly changing command voltages are converted into the voltages of the subcarrier frequencies according to the adopted method; in the second stage they are given their identifying feature and in the third are converted into high frequency radio signals.

In the first stage for converting the commands methods with pulse and harmonic subcarriers can be employed.

Methods with pulse subcarriers are:

The amplitude-pulse method (APM) where the command voltage $u_k(t)$ is converted into voltage pulses the amplitude of which changes in accord with the change in the command voltage;

The frequency-pulse method (FPM) where the command voltage is converted into voltage pulses the repetition rate of which changes according to the law $u_k(t)$;

The time-pulse method (TPM) (phase-pulse or PPM) where the command voltage is converted into voltage pulses the time position of which in relation to the reference pulse changes in accord with the change in the amount and sign of $u_k(t)$;

The width-pulse method (WPM) where the command voltage is converted into pulses the width (duration) of which changes in accord with the law of voltage change $u_k(t)$;

The code-pulse method (CPM) where the voltage $u_k(t)$ is converted into voltage pulse, which are a digital (more often binary) code.

Methods with harmonic subcarriers:

The amplitude-frequency method (AFM) where the frequency of the subcarrier oscillations changes according to the law of the change in the amount of the command voltage;

The phase-frequency method (PFM) where the command voltage is converted into harmonic oscillations the phase of which changes in accord with the voltage $u_k(t)$.

In the second stage the commands are encoded. Pulse combinations, harmonic oscillations and others can be employed as the code.

In the third stage, the subcarrier voltages go to the KPY transmitter where they are converted into high frequency oscillations and sent into space through the antenna.

The missile carries the equipment of the receiving path containing an antenna, a receiver, selector and demodulator. As a result the received command signals are converted into the form of the voltage $u_k(t)$ and are sent to the autopilot.

4. RADAR TROOPS

4.1. Weapons Systems of Radar Troops

The weapons systems of the RTV [radar, lit. radiotechnical troops] include: detection systems (radar complexes and sets, radar altimeters, radar identification systems), automated control systems [ASU] (complexes of equipment for automating the collection, processing and display of data at the RTV command posts and for troop control) and in addition radar data transmission systems.

4.1.1. Detection Systems

The RTV radar detection systems are designed to conduct radar reconnaissance (scanning the air space, detecting aircraft, measuring their current coordinates and radar identification and determining the fighting strength of the air targets) and radar support for controlling the firing complexes of the ZRV [antiaircraft missile troops] and IA [fighter aviation]. A classification of the RTV detection systems is shown in Fig. 4.1.

The radar reconnaissance complexes (sets) are the basic source of information on the air situation in the AD troops. For detecting and tracking aircraft which are not sources of active jamming (SAJ), active pulse radars are employed. The measuring of distance to the target is based upon the pulse method and the measuring of azimuth on the maximum method. Analysis and processing of the current target coordinates make it possible to obtain the horizontal speed of the target and heading and to detect the start of a maneuver.

An analysis of the shape and structure of the echo signal provides a notion of the combat strength of a group target.

For detecting and tracking a SAJ, complexes of passive radar are employed (triangulation or base correlation).

Radar identification is based upon a combination of the principles of two-way automatic radio communications and radar. Radar complexes which support firing complexes differ from reconnaissance radar in the higher accuracy of measuring the current coordinates and in their better resolution.

A classification of detection systems (Fig. 4.1) is not devoid of ambiguity as certain reconnaissance radars under definite conditions can be employed for radar

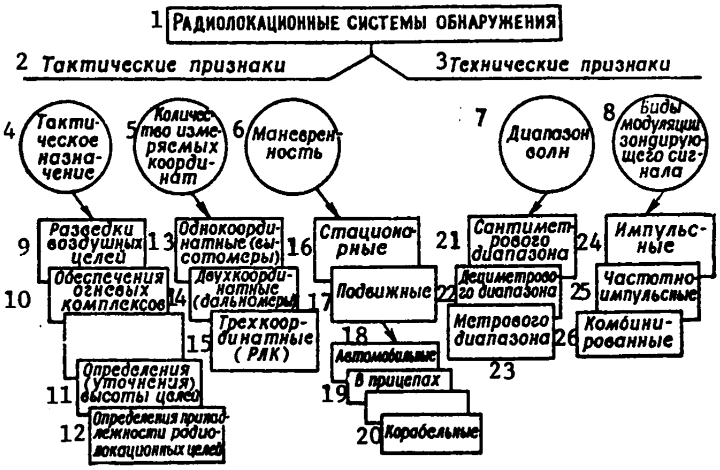


Fig. 4.1. Classification of RTV radars:

Key: 1--Radar detection system; 2--Tactical features; 3--Technical features; 4--Tactical purpose; 5--Number of metered coordinates; 6--Maneuverability; 7--Wave band; 8--Types of transmitted signal modulation; 9--Reconnaissance of air targets; 10--Support of firing complexes; 11--Determining (clarifying) target height; 12--Determining identity of radar targets; 13--Unidimensional (altimeters); 14--Two-dimensional (rangefinders); 15--Three-dimensional (radar complexes); 16--Stationary; 17--Mobile; 18--Motor vehicle; 19--In trailers; 20--Ship; 21--Centimeter band; 22--Decimeter band; 23--Meter band; 24--Pulse; 25--Frequency pulse; 26--Combined

support of firing complexes and, conversely, the support radars can carry out reconnaissance. Altimeters, within certain limitations, can perform the functions of three-dimensional radars.

Radar rangefinders provide detection of aircraft and the determining of their plannar coordinates (azimuth and range). A diagram of a radar rangefinder is shown in Fig. 4.2.

The probing of the air space by pulses of electromagnetic energy is provided by the transmitter and antenna-feeder units of the rangefinder, the receiving of the return signals is carried out by the antenna-feeder unit and receiver. The received signals are displayed on the indicators of the radar or ASU.

The transmitter generates the radio pulses with a duration of τ_i from units to tens of microseconds. The RTV radars employ smooth, linearly frequency modulated and phase-code-pulse modulated transmitted signals. Using a microwave feeder path, the energy of the transmitted pulses through the antenna switch is carried to the antenna and transmitted into space.

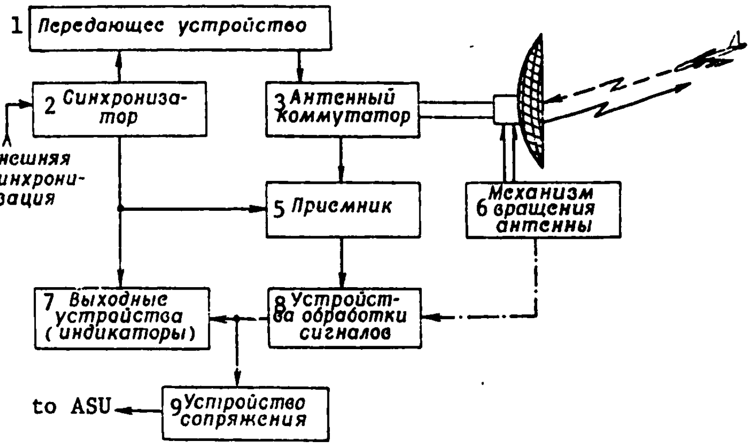


Fig. 4.2. Schematic diagram of a pulse radar rangefinder

Key: 1--Transmitter; 2--Synchronizer; 3--Antenna switch; 4--External synchronization; 5--Receiver; 6--Antenna rotating mechanism; 7--Output devices (indicators); 8--Signal processing devices; 9--Connector unit

The width of the directional pattern in a rangefinder antenna in the horizontal plane is units or fractions of degrees. The scanning of space in the vertical plane is within limits of from -1 to 60°. The designated limits are realized by employing several antennas (antenna channels) or by slanting the antenna in the vertical plane.

The basic method for scanning space in the horizontal plane is even circular scanning which is provided by turning the antenna or azimuth. The rate of antenna rotation is chosen proceeding from the required discreteness of information receiving and the obtaining of a sufficient number of pulses in the echo cluster for normal data processing:

$$n_{\text{в}} \leqslant \frac{\theta_{\beta} F_{\text{р}}}{6N_{\min}}. \tag{4.1}$$

where n_a--antenna rotation rate, RPM;
θ_β--width of directional pattern in azimuthal plane, degree;
F_p--pulse repetition rate, hertz;
N_{min}--minimum number of pulses in echo cluster needed for normal excitation of CRT screen.

The basic parameters of the transmitter and antenna-feeder unit characterizing the capability of the rangefinder are: pulse power of the microwave generator P_i (antenna gain G_0), the pulse duration--τ_i, the type of modulation of the transmitted pulses, the width of the directional pattern in the horizontal and vertical planes.

The returned signals received by the antenna are transmitted through the antenna switch to the receiver input where their frequency selection and amplification are carried out. Subsequent signal processing (neutralization of noise, pulse compression and so forth) is carried out in special processors from which the processed signals go to the indicators or other output devices and the connecting units with the ASU.

The basic parameters of the receiver-indicator path are: responsiveness of the receivers [(3.61), (3.74) and (3.75)], the subnoise visibility coefficient (the noise neutralization coefficient), the pulse compression coefficient, dynamic range and handling capacity of the output units.

The synchronizer generates triggering pulses which coordinate in time (synchronize) the moment of sending the transmitted pulses of the transmitter and the start of the indicator scan as well as the work of the other radar systems. For increasing the probability of the target detection by increasing the number of pulses in the blip cluster and reducing the discreteness of information receiving, the pulse repetition rate F_p is increased. However, in pulse radars the significance of the repetition rate is limited by the demand of detecting targets at the designated ranges. For this reason the maximum repetition rate of the transmitted pulses cannot be more than:

$$F_{p\,\max} < \frac{c}{2D_{\max} K_r}. \tag{4.2}$$

where c--propagation rate of radio waves;
D_{max}--required maximum radar detection range;
K_r--reserve coefficient (in calculations it is set within limits of 1.15-1.25).

For detecting targets with a set probability it is essential to receive from the target and process the required number of pulses over a scan N_{min}. This condition determines the lower limit of the repetition rate for an altimeter (4.3) and for a rangefinder (4.4).

$$F_{p\,\min} \geqslant \frac{N_{\min}\,\Delta\beta\,\Delta\varepsilon}{T_{sc}\,\theta_\beta\,\theta_\varepsilon}; \tag{4.3}$$

$$F_{p\,\min} \geqslant \frac{N_{\min}}{\dfrac{\theta_\beta}{6n_a} - \dfrac{2D_{\max}}{c}}. \tag{4.4}$$

where Δβ--azimuth scan sector;
Δε--elevation scan sector;
θ_β, θ_ε--width of directional pattern for level of half power in the azimuthal and elevation planes, respectively;
T_{sc}--scanning interval;
N_a--antenna rotation rate, rpm.

Radar altimeters are designed to determine the height of an aircraft above the surface of the land and the sea. Most often these are autonomous radars which have equipment for being connected to rangefinders, communications equipment and ASU. In individual instances altimeters are made in a nonautonomous version and are a component part of a three-dimensional radar complex.

The principle for determining altitude by the maximum method comes down to measuring the slant range D, the elevation of the target ε and solving the altitude equation (3.84). High-precision altimeters solve the equation with a correction for refraction in kilometers:

$$H = D\sin\varepsilon + \frac{D^2}{2R_e} + \Delta H_{ref} + h_a. \qquad (4.5)$$

where R_e--earth's radius, 6,368 km;
ΔH_{ref}--altitude correction for radio wave refraction, km;
H_a--height of altimeter antenna electrical center, km;

$$\Delta H_{ref} = 4\cdot 10^{-7}\left(0{,}8 - \frac{2}{3}\cdot 10^{-3}T_{er}\right)(H-50)\,D^2. \qquad (4.6)$$

where T_{er}--equivalent reduced temperature determined by pressure, humidity and temperature of medium on radar--target path;
H, D--altitude of aircraft and range to it.

A uniform correlating of information on the height of targets being tracked by a rangefinder is achieved by sending the altimeter target designation signals (for range and azimuth) from the rangefinder which for the given altimeter is the leader; for this in the altimeters provision is made for a system of measuring (displaying) target azimuth and range. This makes it possible in individual instances (in tracking a small number of targets in circular scanning or in operating in a narrow azimuth sector) to utilize an altimeter for measuring three coordinates.

Three-dimensional radars measure the three current coordinates of a target. Characteristic of them is a simple technical solution for correlating altitude information with the target's planar coordinates and this increases the informational capabilities of the radar to simultaneously track a large number of targets.

The identification system is designed to determine the state affiliation of detected aircraft. A diagram of the identification system is shown in Fig. 4.3.

The ground portion of the identification equipment is called the ground radar interrogator (GRI) and can be coupled to a radar over circuits for synchronization, antenna rotation and the indication (display) of the reply signal.

The GRI transmitter forms a coded interrogation signal which through the antenna switch is transmitted by the antenna toward the aircraft to be identified and which carries the in-flight part of the equipment.

The interrogation signal is received by the antenna of the onboard transponder, it is amplified in the receiver and decoded. In accord with the interrogation signal of the established code, the reply signal encoder and the transmitter are activated and the latter generates a coded reply signal which is sent by the antenna of the onboard transponder.

The reply signal picked up by the GRI antenna is amplified in the receiver and sent to the identification signal decoder where the match of the reply signal code is checked. In the event of a code match, the decoder sends to the signal mixer a signal which is displayed on the indicator.

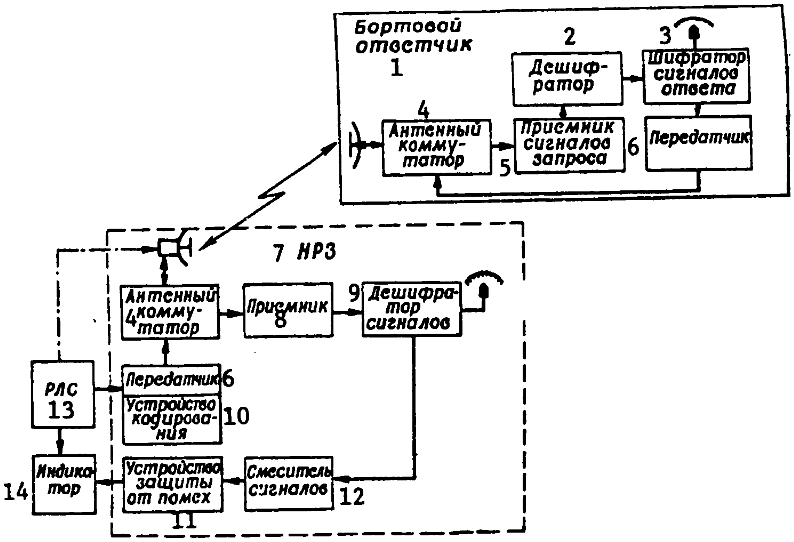


Fig. 4.3. Schematic diagram of identification system

Key: 1--Onboard transponder; 2--Decoder; 3--Reply signal encoder; 4--Antenna switch; 5--Interrogation signal receiver; 6--Transmitter; 7--Ground radar interrogator; 8--Receiver; 9--Signal decoder; 10--Encoding device; 11--Antijamming protective device; 12--Signal mixer; 13--Radar; 14--Indicator

Combat Capabilities

The combat capabilities of radars are quantitative and qualitative indicators characterizing the capability of a radar to perform the combat missions inherent to it under the specific situational conditions over the established time.

Combat capabilities depend upon the technical characteristics of the radar, its combat readiness and the selected operating modes, upon the terrain where the complex is deployed, the target radar cross-section, the electronic situation, the composition and training level of the combat crew, meteorological conditions and other factors. A change in the situational conditions leads to a change in the combat capabilities of the complexes. Combat capabilities are assessed in terms of the specific combat missions and the conditions for carrying them out.

The indicators of radar combat capabilities for radar reconnaissance: the detection zone, radar antijamming capability, information capability, capabilities for identifying targets, accuracy of information and time required to bring to a state of combat readiness.

Indicators for radar combat capability for radar guidance support: zone of guidance support, the number of simultaneously supported guidances (this depends upon the number of guidance indicators and the discreteness of presenting all three coordinates). The accuracy of the provided information determines the probability of radar guidance support within the guidance zone.

The guidance support zone is an area of space in which continuous tracking of the targets and the fighter is provided, as well as the measuring of their current coordinates with the required accuracy and confident radar identification.

Indicators of combat capabilities for radar support of target designation for antiaircraft missile complexes is the zone of target designation support (an area of space in which target designation information is provided) and the number of simultaneously provided target designations. The quality of the target designation information depends upon its accuracy and is characterized by the probability of no-search target designation. The quantity of simultaneous target designations depends chiefly upon the set discreteness of providing coordinate information.

The Detection Zone

The detection zone of a radar complex (radar set) is a spatial indicator of radar capability for radar reconnaissance of airborne objects.

The detection zone is an area of space within which radar targets with a designated radar cross-section (RCS) are detected by the radar in each scan with a probability no less than the designated.

In a majority of operational and tactical calculations for describing the detection zone, the RCS is set as equal to 1 m^2 and the detection probability is 0.5. A knowledge of the designated zone and the availability of simple mathematical procedures given below make it possible to easily determine the radar detection zone for any other values of the RCS and the detection probability. This makes it possible to evaluate the capabilities of the equipment in terms of a specific enemy.

A detection zone can be represented in the form of a table of values of the detection range D of an aircraft with a given RCS at various altitudes H over the surface of the earth; as a half section (a family of half sections) of the zone in the vertical plane as constructed in the H--D coordinates on the given azimuth (azimuths) considering the curvature of the earth (the detection zone in the vertical plane); as a section (family of sections) of a zone with spherical surfaces parallel to the earth's surface at a certain fixed height or at a number of fixed heights (the detection zone in the vertical plane).

In areas with medium rugged terrain at altitudes of over 2 km the effect of the relief on the dimensions and shape of the detection zone becomes nonessential and the spherical sections assume a regular shape.

With the tabular presentation of the detection zone, in addition to detection range at various altitudes, the values are also given for the minimum and maximum elevations ε_{min}, ε_{max}, the maximum altitude of continuous target tracking and the radius of the blind cone R_{bc} at the maximum tracking altitude (Fig. 4.4).

The radar detection zone in the centimeter wave band is:

$$D(\varepsilon) = D_{max}F(\varepsilon), \tag{4.7}$$

where D_{max}--maximum target detection range with given RCS σ_t;
$F(\varepsilon)$--normed directional pattern of radar antenna in vertical plane.

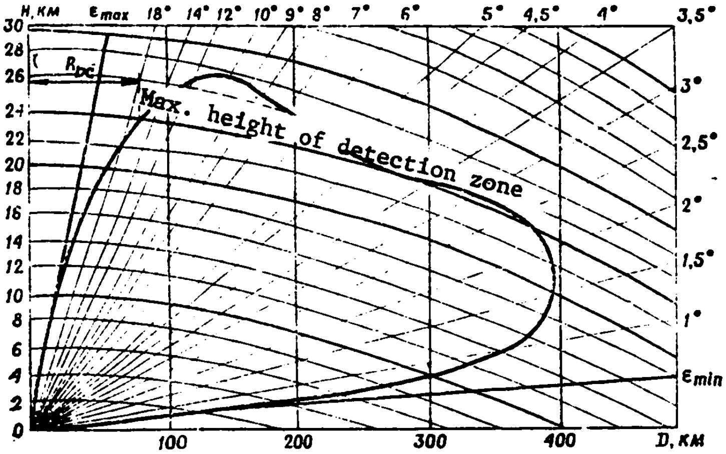


Fig. 4.4. Half section of radar detection zone in vertical plane

The dependence F(ε) is ordinarily given in the technical specifications of the radar or is derived by the well-known method using the radio emission of the sun. The radar detection zone at low altitudes depends substantially upon the amount of the clearance angles which limit detection range in the direction of a terrain feature which creates the clearance angle. The demand on the acceptable clearance angles is the basic one in selecting the position for the radar. Maximum detection range at low altitudes which can be realized with various values of the clearance angle γ is given in a graph (Fig. 4.5). For increasing target detection range at low altitudes the electrical center of the antenna is raised with the simultaneous inclining of its focal axis to a certain negative elevation. For raising the antenna, prevailing heights, special towers, masts and other structures can be employed.

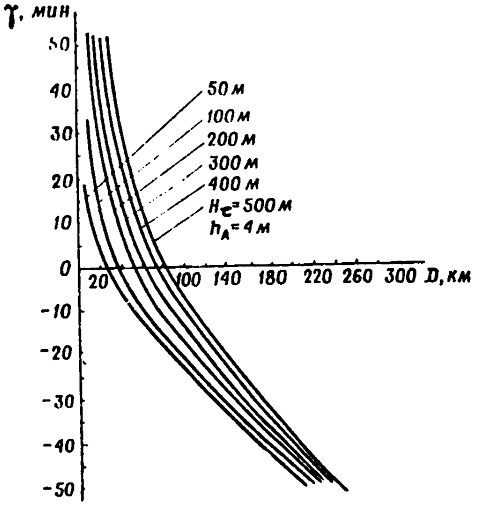


Fig. 4.5. Graph of dependence of maximum possible target detection ranges at low altitudes upon clearance angles (under conditions of standard refraction)

The potential capabilities of radars to detect aircraft range at low altitudes with normal atmospheric radio wave refraction are determined by the formula, km:

$$D_p = 4.12 \cdot K(\sqrt{H_t} + \sqrt{h_a}). \qquad (4.8)$$

where K--radiohorizon utilization coefficient;

H_t--aircraft altitude, m;

h_a--height of raising antenna electrical center, m.

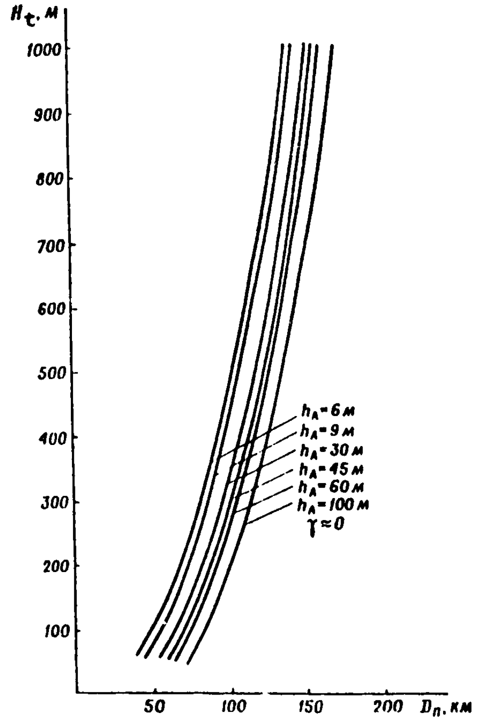


Fig. 4.6. Graph of dependence of potential radar capabilities to detect targets at low altitudes

The dependence $D_p = f(H_t, h_a)$ with $K = 1$ is shown in Fig. 4.6.

For the decimeter and meter wave bands, the radar directional pattern is formed by the adding of the energy direct beam and the energy falling at various angles on the underlying surface and reflected in the direction of the direct beam. The relief and mineral composition of the underlying surface substantially influence the reflection of electromagnetic energy. The radar directional pattern of the meter and decimeter bands is:

$$D(\varepsilon) = D_C F_C(\varepsilon) F(\varepsilon), \qquad (4.9)$$

where D_C--maximum target detection range with given RCS $_t$ in free space;
$F_C(\varepsilon)$--normed directional pattern of radar in free space;
$F(\varepsilon)$--interference multiplier (earth multiplier).

The clearance angles for the radar complexes in these ranges also create a shadow effect at low altitudes and should be taken into account in calculating the detection zones. The additional demands on the positions of these radars include: the acceptable incline (rise) of the position, the minimum platform area around the radar, and the height of the position's unevenness which should not exceed the values of Δh_H. The radius of the level area should be:

$$R_{ar} \approx 23.3\frac{h_a^2}{\lambda} \qquad (4.10)$$

with $h_a/H_t \ll 0.25$.

(In not fulfilling this condition, the radius of the area is

$$R_{ar} = 4.12\sqrt{27\lambda^{2/3} + h_a} - 21\sqrt{\lambda},$$

the unit of measurement for all values is the meter) while the tolerable amount of unevennesses is:

$$\Delta h_H < \frac{\lambda}{16\sin\theta}. \qquad (4.11)$$

where θ--the angle of incidence of the energy from the antenna's electrical center to the point of the unevenness.

The actual detection zones of radars set up at battle positions are calculated considering the influence of the terrain and are checked out by an overflight. In the process of operating the radar statistics is accumulated on target detection at the given position at various altitudes and with various RCS and on the basis of this the detection zone is clarified.

The experimental calculation method of determining the radar detection zone at low altitudes. The calculating of the detection zone is preceded by a topographic surveying of the position which provides for the constructing of the position's relief profiles at various azimuths and the determining of the clearance angles and slope angles of the position γ_{av} for the same azimuths. Then the potential detection range of the radar complex is determined, km:

$$D_p = KD_{\ell s}, \tag{4.12}$$

where K--the radiohorizon utilization coefficient;

$D_{\ell s}$--line-of-sight range.

In knowing the potential detection range, the clearance angles and the position's profiles, the actual detection range is determined for the given azimuth at low altitudes. On the position's profile, a line of sight is drawn as well as the target's flight profile with terrain following (Fig. 4.7) and then the areas of the flight profile are found where the target at the given altitude is not observable (these are below the line of sight). The beginning and end of the area are designated respectively by R_{zh} and R_{zk}.

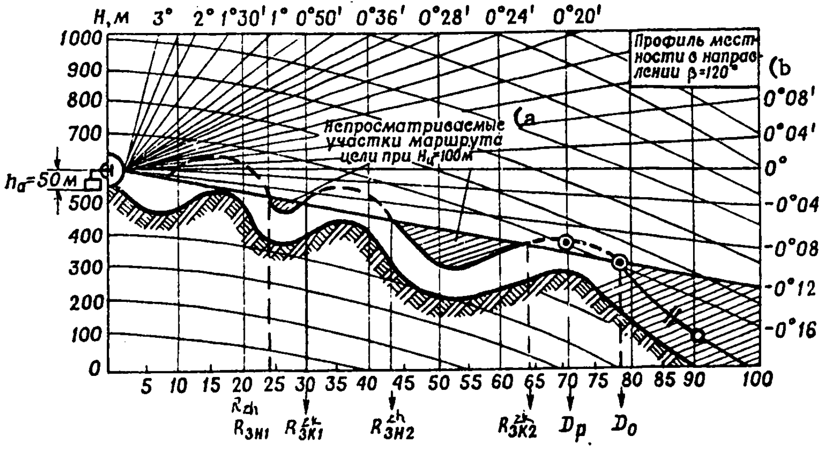


Fig. 4.7. Aircraft flight profile with terrain following

Key: a--Unviewable areas of target route with $H_t = 100$ m; b--Terrain profile in direction of $\beta = 120°$

One then determines the maximum target detection range at the given altitude D . If $D_0 > D_p$, it is accepted that $D_0 = D_p$. Thus, the detection range is determined for other values of target altitude. Having obtained the values of D_0 and the dimensions of the blind areas at various altitudes, a vertical section of the detection zone is constructed for the given azimuth.

In a similar manner the calculated detection zone is constructed for the other azimuths. In constructing the calculated detection zone for radars of the meter and decimeter bands, one must adjust for the amount of the position's slope γ_{av} by shifting all the points of the zone by the slope angle γ_{av} on this azimuth.

The calculated values D_0, R_{zh}, R_{zk} are checked out by an overflight. The overflight is made for one or several azimuths depending upon the various slope angles on the different azimuths. This makes it possible to clarify the actual value of the radio-horizon utilization coefficient K of the given radar as well as the influence of the position's slope. The amount of the deviation of the calculated detection range from the overflight one

$$\Delta D = D_{ov} - D_0 \tag{4.13}$$

is incorporated in the overflight azimuth and the other azimuths for which the position's slope equals zero or is close to the slope angle of the overflight azimuth.

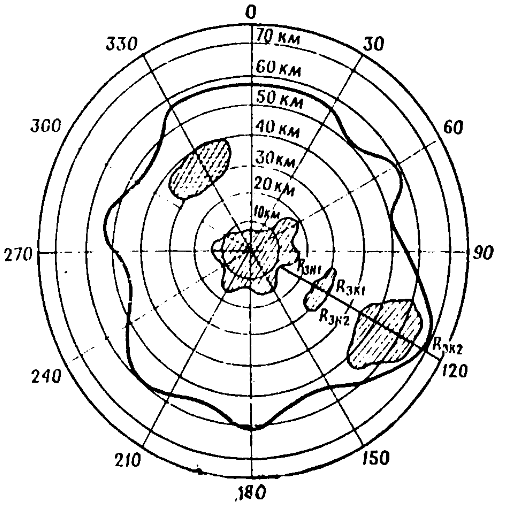


Fig. 4.8. Radar detection zone in the horizontal plane

The horizontal sections of the detection zone for the set values of the aircraft's altitude (Fig. 4.8) are constructed on a map (blank) with a scale of 1:500,000, using an azimuth circle on which are plotted the points corresponding to the adjusted values of the detection range on each of the azimuths. Having connected these points with a free-form curve, we obtain the external limit of the radar detection zone at the given altitude. In an analogous manner the blind areas created by the shadow effect in the detection zone are found.

The constructing of a radar detection zone at medium and great altitudes. For constructing a detection zone at medium and great altitudes it is essential to have a normed directional pattern of the radar antenna for the given position and the true value of detection range for a target with the given RCS at one of the altitude values H_t.

A normed directional pattern is taken by an astronomical method (from the sun's radio frequency radiation) or by using a special generator tuned to the carrier frequency of the radar the antenna of which can be moved in altitude and set up at a distance of at least

$$d > \frac{4\ell^2}{\lambda}, \tag{4.14}$$

the elevation $\varepsilon_i = \varepsilon_1 = 1° = 100$ km. According to the graph (Fig. 4.10) $B_{ov} = 1.04$, $B = 1.10$ (with $\varepsilon_1 = 1°$, $D_1 = 100$ km), then $\alpha = B/B_{ov} = 1.10/1.04 = 1.058$.

The detection range at $\varepsilon_i = \varepsilon_1$ is taken as equal to $D_1 \cdot \alpha = 100 \cdot 1.058 = 105.8$ km.

The constructing of a radar detection zone at maximum high altitudes by the potential dip method. The potential dip method is employed for clarifying the radar detection zone at altitudes exceeding the aircraft service ceiling.

In this instance the overflight is carried out at tolerable altitudes while the potential of the radar complex is artificially reduced. The dip in the potential is equal to the even compression of the detection zone along the constant elevation lines:

$$K_{cm} = \frac{D_{ov}}{D} 10^{-\frac{N}{40}}, \tag{4.19}$$

where D_{ov} and D--detection ranges with reduced and normal potentials, respectively;
N--degree of potential dip, decibel.

The degree of the potential dip is selected in such a manner that the height of the aircraft making the overflight exceeds the altitude of its continuous tracking in the "narrowed zone."

From the results of the overflight, in using the above-described procedure, a narrowed radar detection zone is constructed (Fig. 4.11) and then the real detection zone corresponding to the normal radar potential.

For converting points a, b, c, d of the narrowed zone into their corresponding points A, B, C, D of the real zone, the ratio is employed:

$$D = D_{ov} 10^{\frac{N}{40}}. \tag{4.20}$$

The line connecting points A, B, C, and D is the boundary of the detection zone.

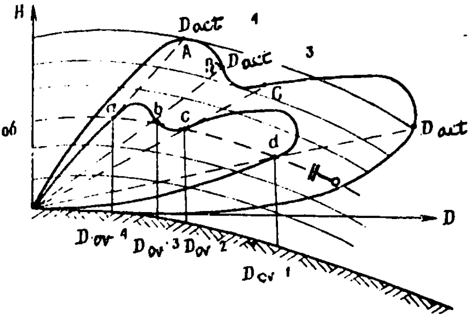


Fig. 4.11. Radar detection zones with reduced and normal potential

Recalculating the detection zone for another value of the RCS relative to the given one. In practice, the need arises using a known detection zone calculated for one value of the RCS σ_1 to obtain the detection zone for targets with a different RCS σ_2.

For the conversion at medium and great altitudes, the formula is employed:

$$D_2 = D_1 \sqrt[4]{\frac{\sigma_2}{\sigma_1}} \text{ with } \varepsilon = \text{const}. \tag{4.21}$$

For the conversion at low altitudes, the change in detection range caused by the change in the RCS is calculated, km:

where d--the distance between the antennas of the radar and the generator, m;
ℓ--maximum linear dimension of radar antenna, m.

The true value of the detection range is disclosed by an overflight of the radar at the given position.

For recalculating the normed directional pattern into a detection zone, one determines the value of the conversion factor (the directivity factor) K_o for elevation ε_{vid} for which the true detection range is determined according to the overflight:

$$\varepsilon_{vid} = \arc\sin\left(\frac{H_t}{D_{ov}} - \frac{D^2_{ov}}{17{,}000}\right). \tag{4.15}$$

In knowing the value ε_{vid} using the normed directional pattern it is possible to determine the value K_o (Fig. 4.9). The values of the detection range D_i for other elevations are:

$$D_i = K_{Di}D_{max}, \tag{4.16}$$

where K_{Di}--value of conversion factor for elevation i:

$$D_{max} = \frac{D_{ov}}{K_o}. \tag{4.17}$$

For considering radio wave refraction attenuation at the given elevation, the value of D_i must be multiplied by the coefficient α:

$$\alpha = \frac{B}{B_{ov}}, \tag{4.18}$$

where B--attenuation factor at angle ε_i;
B_{ov}--attenuation factor at angle ε_{vid}.

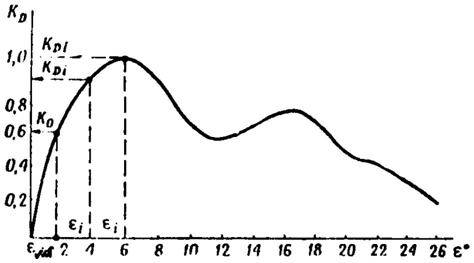


Fig. 4.9. Radar directional pattern

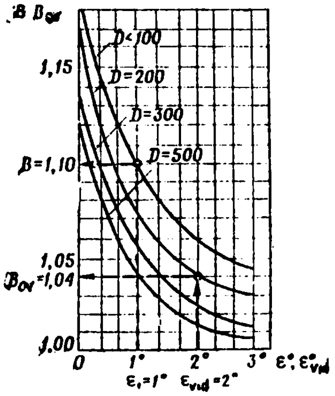


Fig. 4.10. Graph of values for refraction attenuation factor

The values B and B_{ov} are determined from a graph (Fig. 4.10). The value of B is determined for ranges D_i and their corresponding angles ε_i, B_{ov}--for the range D_{ov} and ε_{vid}. For example, $\varepsilon_{vid} = 2°$, $D_{ov} = 200$ km and the calculated value of the range at

$$\Delta D = md, \tag{4.22}$$

where $m = -10\log\frac{\sigma_1}{\sigma_2}$, dB; $d = \frac{5{,}42}{\sqrt[3]{f}}$, $\frac{\text{км}}{\text{dB}}$;

f--radar carrier frequency, megahertz.

The obtained value of ΔD is added to or subtracted from (depending upon the sin of ΔD) D. The newly obtained points are connected by a free-form curve which is the external boundary of the detection zone with the new RCS value.

In conclusion the two parts of the detection zone constructed for the ranges of low and medium altitudes are joined together.

Recalculation of the radar detection zone for a given value of the target detection probability. The range of target detection D with a given probability P is related to the known detection range D_0 and its corresponding probability P_0 thusly:

$$D = D_0\sqrt[4]{-\ln P}. \tag{4.23}$$

Ordinarily the external boundary of the radar detection zone is constructed for values $P_0 = 0.5$. Under this condition for recalculating the detection zone it is possible to use the formula

$$D = 1{,}35 D_{0,5}\sqrt[4]{-\log P} \tag{4.24}$$

The probability of target detection by several radars. The resulting probability P_{res} of detecting the given target by several radars conducting reconnaissance simultaneously and providing information to a single collection point is:

$$P_{res} = 1 - \prod_{i=1}^{n}(1 - P_i), \tag{4.25}$$

where n--the number of radars conducting target reconnaissance;
P_i--probability of detecting the target by radar i at the given point.

$$P_i = e^{-0{,}69\left(\frac{D_i}{D_{0,5}}\right)^4} = 10^{-0{,}3\left(\frac{D_i}{D_{0,5}}\right)^4}. \tag{4.26}$$

where D_i--range to target detection of which is provided with probability i.

Radar Antijamming Capability

The capability of the RTV radars to conduct reconnaissance under passive interference is judged by the amount of the jamming visibility coefficient K_{jv} of the antijamming equipment. In comparing its amount with the real ratio of the signal power of the passive interference to the power of the blips which is characteristic for the area, a conclusion is drawn on the radar's capability to conduct reconnaissance in passive interference under the given jamming situation.

The capabilities for defense against active jamming are characterized by the amount of the detection zone compression coefficient for nonjamming targets outside the effective neutralization sector and by the amount of the effective neutralization sector for jamming targets (sources of active jamming [SAJ]).

The compression coefficient for the radar detection zone for nonjamming targets is:

$$K_{cm} = \frac{D_\rho}{D_0} = \frac{1}{\sqrt[4]{1 + 77\frac{\rho G_{re} f_b \lambda^2}{N R_{jl}^2}}}, \qquad (4.27)$$

where ρ--spectral density of jamming power, watts/megahertz;

G_{re}--receiver antenna gain;

f_b--the level of the side and back lobes in the directional pattern of the radar antenna;

λ--wave length, cm;

N--receiver noise factor;

$R_{j\ell}$--distance from radar to jamming line, km.

For a specific type of radar, the ratio (4.27) can be represented in the form:

$$K_{cm} = \frac{1}{\sqrt[4]{1 + A\frac{\rho}{R_j^2}}}. \qquad (4.28)$$

For the convenience of calculating K_{cm}, it is possible to construct a graphic dependence $K_{cm} = f(R_{j\ell})$ with fixed values of ρ.

The effective neutralization sector is measured by the angle in the azimuthal (or elevation) plane in which the SAJ provides a cover for itself and a screen for the covered targets. The width of the effective neutralization sector depends upon the spectral density of the noise power ρ, the distance to the SAJ, the station's potential, the width of the directional pattern of the radar antenna and the level of the side lobes.

Radar Capabilities for Providing Information and Determining the Composition of Group Targets

The potential information capabilities of the RTV radars are:

$$N_p = \frac{(D_{max} - D_{min})\,\Delta\beta\,\Delta\varepsilon}{\delta D\,\delta\beta\,\delta\varepsilon}. \qquad (4.29)$$

where D_{max}, D_{min}--operational limits of radar for range;

Δβ, Δε--radar scanning sectors for azimuth and elevation, respectively;

δD, δβ, δε--resolutions for coordinates.

The actual realization of these capabilities is restricted by the productivity of the data taking equipment. In this regard the information capabilities of radar depend upon the method of collection, the number of parallel data taking devices, the methods of realizing target indication as well as the space scan rate. In the simplest instance, with autonomous operation of a radar, the information capability for producing the corresponding coordinate is:

$$N_i = K_p m_i \frac{t_{disc\ i}}{t_{c\ i}} \text{ with } t_{disc\ i} \geqslant T_o, \tag{4.30}$$

where K_p--coefficient considering the reduction in information capability due to overlapping of the taking sectors and the redistribution of these sectors;

m_i--the number of devices taking component i of information;

$t_{disc\ i}$--the discreteness of taking component i of information;

$t_{c\ i}$--time spent in taking information and realizing target designation;

T_o--space scan rate.

The capabilities for determining the composition of a group target and the moment of its splitting are characterized by the resolutions of the radars and are assessed using formulas (3.80), (3.81) and (3.82).

Radar Capabilities to Carry Out Support Tasks for Antiaircraft Missile Troops and Fighter Aviation

Radar support for the combat operations of firing complexes of the ZRV and the fighter aviation comes down to the prompt providing of information which ensures continuous target designation for the missile guidance station or the guiding of a fighter to a point from which it can detect and intercept a target with the onboard radar or detect it visually.

The quality of the radar support of a target designation and guidance radar depends upon the mistakes in taking the primary information coming from the radar complex.

Mistakes in measuring target coordinates in terms of the patterns of their occurrence are divided into systematic and random. Random and systematic errors in measuring target coordinates by radar complexes in terms of the reasons of their occurrence are divided into bearing, instrument and dynamic.

Bearing errors arise under the influence of radio wave refraction, the reflection of them from the terrain, the distortion of signal shape due to the dispersion properties of the environment and a change in radio wave propagation rate.

Instrument errors appear due to the inaccuracy of forming the electric scale, errors in interpolating the position of the blip relative to the electric scale line, inaccuracies in lining up the marker with the blip, inaccuracies in the topographic locating of the station and a number of other factors.

Dynamic errors of measurement depend upon the heading and speed of the target's moving as well as upon the method of taking the information:

$$X_{dyn} = V_x(t_1 + t_2), \qquad (4.31)$$

where V_x--speed of target in direction of measured coordinate;
t_1--time of generating blip on indicator screen;
t_2--time spent on taking information for given coordinate.

The systematic components of all the listed errors groups can be determined and then accounted for and compensated for. For this reason, the accuracy of measuring target coordinates basically depends upon the random errors the distribution law for which is considered normal.

Random errors can be judged by the amount of the mean square error σ, the median and maximum error or by the error in 80 percent of the measurements.

The Mean Square Error

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2}. \qquad (4.32)$$

where $x_i = a_i - X$--the random error of measurement i;
a_i--the result of measurement i;
X--the true value of the measured coordinate;
n--the number of measurements.

If we know the mean square errors $\sigma_1, \sigma_2, \ldots, \sigma_n$ caused by various independent sources, then the total mean square error is:

$$\sigma_\Sigma = \sqrt{\sigma_1^2 + \sigma_2^2 + \ldots + \sigma_n^2}. \qquad (4.33)$$

The probability of the mean square error $P(\sigma) = 0.683$.

The probable x_p or median error is the name given to that value the appearance probability of which $P(x_p) = 0.5$:

$$x_p = \frac{2}{3}\sigma. \qquad (4.34)$$

The maximum error is the greatest error which is possible under certain measuring conditions:

$$x_{max} \approx 3\sigma. \qquad (4.35)$$

For comparing the capabilities of the RTV radars for accuracy performance often the errors in 80 percent of the measures are employed and these are determined in testing by the collecting of statistical data. The converting of them into mean square errors is carried out by the formula:

$$x_{0.8} = 1.3\sigma. \qquad (4.36)$$

Accuracy of Measuring Target Range, Azimuth and Altitude

The mean square error for measuring distance is:

$$\sigma_D = \sqrt{\sigma^2_{D\ bear} + \sigma^2_{D\ inst} + \sigma^2_{D\ dyn}}. \tag{4.37}$$

The bearing error $\sigma_{D\ bear}$ ordinarily does not exceed several meters and in a majority of calculations need not be regarded with the visual taking of information.

The basic reasons for the appearance of instrument errors are:

a) A change in the lag time for the passage of the blip through the paths of the radar complex (radar set) determined by the operating mode of these complexes;

b) The inaccuracy of determining the blip's position relative to the range electric scale lines (with the visual method of taking the information) or the inaccuracy of lining up the marker with the blip (with the automated method of taking the information);

c) An error in the range electrical scale;

d) An error in determining the position of the start of the blip caused by the influence of background noise and the end thickness of the range scan.

Since the change in the lag time of the blips in the paths of the radar complex (set) with tuned equipment ordinarily does not exceed fractions of a microsecond, the error caused by this factor can be disregarded.

The instrument error consists of interpolation errors $\sigma_{D\ interp}$, the inaccuracy of forming the range electrical scale $\sigma_{D\ sc}$, the presence of background noise $\sigma_{D\ n}$, and the end thickness of the range scan line $\sigma_{D\ s}$. The mean square values of the designated errors are judged:

$$\sigma_{D\ interp} = \frac{D_{m\ min}}{30}; \tag{4.38}$$

$$\sigma_{D\ sc} = \frac{D\Delta f}{3f_{re}}; \tag{4.39}$$

$$\sigma_{D\ n} = \frac{ct_{fr}}{6\left(\frac{u_s}{u_n}\right)}; \tag{4.40}$$

$$\sigma_{D\ s} = \frac{d_s}{6m_D} \tag{4.41}$$

where $D_{m\ min}$--the distance between the scale marks of the minimum gradation in range units;

$\frac{\Delta f}{f_{re}}$--the relative frequency drift of the reference generator;

t_{fr}--the duration of the blip fronts;

$\frac{u_s}{u_n}$--the signal--noise ratio;

d_s--the diameter of the spot focused on the CRT screen;

m_D--the scale of the range scan, mm/km.

Having assessed the individual components of the instrument error, it is possible to determine its resulting value

$$D\ \text{inst} = \sqrt{\sum_{i=1}^{n} \sigma^2_{D_i}}. \qquad (4.42)$$

The dynamic error with a normal distribution of target headings relative to the radar complex is:

$$\sigma_D\ \text{dyn} = \frac{V_r t_{read}}{3}, \qquad (4.43)$$

where t_{read}--the time lag in reading the information.

With the visual and semiautomatic methods of reading information in a complex air situation, the dynamic error exceeds the instrument one and even more so the bearing error.

With the automatic method of reading information the determining error is the instrument error and the bearing error is commensurable with it.

The accuracy of measuring target azimuth depends upon the horizontal refraction of the radio waves, the curvature of the propagation trajectory under the influence of terrain unevenness (the bearing error), errors in orientation, errors in transmitting the antenna azimuth to the indicator, in the forming of the azimuth scale and in the line-up of the marker (instrument error), as well as the moving of the target along the azimuth over the period of forming and reading the information (the dynamic error).

The bearing, instrument and dynamic errors are determined by a formula analogous to formula (4.42). The total mean square error of measuring azimuth is produced by an expression analogous to expression (4.32).

The reasons for the appearance of errors in measuring target elevation (altitude) are the same as in measuring target azimuth and for this reason they are assessed by an analogous procedure.

4.1.2. Automation of Radar Data Processing

The process of processing radar data for the purposes of constructing optimum processing algorithms can be divided into the following stages: primary data processing (PDP); secondary data processing (SDP); tertiary data processing (TDP).

By primary processing one understands the processing of radar signals coming in from the output of the radar receiver in one scan of space (detecting return signals from the targets, measuring target coordinates and their encoding).

The data obtained on the target coordinates as a result of the primary processing in an encoded form (in the form of a binary code) is stored in the computer's memory. Regardless of optimum methods for detecting the signals returned from the target, due to various types of interference it is impossible to assert with a probability close to one that with PDP signals returned from a target have been detected and not noise. The need arises for subsequent (secondary) data processing based on the relationships of the blips belonging to the same targets.

Secondary processing is the name that has come to be given to the processing of radar data coming in from the same radar in several scans and which has undergone primary processing. In the process of secondary processing the tasks of detecting and tracking the target routes are carried out. This is done using the appropriate algorithms by computer installations. After secondary processing the data on the current coordinates and motion parameters is given to the users.

The same target can be observed by several radars which are a varying distance apart. These radars operate out of synch and provide data on the target coordinates relative to their position. All of this necessitates the next (tertiary) processing of the radar data.

By the tertiary processing of radar data one has come to understand the process of identifying the routes of targets tracked by several sources.

The examined stages of automated radar data processing must be distinguished from the tactical concepts of primary and secondary radar data processing. In tactics, by primary processing one has come to understand the processing of radar data which is provided by the combat crew employing the primary indicators, and by secondary processing the work of the secondary indicators.

Primary Processing

It is possible to have automated and automatic methods for primary radar data processing.

The automated method is a method whereby the operator detects the target visually while the coordinates are measured using the read-out equipment. Here the encoding of the coordinates is done by the equipment without the participation of the operator. The automated method is preferable in detecting targets under the conditions of jamming. It makes it possible to have the selective reading of data displayed on the indicator screen.

The automatic method is a method which envisages the complete exclusion of man from the process of solving the problems of target detection and measuring the coordinates. Automatic primary processing of radar signals is carried out by a specialized computer (a specialized PDP computer) which includes devices for detection and the measuring of coordinates.

The detection device. The optimum method for detecting effective signals against a background of interference (noise) is accumulation. For this reason the detectors employ analog and discrete (digital) storages. For primary digital processing it is essential to convert the voltage received from the output of the radar receiver into a discrete amount expressed in a binary code. This conversion is performed by a quantizer. Then the detector processes the quantized signals by one of two methods: by the quasioptimum or the weightless processing method.

The quasioptimum methods for processing quantum signals are difficult to realize and in practice more often simplified target detection algorithms are employed using the weightless processing method.

This method is based upon an analysis of the density of units within the width of the radar antenna directional pattern. Naturally, the density of units in the target area is always greater than the density of units in the interference area. The decision of detecting the start of a blip cluster is taken using the criterion ℓ out of m and the end of the cluster in recording K misses. The logic of the work carried out by the program detector of the start and end of the return signal cluster is usually written thus: "ℓ/m--K."

The unit for measuring the target coordinates for range D_t, azimuth β_t and elevation ε_t. The measuring of range can be carried out by a special range measuring unit or by a special computer in the process of detecting the target. The measuring of range is based upon measuring the time interval from the moment of sending the transmitted pulse to the moment of receiving the return signal by the radar receiver.

With the weightless processing of quantized signals, the measuring of target azimuth β_t comes down to calculating the azimuth of the middle of the return signal cluster.

The measuring of target elevation ε_t is carried out in an analogous manner.

Secondary Processing

The coordinates measured as a result of PDP characterize the target's position in space at the moment of its radar location. The determining of the parameters of target motion by processing radar data coming over several scan cycles is carried out in the secondary data processing. For constructing optimum algorithms the secondary processing is usually divided into two successive stages: the detection of target trajectory and the tracking of the trajectory.

Depending upon the degree of the operator's involvement, each of the designated stages can be manual, automated or automatic. Automatic detection of a target trajectory is termed autolock-on and automatic tracking is known as autotracking.

The solving of these problems is based upon the principle of a scan-by-scan linking of the target blips the essence of which is that the position of the blips of each target received in the next scan cycles is determined by the nature of this target's motion.

The movement of the target is characterized by the parameters such as heading, speed, acceleration and so forth and these can be calculated from data on the coordinates during the preceding scans. From the parameters it is possible to determine (construct) the target's trajectory. Thus, with the steady and rectilinear motion of a target, its trajectory will be a straight line. For this reason, in the next scan cycle, the blip from the target will appear not in an arbitrary point of space but rather in a certain area which has moved in the direction of the target's motion over a distance determined by the radar's scan interval T_0 and the target's speed.

In the stages of detecting and tracking a target's trajectory in the secondary processing algorithms usually the following operations are established: calculating the parameters of the target's motion (heading, speed or the components of the velocity vector); the extrapolation of target coordinates; strobing or establishing the zone of the probable target location in the following scan cycle; collation or comparing the coordinates of the blips selected by the strobe and selecting one of them for continuing the trajectory.

Calculating the parameters of the target's motion. The parameters are determined on the basis of data on the target's coordinates over n scans of the radar. Since the coordinates are measured with errors, for improving the quality of the data the need arises to smooth out the motion parameters and this can be done by the least square, weighted mean and exponential methods.

Extrapolation of target coordinates. In the general instance, by extrapolation one usually understands the extension of results obtained from observing one portion of a phenomenon to another portion of it. In the extrapolation of coordinates, one studies the law of the target's motion in the time interval over n radar scans and this is extended beyond the interval of observation, for example, to $n+m$ scan. The extrapolation of coordinates can be carried out by the least square method and using the parameters of target motion. In extrapolating the coordinates using the parameters of target motion, one assumes a hypothesis on the steady and rectilinear motion of the target.

Strobing. Due to the presence of measurement errors and the extrapolation of coordinates, as well as the possible maneuvering of a target, in a general instance the extrapolation points in the next scan may not coincide with the current target blips. The current blip in the next radar scan will appear around the extrapolation point. The area of the probable appearance of a current blip in the next scan has come to be called the strobe.

The shape of the strobe can vary. In strobing one calculates the area of the probable appearance of a target and selects the targets which have fallen into the strobe. It is considered that a current blip belongs to the route of the target being processed if the difference for the modulus of the same coordinates of the current blip and the extrapolation point does not exceed the allowable amounts. The ellipsoid is the optimum shape of a strobe in operating in a rectangular coordinate system.

Collation. In the general case it is possible for several blips to fall in a strobe and of these one will belong to the route of the processed target (the remaining blips are spurious from noise or other targets). The blip of the actual target differs from the spurious ones that have fallen into the strobe only by the distance from the strobe center (the extrapolation point). Both for the spurious and for the true blip, this distance is a random amount. But the statistical characteristics of these random amounts differ and this is employed in selecting the blips in the strobe.

The deviation of the true target blip from the strope center is subordinate to a two-dimensional normal distribution law. The probability density for the appearance of a true blip is increased in approaching the extrapolation point while the distribution of the spurious blips within the strobe is even.

Depending upon the values of the mean square deviations σ_x, σ_y, the selection of the true blips can be carried out by the method of minimal elliptical deviations if $\sigma_x \neq \sigma_y$ or by the method of minimum linear deviations if $\sigma_x = \sigma_y = \sigma$.

Tertiary Data Processing

A command center can receive information on the same target from several sources and each source submits reports at arbitrary moments of time.

On the basis of the reports from the sources, in the process of tertiary processing it is essential to make up a general report and for this it is necessary to reduce the information to a uniform start of the count in space and time; to identify the reports belonging to the same targets; to calculate the metric coordinates of the general reports.

The reducing of information to a uniform start of the count in space is carried out by performing the operation of coordinate conversion and to a uniform start of the count in time by performing the operation of extrapolating the coordinates to the moment of processing time. The solution to the problem of converting the coordinates into tertiary processing algorithms depends upon the coordinate system in which the information is exchanged. The simplest are the formulas for coordinate conversion for a rectangular system.

The coordinates can also be extrapolated by the same methods as in the secondary processing algorithms.

Identification of reports. The problem of selecting the reports which belong to one target but which have been received from different sources is the basic and most labor-intensive one in the tertiary processing process. The process of selecting the reports is broken down into rough and precise identification.

Rough identification comes down to assessing the difference in the same target coordinates. Two reports relate to the same target if the difference of the same coordinates does not exceed the acceptable amounts. For the purpose of formalizing this process, a coincidence feature is introduced for the metric coordinates of two reports.

On the basis of the coincidence feature, the A group of reports is formed and these in the general instance can belong to different targets.

Precise identification is carried out on the basis of logical rules and analyzing the metric properties of the space of the reports which have fallen into the A group.

For an analysis of the reports in the A group, it is possible to employ the logical rules: a, b, c, d.

Rule a. If the A group includes reports from one source, then these reports relate to different targets and they must not be considered identical. This rule stems from the impossibility of receiving two reports on one target in one scan.

Rule b. If the A group includes one report from each source, these reports are reports on one target and they may be considered identical. This rule is based on the fact that it is improbable that one of two nearby targets would be observed by one radar and the second by the other.

Rule c. If the A group contains a uniform number of reports from each information source, then the total number of targets in the group is determined by the number of reports from each source.

Rule d. If the A group includes a varying number of reports from the sources, then the most reliable situation is given by the information source which transmits information on a larger number of reports. The logical rules c, d designate variations of report identification. In the cases of the designated logical rules (c, d) there is the subsequent analysis of the reports on the basis of the metric properties of the reports' space.

4.1.3. The System of Taking, Transmitting and Displaying Information

The System for Taking and Feeding In Information

With the automated processing of radar data, the task of detecting the target and measuring its coordinates is carried out by an operator using information taking devices and the method of selective electronic sighting which is based on the principle of converting the observed coordinates of the target blips into an electrical signal. The system for taking information includes an indicator, sensors and a computer.

The Data Transmission System

The exchange of information in an ASU [automated control system] is made up of the transmitting and receiving of discrete messages. The transmission of messages over the communications channels is carried out by special signals which are information carriers. Uniform DC pulses usually serve as the elementary signals.

Performance of data transmission systems. The operating quality of data transmission systems is usually described by the following indicators: data transmission rate, communications capacity and reliability of message transmission.

The message transmission rate characterizes the amount of information which can be transmitted in a unit of time.

By the capacity of a communications channel one understands that quantity of information which can be transmitted in a unit of time with the required degree of transmission accuracy. Communications capacity is the maximum possible transmission rate. Communications capacity in transmitting binary messages can be estimated by the number of elementary pulses transmitted per second, that is, in bauds.

The reliability of message transmission describes the degree to which the received messages conform to the transmitted ones. Quantitatively this can be assessed by the probability of correct reception P_c or the probability of false reception P_f of the information. The designated probabilities are related by the ratio $P_c = 1 - P_f$.

For increasing the reliability of message reception correcting codes are employed which improve reliability by introducing redundancy.

The data transmission system consists of a telereceiver, a teletransmitter and a telex communications channel.

The teletransmitter converts the binary code of the messages received from the automated equipment into signals suitable for transmission over the communications channel. It has switching and channel equipment.

The switching equipment stores the binary code of the messages while the channel equipment converts the code into signals, for example, into phase modulated ones which are transmitted over the communications channel.

The telereceiver carries out the conversion opposite to the teletransmitter.

The Data Display System

This system provides the contact between the commander (the personnel of the combat crews) and the ASU computer complexes. It makes it possible to create an information model of the process being controlled. Here the following are provided:

A visual reproduction of the information on the air enemy, on the combat readiness and combat actions of subordinate and cooperating troops, the results of the machine decisions and monitoring of the control process;

The display of the terrain map and the battle formations of the controlled troops;

The receiving and inputting of information into the computer complexes and into the communications channels and the electronic (digital) exchange of information between the personnel of the combat crews both at the given and cooperating command post (control center).

The information is displayed in the form of digits, symbols and signs.

A display system includes: computer complexes, various types of displays and couplers for the radar equipment and communications channels. The computer complexes following the corresponding algorithms and on the basis of information stored in their memory form the information model.

Displays are Classified as Follows:

In terms of the method of use, including individual and collectively used displays; the individual displays are designed for equipping automated work areas for the members of combat crews at command posts (control centers); collectively used devices display the air situation for a certain group of persons in a combat crew of a command post (control center) and their uniform understanding of the air situation.

By the type of information displayed there are primary and secondary displays; the screens of primary displays show the primary and secondary air situation, while the screens of the secondary displays show the secondary situation; by the primary air situation one usually understands the situation received from the radars and as the secondary the situation received from the computer complex and communications channels.

According to the methods of digit formation there are displays which realize the following methods: small-sized television screen, functional and matrix.

With the method of a small-sized television screen, the sign is formed by the point mosaic method, with the functional method the sign is drawn by a beam on the screen of a CRT, and with the matrix method the sign is printed on the CRT screen. For realizing the matrix method, special printing tubes of the charactron type are employed.

For reproducing the signs on the screen, electronic, electroluminescent and optoelectronic elements can be employed. Information on the situation can be represented on indicators and panels. The PPI [plan-position indicators], altitude indicators, electronic plotting boards and large screens are employed as indicators.

Performance of the data display system. The functional quality of data display systems is usually evaluated by information and technical performance. Among the informational performance of a display one could put the information capacity, the specific information capacity and the speed and reliability of information display.

Information capacity H(C) (binary units) describes the maximum amount of information which can be displayed on the display screen:

$$H(C) = N_{sp}\log_2 K_s, \qquad (4.44)$$

where N_{sp}--number of sign places on the screen;
K_s--number of signs generated by display sign generator.

The specific information capacity j (binary units/sign place) describes the amount of information per sign place. This is determined:

$$j = \log_2 K_s. \qquad (4.45)$$

The information display speed R_o (binary units per second) describes the quantity of information displayed on the indicator screen per unit of time:

$$R_o = \frac{z}{T_s}\log_2 K_s, \qquad (4.46)$$

where z--number of simultaneously filled sign places on display screen;
T_s--writing time of one sign.

The reliability of information display describes the degree to which the reproduced signs conform to the sign which should be reproduced. Numerically this is assessed by the probability of the false P_f or correct P_c reading of the sign. Under the conditions of interference, the specific information capacity (binary units/sign place) is:

$$j = \log_2 K_s + (1-P_f)\log_2(1 - P_f) + P_f \log_2\left(\frac{P_f}{K_s-1}\right). \qquad (4.47)$$

Among the technical characteristics are resolution, brightness and contrast, screen size, playback time, operational reliability and others.

4.2. Combat Capabilities of Radar Troops

4.2.1. Definitions and Quantitative Indicators of Combat Capabilities

By the combat capabilities of the RTV one understands their ability to carry out the missions of radar reconnaissance, radar support for fighter guidance, target designation for the ZRV and radar support for control and command.

Combat capabilities are assessed by a system of indicators which describe: the dimensions of the space for receiving radar information (using radar equipment) corresponding in terms of its performance to the requirements of carrying out the tasks of combat control as well as the information capacity of the system involved in the processing and providing radar information and any of the system's elements.

The combat capabilities of a radar subunit the radar equipment of which is deployed at one combat position are characterized by the information zone of this subunit; the information capabilities for the output of the command post (information channel) is described by the number of simultaneously tracked targets with the set discreteness.

The information zone is an aggregate of the detection zones of the subunit's radars and represents an area of space in which are provided the measuring of the three coordinates, identification and the determining of other tactical characteristics of the radar targets.

The combat capabilities of a group of radar subunits or radar units are characterized by the area of the existence of a radar field of information and which is formed by the aggregate of the subunit information zones. For evaluating combat capabilities, the basic interest is in the area of the existence of a solid radar information field within which continuous tracking of the detected targets is ensured.

The information capabilities of the command posts of a group of radar subunits, radar units and command posts are also assessed by the quantity of simultaneously tracked targets in observing the discreteness permissible for successfully carrying out the specific mission of radar support for control of the firing complexes or troops.

The capabilities of a group of subunits and units to detect SAJ [source of active jamming] are judged by the triangulation zone and field.

By the triangulation zone one understands an area of space in which the coordinates of the SAJ are determined with a preset accuracy. The aggregate of the triangulation zones of three and more radar subunits forms a triangulation field under the condition of processing the bearings to the SAJ from any of the subunits in the given group at a central command post.

The detection zone of radar equipment and the information zone of a radar subunit are limited by the following: the minimum and maximum elevations, the maximum range and the extremal altitude of detection. The rangefinding zone of a passive radar complex (set) is limited by the minimum and maximum elevations for obtaining a bearing to the SAJ. These parameters are ordinarily given in the technical specifications for the specific radar equipment.

The solid active radar zone and the triangulation zone of a group of radar subunits or a unit is restricted by the following: the outer limit of the field at the given elevation, by the elevations of the lower and upper limits of the solid radar field (triangulation field).

The limit of the solid radar field (triangulation field) at a given altitude is the continuous line formed in the intersecting of the field of an imaginary surface equidistant in all its points from the surface of the earth (sea).

The height of the lower limit of the solid radar field (triangulation field) is the name given to the minimum altitude for continuosu tracking of a target (SAJ) flying a course of terrain following. The height of the upper limit of the solid radar field (triangulation field) is the name given to the maximum altitude of continuous tracking of a target (SAJ) flying horizontally.

4.2.2. Methods of Evaluating Combat Capabilities

The information zone of a radar subunit is constructed from the overflight-tested detection zones of the subunit's radar equipment (4.1).

The information zone is a family of horizontal sections at different altitudes and vertical sections in the sectors of the expected actions of an air enemy. The vertical sections indicate the minimum and maximum elevations σ_{min}, σ_{max}, the maximum range D_{max} and the extremal altitude N_{ext} of detection.

The choice of the number of the family section and the computational values for the altitudes of an air enemy are determined by the set combat missions and by the ruggedness of the terrain.

The effect of active interference on a subunit's information zone is considered by the compression coefficient and the sector for the effective neutralization of the detection zones for the radar equipment of this subunit.

The parameters of a solid radar information field of a unit or group of radar subunits are found by analytical and graphic-analytical methods.

The analytical method is employed for an approximate determination of the parameters for the solid radar field in the stage of planning combat operations. The employment of this method presupposes the following assumptions:

a) Radars of the low-altitude (type I) and high-altitude (type II) types are involved in forming the radar field;

b) The positions of the subunits do not distort the radar detection zones;

c) The subunits are positioned at equal distances apart (in terms of the vertices of equilateral triangles).

For calculating the parameters of the radar information field using this method it is essential to know the area of the territory of combat operations S_{ter}, the number of existing subunits n_{sub} and the standard information zones of the type I and type II radars $(H = f(D))$.

The height of the lower limit H_ℓ is determined for the information zone of the type I radar and for this the minimum detection range of radar targets is calculated for which the radar field is solid:

$$D_o = \sqrt{\frac{S_{ter}}{2.6n_{sub}}}. \tag{4.48}$$

The target altitude corresponding to the found minimum detection range D_o is the lower limit H_ℓ of the solid radar field.

For the upper limit of a solid radar field, the extremal height of the information zone for a type II station is employed under the condition:

$$2H_{extII}\text{ctg}\ \varepsilon_{maxII} < K1.73D_o \leqslant D_{maxII} - H_{extII}\text{ctg}\ \varepsilon_{maxII} \tag{4.49}$$

where $K = 1, 2, 3$--integer depending upon the ratio of the number of type I and type II radars in the given battle formation;

H_{extII}; ε_{maxII}; D_{maxII}--parameters for the information zone of the type II radar.

The graphic-analytical method is the basic one in calculating the parameters of a solid radar information field. It makes it possible to consider the influence of real positions on the detection zones of radar equipment and to determine the detection and tracking area for radar targets employing terrain following.

The initial data for calculating the field's parameters using this method are the battle formation of the radar unit (group of radar subunits) plotted on a map with a scale of 100,000 or 200,000 (depending upon the ruggedness of the terrain), a family of horizontal sections for the subunit information fields at various altitudes relative to sea level. The use of this calculation method provides for breaking the positions of the subunits in a radar unit into quadrants. For simplifying the calculations it is advisable to use the reference grid x, y found on the map.

In each quadrant one puts the total of the altitudes of the highest point of the relief above sea level and the selected target altitude over the terrain $H_{\Sigma t}$ in meters. At the same time on the map are depicted the sections of the information zone of the radar subunits at different altitudes (50, 100 and so forth, in meters) and to which is assigned an altitude relative to sea level by adding to the position's altitude H_{det} and then the quandrants are selected which meet the detection condition $H_{\Sigma t} > H_{det}$. The aggregate of these quadrants forms a section of the radar information field at the selected target altitude. The minimum height of the section is chosen as equal to the minimum possible altitude of an air enemy employing terrain following, and the number of sections is determined depending upon the ruggedness of the terrain. The minimum and maximum altitudes of the target at which the section of the radar information field is solid are taken as the height of the lower and upper limits of the solid radar field.

The information capabilities of the RTV command posts depend upon the information capabilities of the incoming information channels of these command posts and their capabilities for processing and putting out information (the technical devices and the combat crew). The informational capabilities of an information channel which are assessed by the number of simultaneously tracked targets with the set discreteness are determined by the information capacity of the links forming this channel.

5. FIGHTER AVIATION

5.1. The Weapons System of AD Fighter Aviation

5.1.1. Design Principles of an Aircraft Missile Complex

Structural Diagram of the Complex

An aircraft missile complex (AMC) is a complex of air and ground devices used to destroy manned and unmanned aircraft in the air.

An AMC includes: an all-weather manned fighter armed with air-to-air missiles and cannons and carrying an onboard radar system for locating the air target, for aiming and weapons control; a complex of ground or airborne control and guidance equipment.

Fighters are employed in the AD Troops for hitting airborne targets chiefly at the distant approaches to the defended installations. Here they can operate individually or in groups and when necessary autonomously, outside of contact with the ground control centers in independently searching for and destroying airborne targets.

The Contents of the Intercept Problem

By an interception one understands the stage in the fighters' flight toward the airborne enemy carried out upon commands from the control center up to the moment the enemy is detected by the onboard equipment or visually.

In the general instance the intercept problem consists in determining the fighter's laws of motion which ensure its rendezvous with the airborne target at the extremal value of any characteristic of the fighter's motion. As such a characteristic one can adopt, for example, fuel consumption expended on the interception, the time of the interception, the place (point or line) of the interception and so forth.

Of the greatest significance are the tasks of determining such laws of fighter motion whereby either a maximum distance of the intercept line is obtained or a minimum flight time to the interception.

An essential condition for bringing the fighter to the point of impact (intercept) with an airborne target is the continuous or discrete control of its flight by providing the pilot with the appropriate commands produced on a basis of information on the current position of the fighter and the target and the kinematic characteristics of their relative movement.

Interaction of the Complex in the Equipment

The interaction of the equipment of the complex in destroying an airborne target (viewing the entire flight by the fighter as a complex process conditionally consisting of several successive stages) consists in the following (Fig. 5.1).

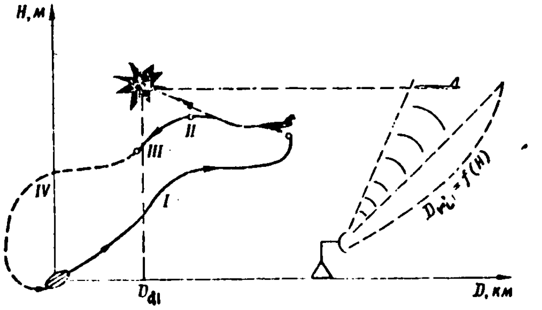


Fig. 5.1. Interaction of equipment in an aircraft missile complex
[Roman numerals designate stages of flight]

In the first stage there is the ground (distant) guidance of the fighter to the airborne target using the ground (airborne or ship) control system.

Ground guidance ensures the bringing of the fighter into a tactically advantageous position relative to the airborne target at a distance of target visibility using the onboard detection equipment or visually.

The stage of ground guidance is preceded by the detection of the airborne target and the notifying of the control centers of it, the adopting of the commander's decision to destroy this target and the issuing of it to executors.

The ground guidance of the fighters to the airborne targets is carried out by the crews of the control centers with the aid of equipment by giving guidance commands, by telling the pilots the flight mode and transmitting information on the target's situation.

The second stage is homing (close guidance) in the process of which the fighter independently closes with the airborne target using the onboard equipment (or visually) for executing the attack.

In practical terms homing commences after the detection of the target by the fighter and ends with the employing of the onboard weapons. The crew of the control center in the homing stage should be constantly ready to provide the pilot with the necessary help even to the point of issuing the command to break off the attack.

The third stage, the breaking off of the attack, is executed by various methods depending upon the type of weapons employed by the fighter. For example, if the fighter employs missiles with passive heat-sensing heads, then the breaking off of the attack can be executed immediately after their launching, while in employing missiles with semiactive radar homing heads, for ensuring control over the missile's flight it is essential to "illiminate" the target with the onboard radar and pull out of the attack after the target has been hit.

The fourth stage or the guiding of the fighter to the landing airfield, is carried out using the ground and onboard radio navigation systems. Guidance can be carried out both to the airfield where the aircraft took off or to any of the previously chosen airfields located in the target intercept area. In the latter instance, the distance of the intercept line can be significantly increased in comparison with the returning to the take-off airfield.

Thus, a significant number of personnel and equipment is involved in carrying out and supporting the intercept flight and this requires the organizing of clear coordination and the all-round training of all the persons participating in and supporting it.

Fighter Guidance Methods

For guiding fighters to an airborne target in a horizontal plane it is possible to use the following basic guidance methods: "pursuit," "interception" and "maneuver."

The choice of one or another guidance method depends upon the tactical situation and the characteristics of the weapons system and the fighter being guided to the airborne target.

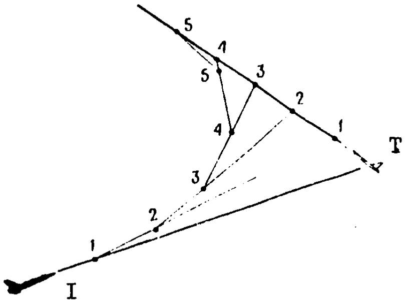


Fig. 5.2. The "pursuit" guidance method

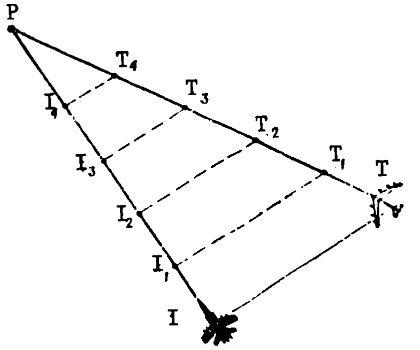


Fig. 5.3. The "interception" guidance method

The "pursuit" guidance method provides for the pursuit of the target by the fighter along a pursuit curve the essence of which is that the fighter's velocity vector at any moment of time is aimed at the target. The fighter's flight trajectory in the horizontal plane with the "pursuit" guidance method can be approximately constructed from the set values of the target's and fighter's speed proceeding from the adopted discreteness of dividing up the time axis (Fig. 5.2).

An important positive property of the "pursuit" method is the simplicity of its realization since in guiding the fighter to the target it is sufficient to know only the coordinates of the target's current position. Moreover, the given method is little sensitive to maneuvering by the target at great distances as well as to errors in measuring target coordinates.

One of the drawbacks of the "pursuit" method is the fact that in guiding the fighter to the target from the rear hemisphere, a sufficient excess of fighter speed over target speed is required while in guidance from the forward hemisphere the curve of the fighter's trajectory rapidly increases in approaching the target and as a consequence of this the g-loads are increased and it is possible that the target may deviate from the kinematic guidance trajectory.

A tactical drawback of the "pursuit" method is that it does not provide an opportunity to intercept a target at a set line or a minimization of the fighter's time and distance in intercepting the target.

Due to the designated positive and negative properties, the given method can be employed on the terminal stage of guiding the fighter to the air target after the fighter has first been brought to the target's rear hemisphere.

The "interception" guidance method consists in bringing the fighter to a certain lead point on the target's flight trajectory (Fig. 5.3). The lead point is selected on an extrapolated target trajectory under the assumption of the even and rectilinear movement of the target. In guidance by the "interception" method the fighter--target line of sight shifts in the guidance plane parallel to itself.

The advantages of the given method consist in the possibility of bringing the fightfighter to the point of impact with the target in a minimum time and that it in many instances makes it possible to provide guidance to airborne targets the speed of which exceeds fighter speed.

The drawbacks of the "interception" method are in the relative complexity of realizing it and the necessity of measuring the parameters of the target's motion as well as in the high sensitivity of guidance errors to errors in measuring the coordinates and parameters of the target's motion. Moreover, using the given method it is impossible to bring the fighter to an airborne target to a definite, preset position relative to the target.

The "interception" method can be employed in the initial guidance stage for rapidly closing with the target.

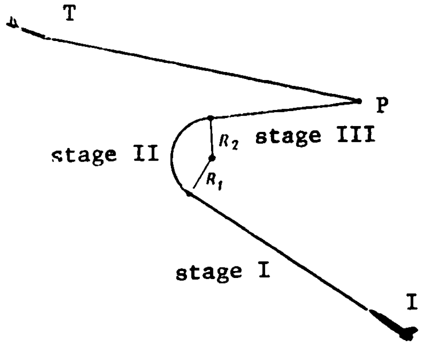


Fig. 5.4. The "maneuver" guidance method

The "maneuver" guidance method is a combined one and brings together the advantages of the designated methods.

For bringing the fighter to a certain position relative to the air target, the "maneuver" method provides three stages: closing, turning and coming in on the target (Fig. 5.4).

In the first guidance stage, the fighter flies along a rectilinear trajectory from the initial guidance point or airfield up to the point of commencing the turn.

In the second guidance stage, the fighter turns along an arc with a variable curve radius to the required angle for bringing the fighter to the set aspect angle to the target.

In the third guidance stage, the fighter flies along a rectilinear trajectory to the lead point. In this stage there is compensation for the guidance errors in the previous stages, the search for and detection of the target by the onboard radar and preparations for the attack. Upon the completion of the third stage, the fighter should be the set distance away from the target. From this moment guidance is carried out by the "pursuit" method and this brings the fighter to the curve for aiming and attacking the target.

Technical Realization of Guidance Methods and the Fighter Control Loop

Technically one or another guidance method in an automated control system can be realized by employing analogue or discrete computers which using the appropriate algorithms calculate the fighter control commands for heading, altitude and speed. The commands generated by the computers are transmitted over the radio link to the fighter and are displayed on the piloting and navigating instruments (Fig. 5.5). Moreover, the ground guidance equipment generates individual fighter control commands and target designation commands which ensure the possibility of the automatic target lock-on by the fighter's radar. These commands are also sent over the command radio link to the fighter, they are fed into the appropriate systems and are employed by the pilot for searching for, detecting and attacking the target.

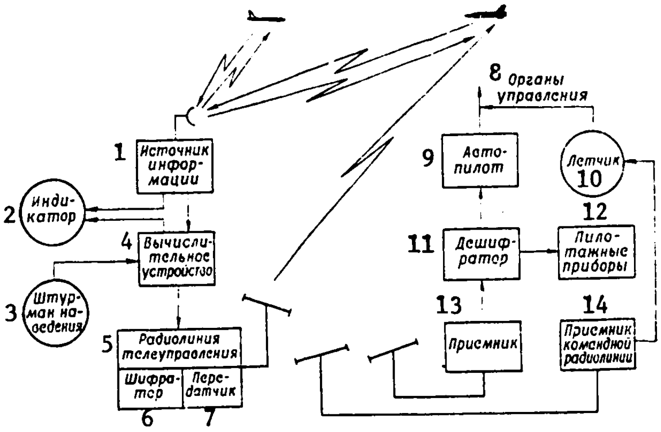


Fig. 5.5. Fighter Control Loop

Key: 1--Information source; 2--Indicator; 3--Fighter controller; 4--Computer; 5--Telecontrol radio link; 6--Encoder; 7--Transmitter; 8--Controls; 9--Autopilot; 10--Pilot; 11--Decoder; 12--Flight instruments; 13--Receiver; 14--Receiver of command radio link.

5.1.2. Technical Realization of Weapons in Aircraft Missile Complex

Requirements on Fighter Aircraft and Possibilities of Satisfying Them

For a fighter to successfully carry out the combat missions of destroying airborne targets, it should possess a number of properties and in designing definite tactical and technical demands are made on it. In a completed, ready-for-action fighter, the tactical and technical requirements are embodied in the tactical and technical characteristics.

All tactical and technical demands on a fighter aircraft can be divided into two groups:

a) Tactical requirements: combat readiness, speed and altitude, maneuverability, range and length of flight, take-off and landing properties, the weapons system, equipment, autonomy of actions and so forth;

b) The technical requirements: strength, rigidity, dependability and survivability of the basic structure, propulsion unit, assemblies and equipment, convenience in operation on ground and in the air, economy, production cost and so forth.

The experience of the designing, operation and combat employment of fighters shows that a majority of the tactical and technical demands made on them are interrelated and contradictory. For this reason only the basic demands on a fighter could be satisfied best. Here in a number of instances compromises had to be made in selecting the basic requirements, considering the specific purpose of the actual type of fighter.

Let us briefly examine some of the designated demands and the possibilities of satisfying them. Here the demands on the weapons system of an AD fighter and the possibilities of satisfying them will be examined separately.

Tactical requirements. High combat readiness of fighters is achieved chiefly by a high level of automating the fighter systems and equipment, by employing special maintenance equipment and by the training level of the flight and maintenance personnel.

Fighter speed and altitude are characterized by the range of speeds and altitudes of steady horizontal flight from their maximum values to the minimal ones.

Advantages in maximum speed over the enemy aircraft make it possible for the fighter to catch up with the target and impose battle on it as well as escape from enemy attack. Moreover, great maximum speed increases the total energy of the fighter and as a consequence of this the range of its dynamic altitudes is broadened and climb performance is improved.

However, in the combat employment of fighters of great practical significance is not only the maximum speed but also the entire range of speeds in which a fighter can provide steady flight. For this reason a fighter's minimum speed should also be of relatively small [sic] significance.

The range of speeds is broadened chiefly by reducing fighter drag and increasing its thrust-to-weight ratio and net wing loading. However, the latter should not be achieved by increasing the fighter's weight as with the given engine thrust this leads to a reduction in the thrust-to-weight ratio.

Increasing a fighter's altitude of steady horizontal flight is achieved by increasing its dynamic qualities and engine thrust and by reducing aircraft weight. The minimum flying altitudes are determined by the conditions of the fighter's combat employment and by flight safety.

Fighter maneuverability is one of its most important flight tactical characteristics. An advantage in maneuverability makes it possible for a fighter to anticipate the air enemy in taking up a tactically advantageous position for the attack, to seize and keep the initiative in air combat and to promptly escape from enemy attack.

High fighter maneuverability is achieved with optimum values for such parameters as the thrust-to-weight ratio, the net wing load and the wing-sweep angle as well as in employing high-lift devices needed for obtaining the required maneuverability at subsonic speeds of flight.

The distance and length of fighter flight characterize the depth and time of their effect on an air enemy. High values of flight range and length for AD fighters provide them with an opportunity to hit the enemy at the distant approaches to the defended installations and to select the optimum method of combat operations under the specific conditions of the combat situation. They also ensure the possibility of retargeting the fighters in the course of combat operations.

The distance and length of fighter flight depend chiefly upon the fuel supply, aerodynamic qualities, engine economy, speed and altitude of flight. For a majority of modern fighters the maximum distances and durations of flight are reached at altitudes of 9,000-12,000 m and with subsonic flight speeds.

The take-off and landing qualities of fighters determine their basing conditions and are characterized by the lift-off and touch-down speeds and by the lengths of the take-off and landing runs.

The basic methods for improving the take-off and landing properties of fighters are to employ high-lift devices, assisted take-off units, wheel braking, landing brake parachutes and engine thrust reversing.

The relatively high take-off weights of fighters lead to the necessity of basing them chiefly at airfields with a man-made surface and significant dimensions of the runways. The use of effective high-lift devices and other methods for improving the take-off and landing properties make it possible to base the fighters at airfields with shorter runway length and at dirt airfields.

Fighter equipment. The successful carrying out of combat missions by an AD fighter to destroy the air enemy under various conditions of the tactical and meteorological situation, at any time of day and over the entire range of altitudes and speeds, can be carried out only due to the employment of a range of equipment (radiotechnical, flight-navigation, high-altitude and so forth). The advanced equipent of modern fighters ensures the fullest and most effective employment of their tactical flight properties in carrying out various combat missions, including in conducting autonomous or semiautonomous combat operations. The automated flight control system is an inseparable part of the equipment of modern fighters.

Technical requirements. The satisfying of the technical demands placed upon AD fighters is related to satisfying the tactical requirements and is determined chiefly by the general level of airframe construction and by the expenditures on the designing and modernization of modern aircraft. Here the increased cost of a modern fighter is substantially influenced by the increased need to employ a large amount of expensive radio electronic equipment and by the significant increase in the amount of exploratory, scientific research and experimental work. In a number of instances a tendency can be noted for a decline in certain tactical and technical requirements which, without substantially reducing the aircraft's combat qualities, make its development less expensive.

The demands on the strength and rigidity of modern fighters with their relatively low weight are achieved by employing combinations of materials from special steels, aluminum and titanium alloys and plastics.

The extensive use of titanium alloys and plastics in modern airframe construction has been caused chiefly by the fact that they possess a comparatively low specific weight and high mechanical strength. Thus, titanium alloys are 2- or 3-fold stronger than aluminum ones, 4- or 5-fold stronger than magnesium alloys and even surpass certain alloyed steels in strength.

Increased survivability and reliability of all systems are a characteristic feature of the new generation of military aircraft generally and fighters in particular.

The demand of increased survivability is met by employing special materials and methods for constructing the airframe, the propulsion unit and the systems which ensure the carrying out of the mission and the safe return of the fighter to the designated airfield with the failing of individual technical devices or the presence of damage.

High fighter reliability manifested in the form of the trouble-free operation of all its systems is determined by the quality of the materials employed in manufacturing it, by the improved manufacturing methods for the technical devices, by the skills of the flight and engineer-technical personnel as well as by the advanced technical and organizational methods for operating, servicing and overhauling the aircraft equipment.

Demands on the Fighter Weapons System and the Possibilities of Satisfying Them

By the fighter's weapons system one must understand its weapons (chiefly guided missiles as well as cannons) designed to hit airborne targets and the sight system which ensures the searching for the airborne target, aiming and control of the weapons.

The basic tactical and technical demands made upon a fighter weapons sytem are: the possibility of employing the weapons over the entire range of fighter altitudes and speeds and in conducting close maneuvering air combat, the all-angle capability of the weapons system, the high fire capabilities, concealment of attack, the possibility of creating various types of interference for the enemy and high antijamming capability.

The all-angle capability of a weapons system presupposes the possibility of attacking the target from any direction. However, satisfying the demand of all-angle capability complicates and increases the weight of the weapons system. With other conditions being equal, this leads to a deterioration of the fighter's flight performance. For this reason the all-angle capability of the weapons system as a requirement must not be considered categorical for any type of fighter. For example, British military specialists consider it extremely complicated and irrational to provide guidance of light missiles under the conditions of close maneuvering air combat in attacking on head-on or collision courses.

High fire capability of a fighter can be achieved by employing the largest possible number of powerful weapons. However, considering the negative influence of the external suspension pods and the weight of the weapons system on the fighter flight performance, it is essential to select an optimum variation of the weapons composition proceeding from the basic purpose of the given type of fighter.

In the opinion of foreign specialists, such a variation would be a range of weapons consisting of short- and long-range guided missiles and a cannon.

Concealment of attack is a most important condition which determines the probability of destroying the enemy.

5.1.3. Combat Capabilities of an Aircraft Missile Complex (AMC)

The Concept of "AMC Combat Capabilities"

By AMC combat capabilities one understands the expected result of the AD fighter's carrying out of the set combat mission and which can be achieved in a certain space over a certain time under the specific situational conditions.

The basis of the concept of "AMC combat capabilities" is the expected result of the AD fighter's carrying out of the combat mission set for it. However, the expected result alone does not provide a full description of the given concept, as it does not answer the question of in what space and over what time this result can be realized. For this reason, a complete description of the concept "AMC combat capabilities" can be provided only by an aggregate of indicators which describe both the expected result as well as the space and time required for the AD fighter to carry out the combat missions set for it.

Classification of Indicators for AMC Combat Capabilities

The indicators describing the AMC combat capabilities can be divided into three groups:

a) The probability characteristics which describe the expected result from the fighter's carrying out of the combat mission;

b) The spatial indicators describing the space within which the fighters are capable of carrying out combat missions;

c) The time indicators describing the time required for the fighter to carry out a combat mission.

The probability of destroying an airborne target is the basic probability indicator for the combat capabilities of individual AD fighters if one proceeds from their chief specific purpose. From the amount of this indicator it is possible to assess the effectiveness of an individual AMC both with the fighter's operation against an airborne target with ground guidance as well as in operations with independent target hunting.

The basic spatial indicator for the combat capabilities of an AD fighter is the distance of the line for destroying an airborne target in terms of the fighter's fuel supply. The position of the destruction line can be set relative to the fighter take-off airfield.

Among the basic time indicators of an AD fighter, are the time required to carry out the combat mission and the time required to prepare for a second sortie.

The Basic Methods for Determining the Indicators for AMC Combat Capabilities

The probability of destroying an airborne target (in viewing an interception as a complex process) is:

$$P_{de} = P_g P_{at} P_h, \qquad (5.1)$$

where P_g--guidance probability, that is, the probability that the fighter will be brought to a certain space relative to the target from whence a successful attack is possible;

P_{at}--the probability of attack, that is, the probability of bringing the fighter into a certain space relative to the target from whence an aimed missile launch (firing of the cannons) can be carried out;

P_h--the probability of a hit, that is, the probability that after the missile has been launched (the cannon fired) the charge will hit in the target kill area.

The probability of destroying an airborne target by an AD fighter with independent search can be determined in an analogous manner but instead of the guidance probability one should consider the probability of target detection by the fighter equipment or visually.

The influence of the dependable operation of the AMC elements and enemy countermeasures on the effectiveness of fighter operations can be considered by determining the designated probabilities considering these factors or by an additional calculation of the corresponding probabilities.

Calculating the maximum line for destroying an airborne target in terms of fuel supply is carried out by the method of the engineer-navigator calculation (ENC) of the fighter's flight.

The initial data for making the ENC are the flight profile and conditions, the conditions for carrying out the flight mission and the calculated aircraft fuel supply.

The basic guide in the ENC of a flight is the instructions on calculating flight range and duration for the given type of aircraft and these are an official document and contain all of the necessary materials for making the ENC.

The calculating of the destruction line in terms of fuel supply is carried out in the following sequence.

1. Fuel consumption is determined for the set flight profile:

$$G_{pro} = G_{gr} + G_{cl} + G_{cr} + G_{ac} + G_{at} + G_{re} + G_{la},$$

where G_{gr}--fuel consumption on the ground;
G_{cl}--fuel consumption in taking off and climbing to cruising altitude;
G_{cr}--fuel consumption on cruising leg of flight;
G_{ac}--fuel consumption in accelerating to a certain flight speed;
G_{at}--fuel consumption in closing in and attacking the target;
G_{re}--fuel consumption in returning to original airfield;
G_{la}--fuel consumption in the landing approach and landing.

2. The difference is determined between the calculated fuel supply for carrying out the mission and the amount of fuel spent in flying the designated profile, that is,

$$\Delta G = G_{cal} - G_{pro}.$$

If $\Delta G < 0$, then the flight mission with the designated flight profile cannot be carried out, but if $\Delta G = 0$, then the mission is possible with the designated fuel supply.

With $\Delta G > 0$, there is surplus fuel which can be employed to increase the legs of horizontal flight toward the target and in returning to the base airfield. This is tantamount to increasing the so-called balance leg of the flight which can be determined by the formula:

$$\ell_{bal} = \frac{\Delta G}{q_{cr_1} + q_{cr_2}}, \qquad (5.2)$$

where q_{cr_1}, q_{cr_2}--kilometer fuel consumption on the cruising legs of horizontal flight in flying out to meet the target and in returning to the base airfield, respectively.

3. The maximum distance of the destruction line is determined for fuel supply as the algebraic total of the projections of the legs of the flight onto the earth's surface:

$$D_{py} = \ell_{cl} + \ell_{cr} + \ell_{ac} + \ell_{at}, \qquad (5.3)$$

where ℓ_{cl}--the leg in climbing to cruising altitude;
ℓ_{cr_1}--the leg in cruising flight toward the target considering the balance leg of the flight;
ℓ_{ac}--the leg in accelerating to a certain flight speed;
ℓ_{at}--the leg in closing in and attacking the target considering the distance covered by the missile (shells) to the moment of hitting the target.

The time for carrying out a combat mission by a fighter in destroying an airborne target includes the passive and flight time, that is,

$$t_{cm} = t_{pa} + t_{fl}.$$

The passive time in an interception is spent mainly on readying the fighter for the sortie.

The flight time equals the total of the flight times on all legs of the adopted flight profile up to the moment of hitting the target and is determined, like the target destruction line, by the ENC method.

The time required to prepare for a second sortie for a single fighter equals the total of the times spent on performing operations which are not coincidental in time by engineer and technical personnel (that is, operations which cannot be performed simultaneously on an aircraft due to safety considerations and so forth) in readying the fighter for a combat mission.

The aircraft preparation time depends basically upon the type of aircraft, the combat mission, the characteristics of the aircraft maintenance equipment as well as the number and training level of the engineer and technical personnel.

5.2. Principles in the Combat Employment of AD Fighter Aviation

5.2.1. Tactical Principles for AD Fighter Air Combat

Air combat is an armed clash in the air of individual aircraft or groups (subunits, units) combining maneuver and fire for destroying the enemy or repelling its attacks.

Air combat is the chief type of combat activity for the AD fighters. It is conducted for decisive goals, that is, to destroy the air enemy or cause him such harm as to force him to abandon the carrying out of a combat mission.

Air combat starts after the fighter has detected the airborne target using the aircraft equipment or visually.

The most important conditions for achieving victory by the fighters in air combat are: an offensive nature of actions during the entire engagement; decisiveness of closing in and surprise of attacks; skillful employment of maneuver in combat; the ability to quickly destroy the enemy, as a rule, in the first attack; the use of tactical procedures which consider the strong points of one's aircraft and the weak points of enemy aircraft; coordinated actions and reciprocal support among the fighters in group air combat.

Success in air combat is achieved only by offensive actions with the seizing of initiative and the maintaining of it during the entire engagement. Of crucial importance are the high skills and combat morale qualities of the flight personnel.

For seizing the initiative, a fighter pilot should have a perfect knowledge of air combat tactics, in the process of the engagement he should correctly determine the possible type of enemy maneuver, he should carry out the most effective maneuver, quickly aim and fire at ranges ensuring the highest probability of a target hit.

The actions of pilots in air combat should be decisive even in encountering a superior enemy. Indecisive actions lead to the drawing out of the engagement and to the loss of initiative.

In the process of air battle, the fighters carry out combat maneuvering and employ tactical procedures for conducting combat.

Combat maneuvering is the name given to the shifting of the fighters (groups) in air space for taking up a tactically advantageous position or for maintaining cooperation between the fighters (groups).

Combat maneuvering in air combat can be offensive and defensive. With offensive combat maneuvering the fighters carry out actions which ensure a successful attack on the enemy aircraft and in defensive maneuver the fighter actions ensure an escape from the attack with the subsequent taking up of an advantageous tactical position for continuing the engagement.

A tactical procedure is the name given to the actions of the crews (subunits) for destroying an air enemy or for escaping from its attack by utilizing the combat capabilities of one's airplane (airplanes) and employing the weak points of the enemy aircraft and the situational conditions.

A classification of air engagements. Depending upon conditions, air engagements can be classified by types:

a) In terms of the number of fighters participating in the engagement, into individual or group air engagements;

b) According to altitudes into air engagements at maximum low, low, medium and great altitudes and air engagements in the stratosphere;

c) In terms of time of day, into daytime air engagements and nighttime air engagements;

d) In terms of meteorological conditions, into air engagements under visual conditions and under instrument conditions;

e) In terms of the type of air target, into air engagements with tactical fighters, bombers, reconnaissance planes, air transports and helicopters;

f) In terms of the presence or absence of visual contact with the enemy, into close and distant air engagements.

By a group air engagement one understands the coordinated actions of crews (subunits) following a single plan to carry out the combat mission. Success of a group engagements depends upon the ability of the commander to promptly take a decision corresponding to the situation, to seize and retain initiative, to impose his will on the enemy and to make a surprise attack against it, employing the enemy's tactical errors.

Group combat is carried out according to a previously elaborated plan.

A distant air engagement is conducted in the absence of visual contact with the enemy. In the process of a distant air engagement the fighters close with the enemy and this can lead to the development of distant combat into near or close combat.

A close air engagement is conducted, as a rule, with visual contact with the enemy. In the absence of surprise, such an engagement with tactical fighters assumes a sharply expressed maneuvering nature.

Stages of Air Combat

Air combat includes closing, one or several attacks, maneuvering between attacks and disengagement.

Closing is the maneuvering of a fighter carried out from the moment of detecting the target until taking up the initial position for the attack. In closing conditions are created for achieving surprise attack, for continuously observing the target and simple execution of the maneuver for going over to the attack.

If a fighter at the moment of detecting the enemy is in a position relative to it from whence the attack can be commenced immediately, then there will be no closing as a stage of an air engagement and the engagement will start directly by an attack on the target.

In closing the fighter pilot identifies the air target, assesses the situation, takes a decision and assumes the initial position for the attack.

Assessing the situation in the stage of closing includes the following elements: the type of enemy airplane (helicopter), altitude, speed and heading of its flight, composition and combat formation of the group, the reciprocal spatial position of the target and one's fighter, the time available for the air engagement, the presence or absence of enemy countermeasures (fire, electronic).

The closing in can be carried out by the following methods: along the pursuit curve; along a straight line on parallel courses; with a lead angle; with a lag angle.

The choice of the method of closing in will depend substantially upon the time which the fighter has available in this stage of the engagement. The time of closing in is:

$$t_{clo} = \frac{D_{s\ clo} - D_{s\ at}}{V_{clo}}, \tag{5.4}$$

where $D_{s\ clo}$--the distance for starting the closing;
$D_{s\ at}$--the distance for starting the attack;
V_{clo}--the rate of closing with the target.

Closing along the pursuit curve is carried out by constantly directing the fighter's longitudinal axis toward the target. The method is employed in closing with a target from the aft and forward hemispheres. In the process of closing along the pursuit curve from the aft hemisphere, the target's heading angle constantly increases and the fighter comes out at a range for starting the attack at an angle of approach equal to 0/4.

In the process of closing along the pursuit line from the forward hemisphere, the increase in the heading angle leads to the arrival of the fighter at a distance for starting the attack at an angle of approach significantly greater than at the start of the closing. With a sufficient closing time, the target's angle of approach at the range for starting the attack can be close to 4/4.

The method can be employed in an air engagement with nonmaneuvering and maneuvering targets in detecting the target at a distance close to the distance of starting the attack.

Closing along a straight line on parallel courses is carried out from the aft hemisphere by catching up with the target. Here the fighter follows the target at an interval of the initial position for the attack.

In the process of closing the target's angle of approach constantly increases. The method can be employed in detecting the target at great ranges and at small angles of attack, if the attack must be executed at an angle of approach greater than in detecting the target.

Closing with a lead angle is carried out by the flying of the fighter to a point located ahead of the target.

The method can be employed in closing both from the aft and forward hemispheres of a nonmaneuvering target as well as in closing with a maneuvering target.

Depending upon the amount of the lead angle ψ, the nature of closing with the target is determined.

In a flight with a lead angle of:

$$\sin\psi_1 = \frac{V_t}{V_i}\sin q$$

(q--target heading angle), the fighter will close with the target at a fixed lead angle and target line of approach along a line connecting the fighter and the target. The target's line of sight in this instance will move parallel to itself (a parallel closing).

With an initial lead angle greater than with a parallel closing, that is, with $\sin\psi_2 > \frac{V_t}{V_i}\sin q$, the fighter will close with the target at a constantly increasing target angle of approach.

With an initial lead angle less than with a parallel closing, that is, with $\sin\psi_3 < \frac{V_t}{V_i}\sin q$, the fighter will close with a constantly decreasing angle of approach to the target and lead angle.

Closing with a lag angle is carried out by having the fighter fly to a point located behind the target. The method can be employed with closing from the aft hemisphere for reducing the angle of approach by the moment of starting the attack in the event that the angle of approach at the moment of detecting the target is great, that is, does not ensure the effective employment of the weapons. In closing with a maneuvering target, the given method is employed on fighters having limitations for the maximum flight g-load or for missile launching.

The designated methods of fighter closure with a target, depending upon the type of weapons to be used, can be employed both in distant and in close air combat.

Depending upon the tactical flight data of the fighter, the capabilities of its weapons system and target altitude, the fighter's can close in on the same altitude with the target as well as in descending or rising relative to the target.

The attack is the crucial stage of an air engagement in the process of which the air enemy is destroyed. This consists of the maneuver toward the target, aiming, launching the missiles (firing the cannons) and disengagement.

The maneuver toward the target starts from the moment the fighter reaches the initial position for the attack and ends with the coming out on the aiming curve.

The initial position for the attack, the nature of the maneuver for coming out on the aiming line and the aiming are determined by the method of closing prior to the attack, by the conditions for launching the missiles (for firing) and by the closing speed.

In closing along a pursuit line, the going over to the attack is carried out without any additional maneuver by the fighter.

In closing on parallel courses the initial position for the attack is characterized by an interval and a distance between the fighter and the target.

In closing with a lead (lag) angle, the initial position for the attack is characterized by an angle of sight and distance to the target which should ensure the execution of a maneuver toward the target for coming out on the aiming line. This range depends upon the speed of closure and the sighting angle to the target.

The launching of the missiles (the firing) is carried out at angles of approach and at distances which ensure the effective hitting of the target. The hitting of the target is possible if the fighter has entered the area of possible launches and firing.

If a fighter employs several types of weapons in one attack, then the sequence of their employment is determined by the properties of each type of weapons as well as by the situational conditions under which the air combat is carried out.

Disengagement is carried out in such a manner as to ensure the possibility of a second attack and safe disengagement. Here it is essential to endeavor not to fall under enemy defensive fire and to ensure safety against colliding with the target.

The safe range for disengagement is:

$$D_{dis} = D_{clo}\sqrt{\frac{2l}{g\sqrt{n_y^2-1}}} + l_{lag}, \tag{5.5}$$

where l--safe interval in disengaging;
g--free-fall acceleration;
n_y--fighter g-load in disengagement;
t_{lag}--time lag in pilot's actions.

Maneuvering between attacks in an air engagement is carried out by turning away from the target in climbing or descending or on the same altitude as the target with the subsequent turn toward it.

Breaking off the engagement is carried out upon the commander's decision after carrying out the mission or as a consequence of the impossibility of continuing it. The break-off from the enemy is carried out by turning from it on head-on courses or by performing an energetic curvalinear maneuver in climbing or losing altitude.

The reciprocal position of the fighters and enemy aircraft has a great impact upon the development of the engagement and its result.

If by the start of the air engagement the fighters have been brought to a tactically advantageous position relative to the enemy, then they, as a rule, are the first to detect the target and maintain tactical superiority over the enemy during the entire engagement. A surprise attack on the enemy is one of the methods for maintaining tactical supremacy.

Surprise makes it possible to catch the enemy unaware, to attack it, to be first in maneuvering and attacking, to seize initiative in the engagement and to create favorable conditions for achieving success even over superior enemy forces. Surprise is achieved by deceptive and rapid actions by the fighters.

In deceptive actions a portion of the fighters usually draws the enemy's attention while the basic forces attack it from another direction. Speed is achieved by closing in and attacking at a high speed, on head-on or collision courses.

If the fighters are in disadvantageous conditions, then they undertake a defensive maneuver for the purposes of thwarting the enemy attack with the subsequent seizing of initiative in combat.

For this reason, regardless of in what position the fighters were at the start of the engagement, the result of its is largely determined by who was the first to detect the enemy. For ensuring prompt detection of the enemy, in anticipating an air engagement the fighters constantly search for it.

Depending upon the altitude at which the air engagement is conducted, it can have a number of particular features.

At low altitudes it is difficult for the pilot to conduct visual orientation or visual and instrument detection of airborne targets against the background of the terrain; due to the proximity of the ground the fighter's maneuvering capabilities in the horizontal plane are restricted. The constant observance of the ground and flight conditions places a great strain on the pilot. This impedes the executing of the closing, attack and maneuver, particularly under instrument flying conditions and at night. A low altitude attack can be executed against a target at the same altitude with slight dive and pitch-up angles.

Particularly complex is an attack on airborne targets flying at maximum low altitudes. The proximity of the ground impedes the pilot's actions and restricts maneuvers in the horizontal and vertical planes and for this reason the aircraft's moves are performed with large radiuses while the attack on the target is carried out from above with a slight dive angle. The effectiveness of an attack on a target at low and maximum low altitudes is significantly increased if the fighter has a weapons system which can carry out the attack from above downwards against the background of the earth. Such an attack is carried out from a position above the target. The amount of the height advantage and the particular features of executing the attack are determined by the combat capabilities of the fighter and by the air combat conditions.

In the stratosphere, there are substantial changes in the aircraft piloting conditions related to the deterioration of flight performance due to the lower pressure and mass density of the air. This is manifested in a reduced range of fighter speeds, lower maximum g-loads and poorer acceleration and deceleration performance. For this reason, in the stratosphere, as a rule, it is possible to carry out only one attack. The direction of the attack (in the forward or aft hemisphere) depends upon the method of ground fighter guidance to the target. An attack on an airborne target in the stratosphere is carried out with a vertical separation relative to the target and the amount of this depends upon the fighter's tactical flight data and the capabilities of its weapons system. One of the particular features of a stratospheric attack is its rapidity caused by the high closing speeds. This particular feature to a greater degree is apparent in carrying out the attack in the forward hemisphere of the target.

In destroying unmanned air attack weapons (air-to-surface cruise missiles and unmanned aircraft), the AD fighters employ the same methods as in air combat with manned aircraft considering the characteristics of the given unmanned device.

The particular features of unmanned devices as objects of fighter operations are the small sizes of the vehicles and the small radar cross-section. As a rule, theirs is a rectilinear flight without defensive maneuvering. These particular features determine the basic types of attacks employed by the fighters in destroying unmanned devices. These include: attacks in the target aft hemisphere and attacks at a great angle of approach. The vertical separation above (below) the target in executing the attack is chosen depending upon altitude just as in air combat with manned aircraft.

5.2.2. Combat Capabilities of AD Fighter Aviation Subunits and Units

Indicators for the Combat Capabilities of the AD Fighter Aviation Subunits and Units

The combat capabilities of the AD fighter aviation subunits and units analogously to the combat capabilities of the AMC, are characterized by probability, spatial and time indicators. A knowledge of the combat capability indicators makes it possible for the commander to take a sound decision for the combat operations of the AD fighter aviation subunits and units, to give them realistic combat missions and to employ them most effectively in the course of combat operations.

The basic probability indicator for the combat capabilities of the AD fighter aviation subunits and units is the mathematical expectation of the number of destroyed airborne targets. Moreover, as the probability indicators for combat capabilities it is possible to employ the capacity of the fighter guidance system and the required detail of fighters for destroying individual and group airborne targets.

The basic spatial indicator for the combat capabilities of the AD fighter aviation subunits and units is the combat effect area (CEA) which is the space within which it is possible to destroy an air enemy.

The dimensions (boundaries) of the CEA are determined by the values for the air target destruction lines which can be preset (required) and calculated (available).

The preset destruction lines are set proceeding from tactical considerations of defending certain installations, while the available ones are calculated from the available radar information on the air enemy and from the available fighter fuel supply.

Moreover, as spatial indicators for combat capabilities it is possible to utilize the lines for committing the fighters to an engagement and the fighter scramble lines.

Among the time indicators for the combat capabilities of the AD fighter aviation subunits and units are the sortie time of the fighter group, the time required to ready the fighter group for the first and second sorties, the combat stress as well as the time it takes for the subunit (unit) to carry out the combat mission.

Procedure for Determining Indicators for the Combat Capabilities of AD Fighter Aviation Subunits and Units

The expectation of the number of destroyed airborne targets in the general instance is:

$$M_t = \sum_{i=1}^{N_t} P_{de_i}, \qquad (5.6)$$

where N_t--the number of targets against which the fighters operate;
P_{de_i}--the probability of destroying target i.

In the particular instance, when the probabilities of destroying all the targets against which the fighters are operating are the same and equal P_{de}, the expectation of the number of destroyed targets can be found by using the formula (5.7):

$$M_t = N_t P_{de}. \qquad (5.7)$$

If the fighters operate against the targets without retargeting, the number of fighters N_i is equal to or less than the total number of targets and the probability of destroying each attacked target is the same and equals P_{de}, then $N_t = N_i$ and the expectation of the number of destroyed targets will be obtained on the basis of the formula (5.7):

$$M_t = N_i P_{de}. \qquad (5.8)$$

Formula (5.8) is frequently employed for approximately determining M_t in one sortie by a fighter group. Here it is essential to bear in mind that for a group consisting of different types of fighters (with different values of the destruction probability), M_t is determined separately for the fighter types and then the results are added up. Moreover, if not all the aircraft of a unit (subunit) are involved in a sortie, then this reduction in the number of fighters is considered by a coefficient of their combat employment and the expectation for the number of destroyed targets is:

$$M_t = K_{ce} N_i P_{de}. \qquad (5.9)$$

In the event when the probabilities for the destruction of all the attacked targets are the same, the fighters operate without aiming, the distribution of the fighters to the targets is even but the number of fighters is greater than the total number of targets, M_t can be determined by the formula:

$$M_t = N_t P_\Sigma = N_t \left[1 - (1 - P_{de})^{\frac{N_i}{N_t}} \right], \qquad (5.10)$$

where P_Σ--the probability of destroying each target by all the fighters assigned to it calculating with the assumption that the probability of destruction, depending upon the number of fighters, changes according to an exponential law.

A particular feature of formula (5.10) is that it is accurate in those instances when one and the same whole number of fighters occurs for each individual target.

The capacity of the guidance system for fighters to air targets is characterized by the number of fighter guidances over a certain interval of operating time for the guidance system and is approximately:

$$n_{gu} = \frac{t_{gu}}{t_{cg}} n_{gc}, \qquad (5.11)$$

where t_{gu}--the set time interval for the operation of the guidance system;
t_{cg}--the duration of one fighter guidance cycle;
n_{gc}--the number of guidance channels in the guidance system.

The required fighter detail for destroying one air target with a set probability $P_{de\ set}$ can be determined by the formula:

$$N_i = \frac{\lg(1 - P_{de\ set})}{\lg(1 - P_{de})}. \qquad (5.12)$$

With the practical utilization of the given formula, the obtained value of N_i is rounded off to the closest larger integer.

The required fighter detail for destroying a set portion of a group target consisting of N_t of uniform targets can be calculated by the formula:

$$N_i = N_t \frac{\lg(1-\mu_{set})}{\lg(1-P_{de})}, \tag{5.13}$$

where μ_{set}--the set share of individual targets to be destroyed from the group target.

Formula (5.13) is analogous to formula (5.10) precisely in those instances when there is the same whole number of fighters assigned to each individual target from the group target. The values of N_i obtained by formula (5.13) are rounded off to the closest larger whole number.

The distance of the destruction line from the available radar information on the air enemy with a flight of targets toward the fighter airfield in a majority of the practically employed instances can be determined from the following formulas:

$$D_{d\ell} = \frac{1}{1+n}(D_{ri} - V_t t_\Sigma + n\ell_\Sigma); \tag{5.14}$$

$$D_{d\ell} = D_{ri} - V_t t_\Sigma, \tag{5.15}$$

where D_{ri}--available distance of radar information on air enemy;
V_t--speed of target flight;
t_Σ--total passive time, fighter flight time under unsteady conditions and missile flight time to moment of target kill;
n--ratio of target flight speed to speed of steady rectilinear horizontal fighter flight;
ℓ_Σ--algebraic total of the projections of the fighter flight legs under steady conditions and the leg of the missile flight on the direction of the target's movement.

A characteristic feature of the amounts t_Σ and ℓ_Σ is that for specific values of target altitude and speed, for the specific type of fighters, their initial position and the chosen intercept program, they have constant and known values. These values are determined (as an example) as follows:

$$t_\Sigma = t_{pa} + t_{c\ell} + t_{ac} + t_{ma} + t_{ae};$$

$$\ell_\Sigma = \ell_{c\ell} + \ell_{ac} + \ell_{ma} + \ell_{ae},$$

where $\ell_{c\ell}$, $t_{c\ell}$--the distance and time for climbing to a certain altitude by the fighter;
ℓ_{ac}, t_{ac}--the distance and time for the acceleration of the fighters to a certain speed;
ℓ_{ma}, t_{ma}--the distance and time for the maneuvering of the fighters for coming out in the set position relative to the target prior to the moment of its detection;
ℓ_{ae}, t_{ae}--the depth and duration of fighter air combat considering the distance and time of the missile's flight to the moment of hitting the target.

The amount of ℓ_Σ according to the given formula is determined when the entire intercept flight is carried out directly toward or in pursuit of a target. If, for example, the climb, horizontal flight and acceleration are carried out directly toward the target and the maneuver and air combat are in pursuit of the target, then

$$\ell_\Sigma = \ell_{c\ell} + \ell_{ac} - \ell_{ma} - \ell_{ae}.$$

The physical sense of formulas (5.14) and (5.15) consists in the following.

Formula (5.14) corresponds to instances when the target is detected before the fighter airfield and is destroyed before the airfield (with $D_{d\ell} > 0$) or after it (with $D_{d\ell} < 0$).

Here in the intercept program there is a leg of steady rectilinear horizontal flight during which the movement of the fighters is directly toward the target. With the actual use of the given formula it is essential to bear in mind that it is valid in meeting the condition $D_{ri} - V_t t_\Sigma > \ell_\Sigma$, regardless of the sign of both parts of the given inequality.

Formula (5.15), like formula (5.14), corresponds to instances when the target is detected prior to the fighter airfield and is destroyed before the airfield ($D_{d\ell} > 0$) or after it ($D_{d\ell} < 0$), but in the intercept program there is no leg of steady rectilinear horizontal flight. The given formula is valid in meeting the condition $|D_{ri} - V_t t_\Sigma| \leqslant \ell_\Sigma$. Here the amount ℓ_Σ can have only non-negative values.

The procedure for calculating the destruction lines for the available fuel supply of the fighters for the AD fighter aviation subunits and units is analogous to the procedure for calculating the same lines for an individual fighter as examined above.

The dimensions of the combat effect area (CEA), as was pointed out above, are determined by the values of the available (or the available and preset) destruction lines for the air targets. Here this means that the capabilities of the guidance equipment (their operating range) do not impose limitations on the dimensions of the CEA boundary. If the operating range of the guidance equipment does impose limits on the CEA, then the dimensions of the latter should be determined considering the dimensions of the guidance field.

Subsequently, by analogy with the names of the destruction lines, those parts of space where the enemy can be destroyed in terms of the available fighter fuel supply and the available radar information on the enemy, for the sake of brevity we will designate, respectively, the combat effect areas for fuel supply and for information, while that portion of the space where the enemy should be destroyed in accord with the set destruction lines will be the set CEA.

Let us examine certain methods for determining the boundaries of the designated CEA.

The boundary of the set CEA is known, as it is determined by the configuration of the set destruction lines.

The boundary of the CEA in terms of fuel supply is determined by the method of the engineer-navigator calculation and for the given altitude actually represents a circle (with the landing of the fighters after the carrying out of the mission back at the home airfield) or an ellipse (with the sortie of the fighters for the mission from one airfield and the landing back at another).

Calculating the boundaries of the CEA for information, when the targets are spread out along the front flying parallel toward the fighter airfield and the line for the start of providing information on the enemy is a straight line perpendicular to the direction of flight of the targets (Fig. 5.6), can be carried out using the formulas:

$$D_{d\ell} = D_{d\ell_0}\frac{1+n}{n+\cos\phi}; \tag{5.16}$$

$$D_{d\ell} = D_{d\ell_0}\frac{1}{\cos\phi}, \tag{5.17}$$

where $D_{d\ell_0}$--the destruction line in flying toward the fighter airfield and which for formula (5.16) is calculated by formula (5.14), and for formula (5.17) by formula (5.15);

ϕ--the angle between the line of the target's path running across the fighter airfield and the direction of the fighters' flight to the point of impact with the target.

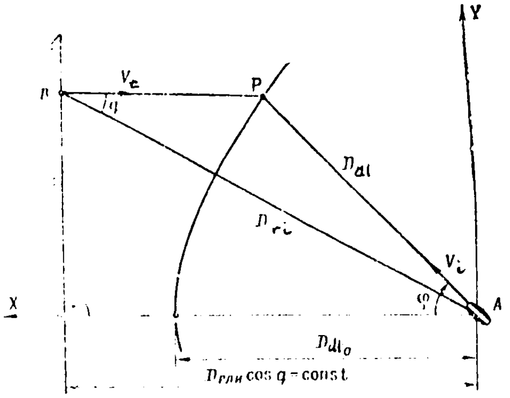


Fig. 5.6. Diagram for determining boundaries of combat effect area

For calculating the current values of $D_{d\ell}$ using these formulas it is essential to set a number of values for the angle ϕ, having first calculated $D_{d\ell_0}$.

The physical sense of formulas (5.16) and (5.17) with $\phi = 0$ is analogous to the physical sense of formulas (5.14) and (5.15), respectively.

With $\phi > 0$, formulas (5.16) and (5.17) have a number of constraints on their employment caused by the kinematic possibilities of executing an interception. For example, formula (5.16) does not have solutions with $n = 1$ and $\phi = 180°$, and for formula (5.17) with $\phi = 90°$.

A characteristic feature of formula (5.16) is that the destruction line calculated using it, depending upon the amount of the velocity ratio n is either a hyperbola (with $n < 1$), or a parabola (with $n = 1$) or an ellipse (with $n > 1$).

The boundaries of the total CEA are determined by comparing the CEA for fighter fuel supply, the available information on the enemy set by the CEA and the guidance field for the specific situational conditions. On maps (plotting boards) this comparison is made by superimposing the designated CEA and the guidance field on one another. As a result of such a comparison, the forward, flank and rear boundaries of the total CEA can have a different appearance determined by the configuration and by the ratio of the dimensions of its component parts.

The line for committing fighters to an engagement is the line on which the air enemy is at the moment of commencing the air engagement.

The distance of the available line for committing the fighters to an engagement with the targets flying toward the fighter airfield and the presence of a leg of steady rectilinear horizontal flight in the intercept program, can be determined from the formulas:

In attacking in the forward hemisphere of the target:

$$D_{fc\ell_{fh}} = \frac{1}{1+n}\,[D_{ri} - V_t t_{\Sigma_{fh}} + n(\ell_{\Sigma_{fh}} + d_{fh})]; \qquad (5.18)$$

In attacking the aft hemisphere of the target:

$$D_{fc\ell_{ah}} = \frac{1}{1+n}\,[D_{ri} - V_t t_{\Sigma_{ah}} + n(\ell_{\Sigma_{ah}} - d_{ah})], \qquad (5.19)$$

where d_{fh}, d_{ah}--the set distances for directing the fighters relative to the target in attacking the forward and aft hemispheres;

$t_{\Sigma_{fh}}$, $t_{\Sigma_{ah}}$--total passive time and flight time of fighters under unsteady conditions until the moment of bringing the fighters to the set distance relative to the target in attacks in the forward and aft hemisphere;

$\ell_{\Sigma_{fh}}$, $\ell_{\Sigma_{ah}}$--the algebraic total of the horizontal projections for the flight legs of the fighters under unsteady conditions in attacks in the forward and aft hemispheres but without the leg of the air combat.

For tactical considerations the set distance of bringing the fighters relative to the target should be considered equal to the target detection range by the fighter equipment in attacking the forward hemisphere and the average missile launching distance in attacks in the aft hemisphere under the specific conditions.

Determining the required lines for committing the fighters to combat according to the set destruction lines is:

$$D_{fc\ell_{fh}} = D_{d\ell} + V_t t_{ae_{fh}}; \qquad (5.20)$$

$$D_{fc\ell_{ac}} = D_{d\ell} + V_t t_{ae_{ah}}, \qquad (5.21)$$

where $t_{ae_{fh}}$, $t_{ae_{ah}}$--the duration of air combat considering the time of the missile flight to the moment of hitting the target in attacks in the forward and aft hemispheres.

The fighter scramble line is the line at which the air enemy is at the moment the crews are given the command to start the engines.

With a set destruction line, the flight of the targets toward the fighter airfield, the presence of a leg of steady rectilinear horizontal flight in the intercept program and an attack in the forward hemisphere, the fighter scramble line is determined from the formula:

$$D_{fs\ell_{fh}} = D_{d\ell}(1+n) + V_t t_{\Sigma fh} - n\ell_{\Sigma fh}, \qquad (5.22)$$

where $t_{\Sigma fh}$--the total flight time of the fighters under unsteady conditions, the missile flight time to the moment of hitting the target in an attack in the forward hemisphere and the passive time not counting the time spent on transmitting information on the enemy, assessing the situation and taking a decision for the interception;

$\ell_{\Sigma fh}$--the algebraic total of the horizontal projections of the fighter flight legs under unsteady conditions and the leg of the missile's flight to the moment of hitting the target in attacking the forward hemisphere.

The formula for determining the fighter scramble line with an attack in the aft hemisphere has the same appearance as formula (5.22) but other values for the amounts t_Σ and ℓ_Σ.

Formulas for determining the lines for the commitment to battle and for scrambling, with the flight of targets toward the fighter airfield and with the absence of a steady rectilinear horizontal flight in the intercept program, can be obtained from the appropriate formulas for calculating the designated lines with the presence of such a leg in the intercept program, considering in them $n = 0$ (hypothetically).

The nature and significance of the time indicators for the combat capabilities of the AD fighter aviation subunits and units are analogous to the spatial indicators, however they to a greater degree describe the dynamics of combat operations and the organization of fighter control in combat.

The sortie time for a group of fighters larger than a two-plane element, flight or squadron, proceeding from the standard sortie times of a two-plane element, flight and squadron, is:

$$t_{so_g} = t_{so_1} + n_{to}\Delta t_{to}, \qquad (5.23)$$

where t_{so_1}--the sortie time of the first two-plane element (flight, squadron);

$n_{to}\Delta t_{to}$--the number and time interval for the take-off of the following groups or individual aircraft.

The time for readying a group of fighters for the first and second sorties is:

$$t_{re} = \frac{N_i}{N_g} t_{op}, \qquad (5.24)$$

where N_i--the number of fighters being prepared for the first (repeat) sortie;

N_g--the number of engineer and technical groups performing the most labor-intensive operation in readying the fighters;

t_{op}--the required time for performing the most labor-intensive operation on one fighter.

Combat stress is characterized by the number of combat sorties per crew, subunit or unit in a certain period of time (day, night, 24 hours, month or period of carrying out a combat mission).

The combat stress is set by the senior chief and depends upon the combat mission, the conditions of executing it, the training level and physical capabilities of the crew, upon the number of combat-ready aircraft, the base conditions and the possibilities of maintaining and readying the aviation equipment for flights.

The time for carrying out a combat mission by an AD fighter aviation subunit or unit is determined analogously to the time of carrying out a combat mission by individual fighters, but the component parts of this time have different values corresponding to the subunits and units.

6. ANTIAIRCRAFT MISSILE TROOPS

6.1. Antiaircraft Missile Weapons Systems

6.1.1. Combat Characteristics, Classification, Structure and Operational Principle of Antiaircraft Missile Systems (SAMS)

Classification and Combat Characteristics of SAMS

Antiaircraft missile weapons are among the surface-to-air missile weapons and are designed to destroy enemy air attack weapons by surface-to-air guided missiles [SAM]. They are represented by various systems.

A system of antiaircraft missile weapons (an antiaircraft missile system) is an aggregate of the antiaircraft missile complex and the equipment supporting its combat employment.

The antiaircraft missile system (SAMS) is the aggregate of SAM, the systems and equipment which ensure the preparation of data for the filing, the launch, the guiding of the missile to the target and the hitting of the target. In accord with this the SAMS include target acquisition and tracking equipment, equipment for generating and transmitting commands, launchers and the SAM which carry the warhead to the target.

The SAM control system comprises the technical base of the SAMS. Depending upon the adopted control system, a distinction is made between the following types of systems: telecontrol of the SAM, homing of the SAM and combined control of the SAM. Each SAMS possesses certain combat characteristics and particular features the aggregate of which can serve as classification features making it possible to put it in a certain type.

Among the combat properties of a SAMS are: all-weather capacity, antijamming capacity, mobility, universality, the degree of automating the combat work processes, reliability and so forth.

All-weather capability is the capability of the SAMS to destroy airborne targets under any weather conditions. A distinction is made between all-weather and non-all-weather SAMS. The latter destroy targets under certain weather conditions and at certain times of day.

Antijamming capability is the property ensuring the capacity of the SAMS to destroy airborne targets under the conditions of interference created by the enemy for neutralizing electronic (optical) equipment.

Mobility is a property manifested in the transportability and the time for converting from a march to a combat position and from the combat back to the march position. A relative indicator of mobility is the total time needed to change the launch position under designated conditions (a certain type of transporting, distance, the condition of roads and so forth).

Maneuverability is a component part of mobility.

The most mobile is a system which possesses greater transportability and requires less time to carry out a march. Mobile systems can be self-propelled, vehicle-carried and portable. Non-mobile SAMS are termed stationary.

Universality is the property characterizing the capability of the SAMS to destroy airborne targets in a large range of distances and altitudes.

In terms of the degree of automation, the SAMS are divided into automatic, semiautomatic and nonautomatic. In the automatic SAMS, all operations involved in target tracking and missile guidance are performed by automatic devices without human interference. In the semiautomatic and nonautomatic SAMS, man is involved in carrying out a number of tasks.

Reliability is the capacity to function normally under the designated operating conditions.

In addition, the SAMS differ in terms of the number of target and missile channels. Systems which can simultaneously track and fire on one target are termed single-channel and those which do this for several targets are known as multichannel ones.

In terms of firing range, the systems are divided into long-range (LR), medium-range (MR), short-range (SR) and close-range (CR).

Structure and Composition of SAMS

In accord with the missions to be carried out, the functionally necessary elements of a SAMS are the target acquisition and identification equipment, the target and missile tracking equipment, the equipment for generating control commands, the equipment for transmitting the commands (the control command radiolinks), the launchers and the SAM. Each type of SAMS has its own particular design features and this determines the composition of its elements (Fig. 6.1).

Detection equipment and methods. In the SAMS with telecontrol of the SAM, radars and optical devices are employed as the means for target detection.

Target detection can be carried out by scanning space by an adopted method: panoramic scanning or spatial scanning in a narrow sector.

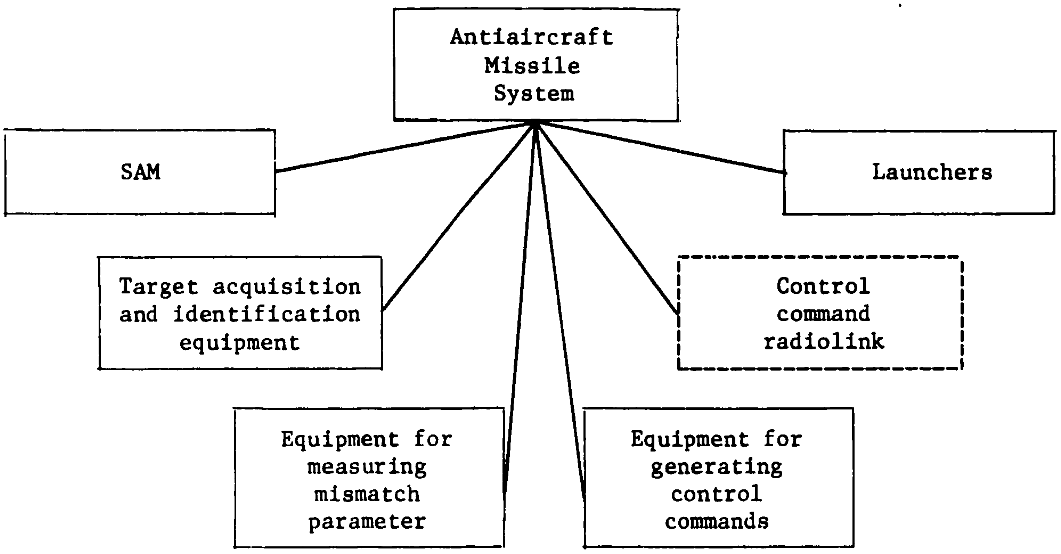


Fig. 6.1. Typical Structure of SAMS

With panoramic scanning, space is scanned for azimuth by 360° (Fig. 6.2a). The scan time is:

$$T_{ps} = \frac{360°}{\omega_a}, \tag{6.1}$$

where ω_a--angular antenna rotation rate.

The merit of the method is the possibility of scanning space in the entire upper hemisphere while the drawback is the long scan time.

Among the methods of spatial scan in a narrow sector are the line method, the method of linear sawtooth scanning and the spiral method.

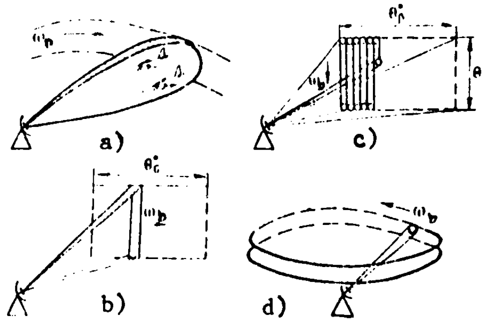


Fig. 6.2. Possible Scanning Methods: a--Panoramic; b--Line; c--Linear sawtooth; d--Spiral (helical)

With the line method scanning is carried out by a narrow beam moving back and forth in two mutually perpendicular planes in a set sector (Fig. 6.2b). The scan time is:

$$T_{\text{стр}} = \frac{\theta^\circ_\varepsilon\ \theta^\circ_\beta}{\omega_b \theta^\circ_a}. \tag{6.2}$$

where θ°_ε, θ°_β--the width of the sector in vertical and horizontal planes;
θ°_a--width of beam (width of antenna directional pattern);
ω_b--antenna beam rate.

The moving of the beam in space can be carried out mechanically or electrically. The merit of the method is the comparatively short scan time while the drawback is the complicated design of the beam moving system.

With the method of linear sawtooth scanning, space is scanned in the designated sector by one or two mutually perpendicular blade-shaped beams (Fig. 6.2c). The speed of movement should be such that in a cluster at least the set number $N_{\min}$ of pulses is obtained. The sector scan time is:

$$T_{\text{лп}} = \frac{\theta^\circ_c N_{\min}}{\theta^\circ_a F_p}. \tag{6.3}$$

The given method makes it possible to determine the relative coordinates of all targets in the scanning sector.

With the spiral scanning method, the antenna beam moves in a spiral. The method is employed for antenna beam search and guidance for tracking target heading (Fig. 6.2d).

Target identification equipment makes it possible to determine the nationality of a detected aircraft and put it in the "friend or foe" category.

Identification equipment can be combined and autonomous. In combined equipment the interrogation and reply signals are sent (received) by the radar equipment. In certain types of close-range SAMS (the portable Red Eye type), an identification device is lacking. The targets are identified by the operator-firer from the aircraft's silhouette.

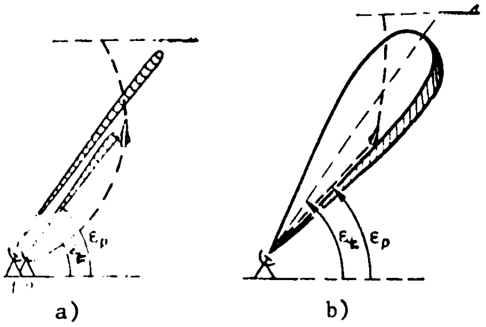
Target tracking equipment can be radar, optical and television-optical. They provide manual and automatic tracking.

Manual tracking (MT) is when the operator tracks the target by lining up the radar blip (image) of the target with the sight mark. Manual tracking can be for position, speed or for position and speed. Manual tracking for speed means the moving of the sight mark (the antenna or optical system) proportionally to the turning of the mark control wheel. Manual tracking for speed (semiautomatic tracking) means that the rate of moving the sight mark (the antenna or optical system) is proportional to the turning of the tracking wheel. Tracking for position and speed means that the amount and speed of moving the sight mark (antenna or optical system) are proportional to the turning of the tracking wheel.

Automatic tracking (AT) is target tracking without the intervention of an operator. Tracking is carried out for each of the measured coordinates and for this the corresponding tracking systems are employed.

Combined tracking (CT) involves the tracking of the targets automatically for some coordinates and manually for others. This can be employed in the event of the impossibility of automatic target tracking for one or several coordinates.

The radar devices for tracking the targets and the missiles for direction (for angular coordinates) can be autonomous and combined (Fig. 6.3).



a) b)

Fig. 6.3. Target and missile radars:

a--Autonomous (1--Target tracking radar; 2--Missile tracking radar); b--Combined

The merits of the autonomous devices are the independence of operation from the reciprocal position of the target and the missile in space and the comparatively great range of steady tracking; the shortcomings are the complexity of realization and the large errors in measuring the difference of target and missile angular coordinates.

The merits of the combined equipment include the high accuracy in measuring the difference of the target and missile angular coordinates and the comparatively smaller volume of the equipment.

Optical tracking devices are employed in short- and close-range SAMS and can be in the form of sighting columns [?donkey ears] and sights. In the tracking process the operator lines up the target image with the sight mark. The merit is the high accuracy of tracking with slow rates of change in the target angular coordinates; the drawbacks include the short tracking range, the impossibility of measuring target distance and dependence on weather conditions.

The television-optical tracking devices can be installed in the short- and medium-range SAMS for tracking the target and the missiles. In certain systems such devices are an integration device and are employed for intense electronic jamming. The range of their operation depends upon the weather conditions.

Devices for generating commands are made in the form of analogue and digital computers. Their task includes generating the control commands and the one-shot commands, the preparation of firing data and generating the control signals for the ground and onboard equipment.

Command transmission devices (the control command radiolinks) are used for converting the control commands and single commands into radio signals and transmitting them to the missiles being guided to the target.

Launchers provide for the preparation and launching of the missiles. Depending upon the type of SAMS, these can be stationary, semistationary and mobile; with vertical or slant launching and providing the simultaneous launching of one or several missiles.

Stationary launchers are made in the form of launch tables and guides mounted on a reinforced concrete base.

Semi-stationary launchers are set up at previously prepared positions. These can have a vertical and slant launch.

Mobile launchers are employed in mobile SAMS and can be self-propelled, vehicle-transported and portable. Self-propelled launchers are mounted on tracked or wheeled mounts. These provide a quick transition from a travel position to a combat one and have a slant launch with a variable elevation angle.

Vehicle-transported launchers are mounted on tracked or wheeled non-self-propelled chassis and are pulled by tractors.

Portable launchers are made in the form of launch tubes in which the rocket is inserted prior to launching. The launch tube can have a sight device for preliminary aiming and a launch mechanism. Such devices are employed in close-range SAMS and these are based upon homing and telecontrol systems. In the latter instance, the launch tube has devices for tracking the target and the missile.

Antiaircraft guided missiles [SAM] are classified by flight speed, by the number of stages, by the aerodynamic system, by the method of guidance and by the type of warhead.

Speeds can be sub- and supersonic.

The missiles can be single-, two- and three-stage. A majority of the foreign-produced SAM is single- and two-stage.

In terms of aerodynamic design, there are SAM made according to the normal system, the "tilting wing" and "canard."

In terms of guidance method a distinction is drawn between homing and telecontrol SAM. A homing SAM is a missile which carries equipment for guiding its flight. Telecontrolled missiles are those which are controlled (guided) by ground control (guidance) equipment.

In terms of the type of warhead, abroad the SAM are differentiated into those with conventional and those with nuclear warheads.

Operating Principle of a SAMS, the Launch and Kill Zones

According to the data of external target designation or independently, the system searches out and detects an air target. After identification the target is turned over for tracking and as a result of this its current coordinates, direction and speed are determined. These are the initial data for determining the missile launch moment, for selecting the type of fire and so forth. During the time these data are prepared, the target will travel a distance $\Delta d = V_t t_{re}$.

The missile is launched upon reaching a certain range of the target relative to the position of the SAMS. Here the missile is launched at a target range whereby the rendezvous of the first missile with the target will be within the range $d_{ctp\ min} \leqslant d_r \leqslant d_{ctp\ max}$. The launch range is:

$$D_\ell \leqslant \sqrt{[d_{\text{стр max}} + V_t(t_{\text{ст}} + t_{p_1})]^2 + H_t^2},$$

where $d_{\text{ctp max}}$--the maximum possible firing range;
d_{p1}--the flight time of the first missile to the maximum firing range;
t_{ct}--missile launch time.

The launch zone [firing bracket] is an area of space through which the target passes and during which time the missile can be launched. Here the rendezvous of the missile with the target will occur in the so-called kill area.

The kill area is an area of space in which the probability of hitting the target has a value at least equal to the set one.

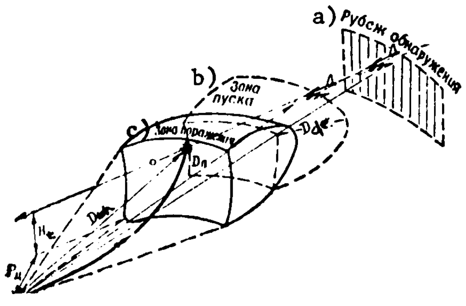


Fig. 6.4. Combat areas of SAMS

Key: a--Detection line; b--Launch area; c--Kill area

The launch and kill areas are limited by the maximum and minimum values of the distances and altitudes which form the boundaries of the kill and launch areas. In accord with this a distinction is drawn between the distant and near, the upper and lower boundaries of these areas.

From Fig. 6.4 it can be seen that the launch area has been shifted relative to the kill area toward the greater target ranges. Its position in space depends upon the position of the kill area and the target's speed.

Distances to the far and near limits of the launch area are:

$$\left.\begin{aligned} d_{\ell f} &= d_{zf} + V_t(t_{ct} + t_{p_1}); \\ d_{\ell n} &= d_{zn} + V_t(t_{ct} + t_{p_n}), \end{aligned}\right\} \qquad (6.4)$$

where d_{zf}, d_{zn}--horizontal distances to the far and near boundaries of the kill area;
t_{ct}--missile launch time;
t_{p_1}, t_{p_n}--the flight time of the first missile to the far boundary of the kill area and the flight time of the last missile to the near boundary of the kill area.

The upper and lower boundaries of the launch area with the target's horizontal flight correspond to the upper and lower boundaries of the kill area. With the target descending in altitude, the upper limit of the launch area exceeds the upper limit of the kill area by an amount:

$$\Delta H = (t_{ct} + t_{p_1}) \frac{dH_t}{dt}. \qquad (6.5)$$

For SAMS which fire in any direction, the launch area, like the kill area, occupies in space a position corresponding to the direction toward the target.

The far boundary of the kill area has a range determined by the maximum possible firing range for the given SAMS. Sometimes the far limit of the kill area is a surface formed by the geometric locus of points for the end of the maximum firing range vector. In certain instances it is represented by a more complex surface.

The near limit of the kill area has a range:

$$D_{zn} = Vt_r, \tag{6.6}$$

where t_r--the time for bringing the missile to the kinematic trajectory.

The shape of the near limit depends upon many factors and for this reason it has a complex configuration.

The upper limit of the kill area has an altitude determined by the operational range of the missiles and the survivability of the target and by the ratio of the available and required SAM g-loads. With a change in altitude the survivability of the target changes and this causes a change in the probability of target kill.

The lower limit of the kill area is determined by the capability of the SAMS to detect and guide the missiles to low-flying targets.

The depth of the kill area is:

$$\Delta d_{zk} = d_{zf} - d_{zn}, \tag{6.7}$$

where d_{zf}, d_{zn}--horizontal distances to the far and near limits of the kill area.

The amount of Δd_{zk} for the given SAMS is measured by altitude and depends upon the type (survivability) of the target. In destroying targets the kill probability of which is low, the depth of the kill area is reduced.

The required amount of the depth of the kill area $\Delta d_{zk\ re}$ which ensures the firing on the target with the set number n_p of missiles with a firing rate t_c is

$$\Delta d_{zk\ re} \geqslant V_t t_c (n_p - 1). \tag{6.8}$$

In the process of guiding the missile to the target, commands are generated for controlling the position of the missile's control surfaces. As a result the missile follows a trajectory close to the calculated one.

6.1.2. Combat Capabilities of the SAMS

By combat capabilities one understands the ability of the SAMS to destroy airborne targets under various situational conditions. These depend upon the principles realized in the system as well as the purpose and composition of the equipment.

Among the combat capabilities are the capability to destroy the targets at various ranges, at various altitudes, the capability to destroy targets flying at different speeds, the capability of destroying maneuvering targets, the capability for successive firing on targets and the capability to destroy targets under ECM conditions.

The capability to destroy targets at various distances are characterized by the range of target destruction distances.

The capability to destroy targets at various altitudes is the ability of the SAMS to ensure the destruction of targets within a certain range of altitudes. These capabilities depend upon the speed of target flight, the energetics of the SAM and other factors.

Capability to destroy targets flying at different speeds is determined by the range of speeds for destroyable targets. This is determined by the target detection ranges and the available missile g-loads.

Capability to destroy maneuvering targets is characterized by the capacity of the SAMS to destroy targets maneuvering with certain g-loads. The basic factors which determine this capability is the available load factors and the inertia in the SAM flight control system.

The capacility for successive firing on targets is the capacity of the SAMS to destroy targets successively entering the launch area. The time intervals between the targets serve as the indicators of this capability. They depend upon the number of target and missile channels of the SAMS and the firing cycle.

The capability to destroy targets under ECM conditions describes the ability of the system to destroy targets with the presence of jamming. The intensity of jamming whereby the probability of destroying the target has a value of at least the designated can serve as the indicator of this.

An analysis of the combat capabilities of the SAMS to destroy specific types of targets requires an analysis of the capabilities for detection, identification and tracking of targets, the capabilities for guiding the SAM and the capability for hitting the targets with the missile warhead.

Capability to Detect and Identify Targets

Detection capability is the ability of the SAMS to detect the target in the designated volume of space over a certain time. The quantitative indicators for detection capability can be: target detection range D_{de}, detection altitude $H_{de\ max}$, $H_{de\ min}$, detection time t_{de}, resolutions for range, angular coordinates and speed ΔD, $\Delta\beta$, $\Delta\varepsilon$, ΔV, and the target detection probability p_{de}.

The required target detection range which provides a rendezvous of the first missile with the target at the far limit of the kill area is:

$$D_{de\ re} \geq \sqrt{(d_{ct} + V_{t} t_{\Sigma})^2 + H_{t}^2}. \qquad (6.9)$$

where $t_{\Sigma} = t_{op} + t_{\ell o} + t_{re} + t_{ct} + t_{p1}$ (t_{op}, $t_{\ell o}$, t_{re}, t_{ct}, t_{p1}--the time required to identify the target, tracking lock-on, preparing firing data, launching and guiding the missile with the point of impact at the far limit of the kill area, respectively).

The possible target detection range by radar is

$$D_{de\ pos} \leqslant \sqrt[4]{\frac{P_p G_1 G_2 \lambda^2 \sigma_t}{(4\pi)^3 P_{re\ min} \gamma_p}}\, e^{-0{,}115\gamma_a D_{de}}, \qquad (6.10)$$

where P_p, G_1, G_2, λ, $P_{re\ min}$--sending power, coefficients for directional effect of transmitting and receiving antennas, operating wave length, radar receiver sensitivity;
γ_p--coefficient of discrimination;
γ_a--coefficient for absorption of radio wave energy in atmosphere;
σ_t--target radar cross-section.

Target detection range under ECM conditions is:

$$D^j_{de\ max} \leqslant \sqrt[4]{\frac{P_p G_1 G_2 \lambda^2 \sigma_t}{(4\pi)^3 \sqrt{P^2_{re\ min} + P^2_j}}}. \qquad (6.11)$$

where P_j--jamming power on input of radar receiver.

The maximum possible target detection range (the radius of the open zone) for a target traveling under the cover of active jamming (detection under the condition $P_c = P_j$) is:

$$D^j_{de\ max} \leqslant \sqrt[4]{\frac{P_p G_1 G_2 \lambda^2 \sigma_t}{(4\pi)^3\, 1{,}41\, P_{re\ min}}}. \qquad (6.12)$$

Detection range is limited by the line-of-sight range

$$D_{de} \leqslant D_{\ell s} = 4.12(\sqrt{H_a} + \sqrt{H_t}), \qquad (6.13)$$

where H_a, H_t--radar antenna height and target height, m.

Target detection range by an optical sight is:

$$D_{de\ op} \leqslant \sqrt{\frac{C_T \eta_1 \eta_2 (\varepsilon_t T_t^4 S_t - \varepsilon_b T_b^4 S_b)}{\pi F_{th}}}. \qquad (6.14)$$

where $C_T = 5.67 \cdot 10^{-5}$ erg$\cdot$cm$^{-2}\cdot$s$^{-1}\cdot$deg^{-4};
η_1, η_2--energy absorption coefficients in atmosphere and optic;
ε_t, ε_b--darkness factors of target and background;

T_t, T_b--temperature of target and background;
S_t, S_b--areas of target and background;
F_{th}--threshold value of power flux.

Target detection altitudes depend upon radar properties; detection range, maximum and minimum elevations of antenna beam, beam width:

$$\left.\begin{aligned} H_{de} &= D_{de} \sin \varepsilon_t; \\ H_{de\ max} &\leqslant D_{de\ max} \sin \varepsilon_{a\ max}, \end{aligned}\right\} \tag{6.15}$$

where $\varepsilon_{a\ max}$--maximum possible elevation of antenna beam;

$$H_{de\ min} \geqslant \left(\frac{D_{\ell s}}{4.12} - \sqrt{H_a}\right)^2 . \tag{6.16}$$

Target detection time is the time required on receiving and processing the target designation t_{td}, launching t_ℓ and observing t_{ob} the target:

$$t_{de} \geqslant t_{td} + t_\ell + t_{ob}. \tag{6.17}$$

The target observation time is the time of the varified observation of a target signal on the indicator screen. For obtaining a set probability for correct target detection, several scan intervals are observed: $t_{ob} = n_{sc} t_\ell$.

The amount

$$n_{sc} \geqslant \frac{\lg(1 - p_{s\ de})}{\lg(1 - p_{1\ de})}, \tag{6.18}$$

where $p_{s\ de}$--the set probability of target detection;
$p_{1\ de}$--detection probability with one scan interval.

Resolutions in target detection are: for range

$$\Delta D = \frac{c\tau_i}{2} + M_D d_s, \tag{6.19}$$

where τ_i--duration of transmitter pulse;
M_D--distance scan scale of indicator;
d_s--diameter of electronic spot on indicator CRT;

For azimuth (elevation)

$$\Delta\beta(\Delta\varepsilon) \geqslant \theta^\circ_{n\beta(\varepsilon)} + M_{\beta(\varepsilon)} d_s, \tag{6.20}$$

where $M_{\beta(\varepsilon)}$--indicator scan scale for aximuth (elevation);

For azimuth in observing targets on PPI

$$\Delta\beta_{\kappa} \geqslant \theta_a^{\circ} + M_D d_s; \qquad (6.21)$$

For speed

$$\Delta V_r \geqslant \frac{\Delta F_f \lambda}{2}. \qquad (6.22)$$

where ΔF_f--width of pass band for target signal fine selection filter for Doppler frequency (it is assumed that $\Delta F_{sp} \leqslant \Delta F_f$, that is, the spectrum of the Doppler frequencies is less or equal to the width of the filter pass band);

λ--operating radar wave length.

Target detection probability is the probability of exceeding signal power on the radar receiver input by a set number of times over the noise strength whereby the target is detected:

$$P_{de} = p(P_c \geqslant \gamma_p P_{re\,min}). \qquad (6.23)$$

Since the amount $P_c = f(\sigma_t, D_t, \ldots)$, detection probability with all other parameters depends upon target type and range. If target detection probability for one observation equals $P_{1\,de}$, then with n_n, its value is:

$$P_{de} = 1 - (1 - P_{1\,de})^{n_n}. \qquad (6.24)$$

Target identification capability describes the capacity of the SAMS to identify targets in the designated volume of space over the established time. As a result of detection the aircraft can be categorized "friend or foe."

The required identification range is:

$$D_{id\,req} \geqslant D_{de\,max}.$$

The technically possible identification range is:

$$D_{id} \leqslant \sqrt{\frac{P_{in} G_1 G_2 \lambda_{in}^2}{(4\pi)^2 P_{re\,in}}} - \sqrt{\frac{P_{re} G_1 G_3 \lambda_{re}^2}{(4\pi)^2 P_{re\,re}}}. \qquad (6.25)$$

where P_{in}, P_{re}--the strength of the interrogation and reply transmitter;

G_1, G_2, G_3--coefficients for directional effect of interrogator and responder antennas;

λ_{in}, λ_{re}--interrogator and responder wave length;

$P_{re\,in}$, $P_{re\,re}$--sensitivity of interrogator and responder receivers, respectively.

The resolution of the identification device is the ability to recognize [or resolve] the targets being identified in terms of distance and direction.

Range resolution is:

$$\Delta D_{id} \geqslant \frac{c(\tau_i + \Delta t + t_{cod})}{2}, \qquad (6.26)$$

where τ_i--duration of radar transmitter pulse;
Δt--time lag in reply pulse (code pulse) relative to target blip on indicator screen;
t_{cod}--length of code (reply pulse).

Direction (angular coordinate) resolution is:

For an autonomous identification device

$$\Delta\varepsilon_{id}\,(\Delta\beta_{id}) \geqslant \theta^{\circ}_{a\,id} + M_{\varepsilon(\beta)}\,d_s; \qquad (6.27)$$

For a combined identification device

$$\Delta\varepsilon_{id}\,(\Delta\beta_{id}) \geqslant \theta^{\circ}_{a\,ra} + M_{\varepsilon(\beta)\,ra}\,d_s, \qquad (6.28)$$

where $\theta^{\circ}_{a\ id}$, $\theta^{\circ}_{a\ ra}$--width of beam (directional pattern) for antennas of identification device and radar to which given device has been coupled;
$M\varepsilon_{(\beta)}$--elevation scan scale for air situation displays;
d_s--diameter of spot of electronic beam of CRT.

The reliability of identification is the probability that the given target has been classified in the appropriate category. The numerical value of the probability P_{id} depends upon the selected code of the interrogation and reply signals, the jamming situation and the advanced nature of the identification device.

Target Tracking Capability

The capability for tracking targets and determining their coordinates characterizes the ability of the SAMS to provide automatic (manual) tracking for various types of targets with the possible flight speeds and the measuring of their coordinates with acceptable errors.

The quantitative indicators for this capability are: maximum range of steady automatic (manual) target tracking, minimum target tracking range, the boundary values of the angular coordinates, distance and speed of the targets and their derivatives whereby tracking is on the boundary of stability, the acceptable tracking errors and the probability of dependable tracking.

Target Range Tracking Capability

The maximum possible tracking range is the one starting from which the device tracks the target dependably (without breaks). Its value depends upon the ratio P_s/P_n, the nature of the target's movement and the properties of the tracking device.

The required range of steady tracking whereby the maximum possible firing range for the given SAMS is realized is:

$$D_{c\ req} \geqslant \sqrt{[d_{c1p\,max} + V_t(t_{re} + t_{cr} + t_{p1})]^2 + H_t^2}. \qquad (6.29)$$

The technically possible steady tracking range with the set ratio P_s/P_n on the input of the tracking device is:

$$D_{c\ st} \leqslant \sqrt[4]{\frac{P_p G_1 G_2 \lambda^2 q_t}{(4\pi)^3 P_{re\,min} \gamma_c}}. \qquad (6.30)$$

where γ_c--the given signal--noise ratio.

The minimum possible target tracking range for distance is:

In a pulsed radar:

$$D_{c\,min} \geqslant \frac{c(\tau_i + t_r)}{2}. \qquad (6.31)$$

where $\tau_i t_r$--duration of transmitted pulse and sensitivity recovery time in receiver path, respectively;

Onboard radar tracking devices:

$$D_{c\,min} \geqslant \frac{V_t \sin q_t - V \sin q_p}{\dot{\varphi}_{D\,per}}. \qquad (6.32)$$

where V_t, V--speeds of target and missile;

q_t, q_p--angles between velocity vectors of target, missile and missile--target distance line;

$\dot{\phi}_{D\ per}$--maximum permissible value of angular rotation rate of missile--target distance line.

Target Tracking Capability for Angular Coordinates:

For elevation:

$$\left.\begin{array}{l} \varepsilon_t \leqslant \varepsilon_{a.per}; \\ \dot{\varepsilon}_t \leqslant \dot{\varepsilon}_{a.per}; \end{array}\right\} \qquad (6.33)$$

For azimuth:

$$\left.\begin{array}{l} \beta_t \leqslant \beta_{a.per}; \\ \dot{\beta}_t \leqslant \dot{\beta}_{a.per}. \end{array}\right\} \qquad (6.34)$$

where $\varepsilon_{a.per}$, $\beta_{a.per}$, $\dot{\varepsilon}_{a.per}$, $\dot{\beta}_{a.per}$--permissible values of antenna elevation, azimuth and their rate of change.

Target Tracking Capability for Speed:

$$V_{r\ t\ max} \leqslant \frac{F_{d\ max}\lambda}{2}, \tag{6.35}$$

where $F_{d\ max}$--maximum value of instrument Doppler frequency.

Errors in target tracking (measuring coordinates) due to reasons of occurrence can be fluctuation, dynamic and instrument; in terms of nature they are random and systematic.

Random errors are more often assessed by mean square values σ_c.

Range Tracking Errors:

$$\left.\begin{aligned} \sigma_{cD} &= \sqrt{\sigma_{fl}^2 + \sigma_{in}^2 + \sigma_{dyn}^2}; \\ \delta_{cD} &= |\delta_{dyn}| + |\delta_{in}|. \end{aligned}\right\} \tag{6.36}$$

where $\sigma_{f\ell}$, σ_{in}, σ_{dyn}--mean square values of random fluctuation, instrument and dynamic errors, respectively;
δ_{dyn}, δ_{in}--systematic components in errors of target range measurement.

The maximum error in measuring target distance is:

$$\Delta_D = |\delta_{c\cdot D}| + 3\sigma_{c\ D}. \tag{6.37}$$

The values of the amounts $\sigma_{f\ell}$, σ_{dyn}, σ_{in} depend upon the properties and nature of motion of the target, the weather conditions, the quality of operation and the operating stability of the equipment, the adopted method of measurement and the properties of the tracking system.

The permissible errors in tracking a target for range are those errors which when exceeded cause a failure of automatic tracking.

For analogue systems with time discriminators

$$\Delta_{D_{per}} \leqslant \frac{c\tau_{ctp}}{2}.$$

where τ_{ctp}--duration of tracking strobe.

A failure in AT occurs with (for systems of the first order of astatism)

$$\dot{D}_t \approx V_t > (\Delta_{D_{per}} - 3\sigma_{D\ fl})K_V.$$

Errors in target tracking for angular coordinates (elevation, azimuth) depend upon the adopted method of measurement and the properties of the tracking system and the target.

Random errors in measuring angular coordinates are caused by random changes in the shape of the return signals as well as by random deviations in the technical parameters of the tracking systems from the rated values and by external random disturbances.

The mean square value of the measurement error for an angular coordinate is:

$$\sigma_{\beta(\varepsilon)}=\sqrt{\sigma_{fl}^2+\sigma_{in}^2+\sigma_{dyn}^2} \tag{6.38}$$

where $\sigma_{f\ell}$--error caused by presence of angular and amplitude noise and by the signal--noise ratio determined as:

$$\sigma_{fl}^2=\sigma_{an}^2+\sigma_{mn}^2+\sigma_{io}^2. \tag{6.39}$$

Here

$$\sigma_{an}^2=\frac{2\delta_{an}^2}{\alpha_{an}}\Delta F_{e}, \tag{6.40}$$

where $\delta_{an}\approx\left(0.5\frac{L_t}{D_t}\right)^2$ (L_t--characteristic linear dimension of target, D_t--target distance);
ΔF_e--equivalent band of closed tracking system;
α_{an}--an amount depending upon type of target.

The reason for the appearance of angular noise (an) is the shift in the effective center of the signal's return along the length of the target.

Amplitude noise (mn) is caused by random changes in the intensity of the electromagnetic field at the signal receiving point.

Systematic errors:

$$\delta_{\beta(\varepsilon)}=|\delta_{\beta(\varepsilon)in}|+|\delta_{\beta(\varepsilon)dyn}|. \tag{6.41}$$

where $\delta_{\beta(\varepsilon)in}$--systematic component of instrument error;
$\delta_{\beta(\varepsilon)dyn}$--systematic component of dynamic error.

The dynamic error is caused by the system's properties and by the nature of the target's movement.

For a system of first-order astatism

$$\delta_{\beta\,dyn}\approx\frac{\dot{\beta}_t}{K_{\beta v}}. \tag{6.42}$$

For a system of second-order astatism

$$\delta_{\beta\,dyn}\approx\frac{\ddot{\beta}_t}{K_{\beta w}}. \tag{6.43}$$

where $\dot{\beta}_t$, $\ddot{\beta}_t$--rate and acceleration of change in target angular coordinate;
$K_{\beta V}$, $K_{\beta W}$--gain factors for target tracking system for angular coordinates.

A failure in target AT will occur (in a system of first-order astatism) with

$$\dot{\beta}_t(\dot{t}_k) \leqslant (|\delta_{\beta(\varepsilon)\text{per}}| - 3\sigma_{\xi l})K_{\beta V}. \qquad (6.44)$$

Hence

$$|\delta_{\beta(\varepsilon)}| + 3\sigma_{\varphi l} \geqslant \delta_{\beta(\varepsilon)\text{per}}. \qquad (6.45)$$

The permissible target tracking error with the method of instantaneous equisignal zones is:

$$\delta_{\varphi\,\text{per}} \leqslant \frac{\theta_a^\circ}{4}. \qquad (6.46)$$

Target tracking is possible with

$$\dot{\varphi}_t \leqslant \left(\frac{\theta_a}{4} - 3\sigma_{\varphi l}\right)K_{\varphi V}. \qquad (6.47)$$

Errors in measuring the radial component of target speed are caused by external and internal factors. The potential mean square area in measuring speed is

$$\sigma_{V\,\text{pot}} \simeq \frac{\lambda}{2\pi}\frac{\sqrt{\pi}}{\sqrt{\frac{2E}{N_0}}\tau_i}. \qquad (6.48)$$

where λ--radar operating wave length;
τ_i--duration of radar pulse.

Target tracking errors with manual tracking depend upon the adopted tracking method and the operator's training level.

In using a mechanical scale the mean square error of the calculation is

$$\sigma_{in} \simeq 0.15\Delta LM_s,$$

where ΔL--distance between adjacent scale division;
M_s--scale for given coordinate.

In using an electronic scale

$$\sigma_{in} \simeq (0.05 \div 0.1)\Delta LM_s. \qquad (6.49)$$

In using an electronic sight lined up with the target mark

$$\sigma_{in} \simeq \sqrt{\sigma_{un}^2 + \sigma_{\ell i}^2 + \sigma_{it}^2}, \qquad (6.50)$$

where σ_{un}--the error caused by the instability of the electronic sight;
$\sigma_{\ell i}$--error of lining up sight with target blip equal to fractions of the diameter of the CRT spot;
σ_{it}--error of interpolation in reading the sight setting on the scale of the device.

The probability of stable target tracking is the probability that the tracking error does not exceed the permissible value

$$P_{c\ st} = P(\Delta \leqslant \Delta_{per}).$$

The amount of the probability depends upon the properties of the target, the range and speed of flight, and the properties of the given tracking system. Its value can be determined for the given conditions.

Manual target tracking errors in television--optical sights are

$$\Delta\varphi \approx \frac{1}{2}\frac{L_t}{D_t}. \tag{6.51}$$

where L_t--linear dimension of target in mirror plane.

SAM Guidance Capability

The capability of the SAMS to guide SAM to the target is the ability of the system to bring simultaneously the determined number of missiles to the target with an accuracy not less than the set with the possible firing ranges. This depends upon the number of missile channels, the properties and nature of the target's movement and the properties of the control system. The quantitative indicators for this capability are the number of missile channels, the errors in guiding the missile to the target and the probability of guiding the missile to the target with an error that does not exceed the permissible.

The number of missiles needed to hit the target is:

$$n_p \geqslant \frac{\lg(1-P_s)}{\lg(1-P_1)}. \tag{6.52}$$

where P_s--the set value of target probability;
P_1--the probability of hitting the target with one missile.

With jamming:

$$n_p^j \geqslant \frac{\lg(1-P_s)}{\lg(1-\xi_j P_1)}. \tag{6.53}$$

where ξ_j--the coefficient for the decline in probability P_1 with the presence of interference.

Errors in guiding the missile to the target describe the guiding accuracy. These can be random and systematic and are caused by errors in measuring the mismatch parameter, the nature of the target's movement and by the properties of the control system.

The mean square value of the guidance error is:

$$\sigma_g = \sqrt{\sigma_{f\ell}^2 + \sigma_{in}^2 + \sigma_{dyn}^2} \; . \tag{6.54}$$

The amount of $\sigma_{f\ell}$ is basically determined by the fluctuation error of the mismatch parameter:

$$\sigma_{f\ell} = \frac{\sigma_{f\ell\, i}}{\sqrt{K_f}} \, , \tag{6.55}$$

where K_f--filtration coefficient for control loop.

The dynamic component of the error depends upon the nature of the target's motion and the external disturbances operating on the missile.

The systematic guidance error is:

$$\Delta_g = \Delta_{dyn} + \Delta_{in} + \Delta_m, \tag{6.56}$$

where Δ_{dyn}, Δ_{in}--systematic components of dynamic and instrument guidance errors; Δ_m--error in measuring mismatch parameter.

The probability of destruction. With the presence of guidance errors, the probability of hitting the target with one missile is:

$$P_1 = \frac{a^2}{a^2 + \sigma_g^2} \, e^{-\frac{\Delta^2}{2\left(a^2+\sigma_g^2\right)}} . \tag{6.57}$$

where $a = K_v \sqrt[3]{Q_{wh}}$--the parameter of the law of destruction numerically equal to a miss whereby the probability of destruction has a set value (K_v--the target survivability coefficient, Q_{wh}--the weight of the missile warhead).

Considering that the systematic errors can be compensated for, the permissible values of guidance errors for obtaining the set probability of target destruction should be:

$$\left.\begin{aligned} \sigma_{g\ per} &< \sqrt{\frac{P(\Delta_g)}{P_1} - 1}\,; \\ \Delta_{g\ per} &< \sqrt{0.1\left(a^2 + \sigma_g^2\right)}. \end{aligned}\right\} \tag{6.58}$$

where $P(\Delta_g) = 0.95$--component of probability of hitting target with one missile caused by the presence of systematic guidance error. The maximum value of the guidance error is:

$$\Delta_{g\,max} = |\Delta_g| + 3\sigma_g \approx |\Delta_i| + |\Delta_{dyn}| + 3\sigma_g$$

The systematic component of the dynamic guidance error in a general form can be expressed as

$$\Delta_{dyn} = C_0 x_{in}(t) + C_1 \frac{dx_{in}(t)}{dt} + \frac{1}{2} C_2 \frac{d^2 x_{in}(t)}{dt^2} + \cdots + C_k \frac{d x_{in}^k(t)}{dt^k}. \qquad (6.59)$$

where $C_k = \frac{d^k [L_0(P)]}{dP^k}$--error factor of (k+1) term, the error transfer function.

From expression (6.59) it follows that for determining the dynamic guidance error it is essential to find the error transfer function $L_0(P)$ by which the relationship of the current guidance error is correlated to the input effects $x_{in}(t)$. The appearance of $L_0(P)$ will depend not only upon the type of system but also upon the adopted guidance method.

The number of components in expression (6.59) depends upon the type of guidance system. In static systems, the dynamic error equals the total of all the components of expression (6.59). In first order astatic systems, the error equals the total of the components without the first term of expression (6.59), and in second order astatic systems, it equals the total without the first two components and so forth, that is, for first order astatic systems the coefficient $C_0 = 0$, and for second order astatic systems $C_0 = C_1 = 0$ and so forth.

The current value of the dynamic error in the first and second order astatic systems with $D_p = D_t$ will be determined by:

$$\Delta_{dyn} = \frac{1}{K_0} D_t \frac{d\varepsilon_t}{dt} + \frac{1}{2K_0} a_0 D_t \frac{d^2 \varepsilon_t}{dt^2}. \qquad (6.60)$$

where K_0--gain of control loop;
a_0--coefficient depending upon the nature of the target's motion and the properties of the guidance system.

With the movement of the target at a fixed speed at a certain angle θ_t to the horizontal plane, the dynamic error in a first order astatic system is:

$$\Delta_{q\,dyn} = \frac{1}{K_0} D_t \dot{\varepsilon}_t. \qquad (6.61)$$

where $\dot{\varepsilon}_t = V_t \sin q_t$ (q_t--target heading angle).

With the target's horizontal flight ($\theta_t = 0$), the amount

$$\Delta_{q\,dyn} = \frac{V_t \sin \varepsilon_t}{K_0}. \qquad (6.62)$$

The fluctuation guidance errors in homing systems are insignificant as with short distances between the missile and the target, the power of the returned (transmitted) target signal is sufficiently strong and the signal has a steady form.

Considering that the instrument and dynamic errors are small and can be compensated for while fluctuation errors are insignificant, the resulting guidance error can be considered:

$$r=\frac{\dot{\varphi}_D D^2_{\min}}{V_{rel}}. \qquad (6.63)$$

where $\dot{\varphi}_D$--rate of rotation of missile--target line at which automatic target tracking by coordinator would fail;
D_{min}--minimum failure range;
V_{rel}--relative rate of missile's closing with the target.

The amount $\dot{\varphi}_D$ depends upon the speed and direction of the target's motion relative to the missile--target line and upon the speed of the missile's movement. With the moving of the missile in a vertical plane

$$\dot{\varepsilon}=\frac{V_t \sin q_t - V \sin q_p}{D}. \qquad (6.64)$$

where q_t, q_p--target and missile heading angles;
D--missile--target distance.

The greatest value of $\dot{\varepsilon}_t$ with a change in target motion will occur when $q_t = 90°$. Then

$$\dot{\varepsilon}=\frac{V_t - V \sin q_p}{D}. \qquad (6.65)$$

Assuming $D = D_{min}$, we obtain

$$\dot{\varepsilon}=\frac{V_t - V \sin q_p}{D_{\min}}.$$

In substituting the obtained expression in formula (6.63) we obtain:

$$r=\frac{(V_t - V \sin q_p)\, D^2_{\min}}{V_{rel}}. \qquad (6.66)$$

6.2. Principles of Firing Antiaircraft Guided Missiles

6.2.1. Tasks and Essence of Firing Antiaircraft Guided Missiles

The process of a combat crew in an antiaircraft missile subunit from the moment of obtaining the firing mission to destroy the airborne target to the exploding of the SAM warhead by the target has come to be called firing.

The task of each individually taken firing is to destroy the target. For carrying out this task it is essential, in the first place, to have the missile close with the target with the required accuracy and, secondly, when this closing has occurred, to detonate the missile warhead in such a manner that its destructive elements cover the target. Consequently, SAM firing includes: immediate preparation of firing, the launch and the guidance of the missiles to the airborne target.

Immediate Preparation for Firing

Immediate preparation for firing starts the moment the firing mission is received to destroy the target and ends the moment the subunit is ready to launch the SAM.

The firing task includes target designation (instructions on the location of the target in space), the command to destroy the target and when necessary instructions on the procedure for firing at it.

The basic content of immediate firing preparations is:

a) Studying the firing task and assessing the air situation;

b) Searching for the target using the target designation data and its detection;

c) Locking on the target with the tracking radar and the changeover to precision tracking for angular coordinates, range, and if possible, also speed;

d) Solving the SAM launch problem and preparing the initial data for firing;

e) Target guidance and lock-on by the GSN [?homing head] (if this operation is carried out in the homing system before launch while the SAM is on the launcher).

Simultaneously with the performing of these operations the launchers are also prepared to launch the missiles.

Missile Launch and Guidance to the Airborne Target

When the target has reached a certain range relative to the SAMS the SAM are launched. After the launch of the SAM its closing with the airborne target that is constantly moving in space is carried out by the control system by which one understands the aggregate of devices determining the reciprocal position of the missile and the target and generating the control commands and guiding the missile to the target during the entire time of its flight until the rendezvous with the target.

The required trajectory for the missile's closing with the target is set by the linkage equations which determine the missile's motion depending upon the coordinates and parameters of the target's motion.

The type of linkage equations determines the method of guiding the missile to the target. Missile control in the foreign SAMS is provided only for direction. The concept of the required range to the missile is not introduced. Consequently, for guiding the missile it is sufficient to set a linkage equation for the angular coordinates, for example, for ε and β.

The measure of linkage disruption in each guidance plane can be termed the control parameter or the mismatch signal. This parameter is proportional to the deviation of the controlled amount from the required value, that is, it is an error of the control system. The control system, in altering the direction of the missile's flight, should eliminate this error and maintain it within limits which ensure the set accuracy of the closing of the missile with the target.

The real trajectory will differ from the required. According to the guidance feature, it can be divided into three legs: the initial leg, the lead leg and the guidance leg.

The initial leg is the leg of the trajectory for the missile's unguided flight after the launch. The necessity of this leg is caused by a number of circumstances: missile control becomes sufficiently effective after it has reached a certain speed, control should be carried out after the dropping of the boosters and so forth.

At the end of the uncontrolled flight, the missile's position may not correspond to the selected guidance method and to the target's position. The leading of the missile to the required trajectory is considered complete if its deviation does not exceed a set amount determined by the effective action of the SAM warhead against the target.

The leg for leading the missile to the required trajectory is the trajectory leg intermediate between the initial and guidance legs.

In viewing the maximum SAM firing ranges, the trajectory leg from the point of the missile launch to the obtaining of a permissible error in its position is frequently understood as the lead leg.

The guidance leg is the trajectory leg over which the missile is guided to the target according to the set guidance method.

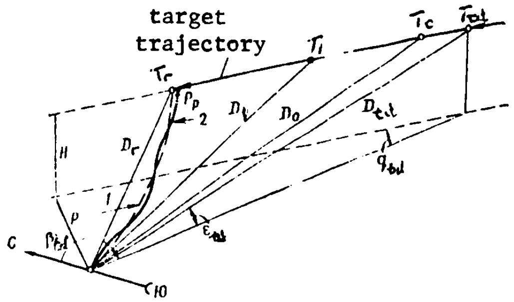


Fig. 6.5. On determining the essence of SAM firing

The detonating of the missile warhead in the area of the point of impact can be carried out by two methods: using a proximity fuze and by command from the ground.

An overall diagram for firing a SAM is shown in Fig. 6.5, where the points T_{td}, T_o, T_ℓ and T_r designate the positions of an airborne target, respectively, at the moments of receiving the target designation data, the detecting of the target by the missile guidance station, the launching of the missile and the rendezvous of the missile with the target; 1 and 2--the required and actual SAM trajectory; P_p--the point on the trajectory where the missile warhead is detonated.

During the time the target moves from point T_{td} to T_ℓ, immediate firing preparations are carried out and from point T_ℓ to T_r--missile guidance.

6.2.2. SAM Guidance Errors

The accuracy of missile guidance is assessed by the characteristics of the guidance error law in a picture or any other characteristic plane near the target.

A plane perpendicular to the target's line of sight is called a picture plane or plane of projection (Fig. 6.6a).

In a theoretical analysis of firing effectiveness, as a plane for assessing missile guidance errors it is possible to use a plane perpendicular to the vector of its relative speed (Fig. 6.6b).

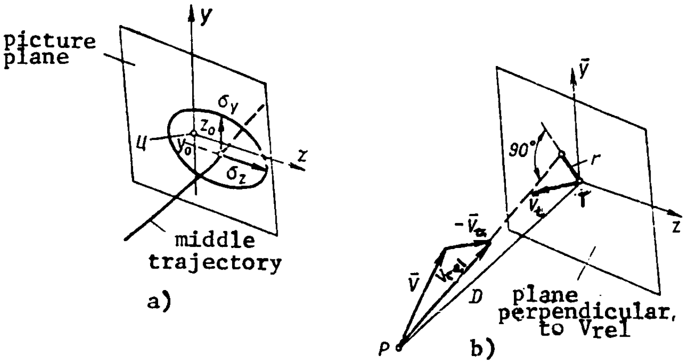


Fig. 6.6. Planes for assessing guidance errors
(a--Picture plane, b--Plane perpendicular to V_{rel})

The Nature and Reasons for the Occurrence for SAM Guidance Errors

In terms of their nature, guidance errors can be systematic and random.

Systematic errors are those errors which in firing remain constant or change according to a completely determined law. A systematic error can be disclosed and eliminated by introducing the corresponding corrections. If the amoung of the systematic error depends upon the parameters of the target's movement and which change largely in firing, then in a number of instances a precise compensation for such an error will be difficult.

The amount of the systematic errors y_0 and z_0 determines the position of the center of dispersion for the points of intersecting the actual trajectories relative to the target in the picture plane (Fig. 6.6).

Random errors is the name given to those errors which in each missile launch can assume different values of amount and sign and precisely which ones cannot be predicted beforehand. These errors cause random deviations in the intersection points of the actual trajectories with the picture frame relative to the center of dispersion.

It can be considered that the random missile guidance errors are subordinate to a normal distribution law, that is, they can be described by a probability density of the sort:

$$f(y, z) = \frac{1}{2\pi\sigma_y\sigma_z} e^{-\left[\frac{(y-y_0)^2}{2\sigma_y^2} + \frac{(z-z_0)^2}{2\sigma_z^2}\right]}. \qquad (6.67)$$

where y, z--the amount of SAM deviations from the target and the corresponding guidance plane;
σ_y, σ_z--mean square errors of the deviations.

The mean square error σ of a random amount is the characteristics of the dispersion of the random amount's values relative to its mathematical expectation. The square of the mean square error is called the variance

$$\sigma^2[X] = M[(X - m_X)^2], \tag{6.68}$$

where X--random amount;
m_X--expectation of random amount;
$M[(X-m_X)]$--expectation of deviation of random amount from expectation.

The statistical variance of a random amount is:

$$\sigma^2_{\text{ст}}[X] = \frac{\sum\limits_{i=1}^{n} (x_i - x_{\text{ср}})^2}{n-1}, \tag{6.69}$$

where x_i--observable values of random amount;
x_{cp}--statistical average of random amount.

In artillery practice, in assessing the dispersion of random amounts subordinate to a normal law, instead of the mean square error frequent use is made of a numerical characteristic which has been termed the mean error or the mean deviation.

The mean deviation is the name given to one-half the length of a sector which is symmetrical relative to the dispersion center the hit probability of which equals 0.5. The mean error E is related to the mean square error σ by the ratio $E = 0.675\sigma$.

The dispersion of a random value in practical terms keeps on the sector ±3σ or ±4E. The scale of the mean square and mean errors of a normal law is shown in Fig. 6.7.

The guidance errors accompanying the firing of missiles, according to the reasons for their occurrence, have come to be divided into dynamic, instrument and fluctuation.

A dynamic error in guiding a missile to the target is the name given to the deviation tion of the missile from the target arising as a result of the effect of incoming signals from the moving target on the guidance system in the processing of these signals by the missile as well as signals caused by the longitudinal movement of the missile. If the target does not maneuver then the incoming effect changes slowly and the loop operates without transfer processes. The errors corresponding to such operating conditions in the guidance system are termed steady dynamic errors. With abrupt maneuvers by the target, transfer processes arise in the control loop and these lead to increased errors in guiding the missile to the target.

In firing on a nonmaneuvering target, the dynamic guidance error will be:

$$h_d = \frac{W_{nt}}{K_0}, \qquad (6.70)$$

where W_{nt}--normal acceleration of missile moving along required trajectory;
K_0--gain coefficient for open control loop.

The required trajectory along which the missile should move in its closing with the target in a general instance is rectalinear. The gain of the control loop is not infinite. Consequently, the missile can move along a curvalinear trajectory only in the presence of its error relative to the required position at each moment of time. The greater the trajectory curvature with the set gain in the open control loop the larger the error amount should be. The error characterizing the required amount of the mismatch parameter for realizing the required movement of the SAM is usually called the dynamic error of the guidance method (Fig. 6.8).

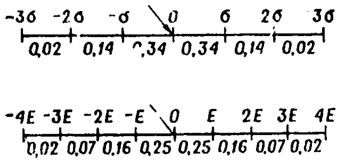


Fig. 6.7. Scales for σ and E of a normal law

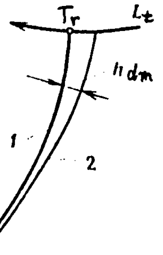


Fig. 6.8. Illustration of error H_{dm}:
1--Kinematic trajectory; 2--Dynamic trajectory

The amount of the gain K which includes as one of the comultipliers the missile gain K_p characterizing its maneuvering properties, depends upon the SAM speed and altitude. If the available missile g-loads become less than the required ($n_p < n_k$), then the missile will leave the required trajectory and travel along a circular arc with a radius:

$$\rho_{\min} = \frac{V^2}{n_p g}. \qquad (6.71)$$

Consequently, the missile control loop is an automatic control system with limited capacity due to the restriction on the available missile g-loads. The limited maneuverability of the SAM leads to an increase in the dynamic error of missile guidance (Fig. 6.9).

The maneuvering of the target in direction or speed leads to an abrupt change in the parameters of the SAM required trajectory and to a rise in the mismatch signal on the input of the control system. The dynamic error for missile guidance to a maneuvering target in the area of the point of impact depends upon the ratio of the g-loads developed by the target and the missile, the inertia of the control loop and the time of the start of the target's maneuver relative to the moment of impact.

The target's maneuver does not lead to an abrupt rise in the guidance error if the ratio of available g-loads $n_p/n_t \geqslant 1.5\text{-}2$. The most effective is a maneuver by the target which is executed several seconds before impact.

A sharp rise in the input signal caused by a transfer process can be a consequence of a change in the target tracking method or the guidance method in the process of the missile's flight, of gas dynamic disturbances in a loop and so forth.

The possible ways for reducing the dynamic error in guiding the missile to a target are: a low curvature in the required SAM trajectory particularly in the area of the point of impact, its dependence upon the target's maneuver, a high quality of control loop and the incorporation of compensation adjustments into the control commands.

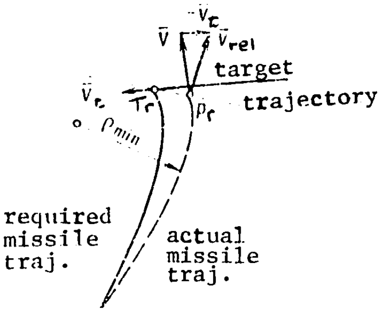


Fig. 6.9. Occurrence of error with $n_{av} < n_t$

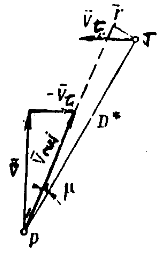


Fig. 6.10. Instantaneous miss of homing missile

Fluctuation errors in their essence are random and are caused by amplitude and angular fluctuations in the signal returned from the target, by the intrinsic noise of the equipment and by other random disturbances operating on the missile control loop.

The amount of the fluctuation guidance error in telecontrol systems, as a rule, depends upon the type and parameters of the airborne target's movement, the method of its tracking, the guidance method, the type of target countermeasures as well as the meteorological conditions and the nature of the underlying surface (in firing on low-flying targets). With an accuracy sufficient for practical use it can be considered that this error is proportional to the fluctuation error of target tracking

$$\sigma_f = K_f \sigma_{tr\ f}. \tag{6.72}$$

Homing systems which employ bearing taking devices with instantaneous equisignal directing are insensitive to amplitude fluctuations in the signal returned from the target. The angular fluctuations of this signal influence the accuracy of determining the mismatch parameters, being the basic source of fluctuation errors.

Instrument errors is the name given to errors caused by design and production flaws in the control equipment, by the imperfection in the employed methods of measuring the target and missile coordinates and generating the mismatch parameter and control commands, by the limits for introducing compensation corrections and so forth.

A guidance instrument error can be also introduced by the operators if they are an element in the missile control loop or participate in determining the coordinates and parameters of the target's movement.

The resulting instrument error has systematic and random components within it.

The miss of a homing missile r (Fig. 6.10) as caused by an error in the position of the missile velocity vector V relative to the point of impact at a moment of failure in the SAM homing is:

$$r = \frac{D^{*2}_{\min}\varphi_D}{V_{rel}} \approx -\frac{D^{*2}_{\min}\varphi_D}{\dot{D}}, \qquad (6.73)$$

where $D^{*}_{\min}$--the missile--target distance at the moment of failure of the missile's homing;
ϕ_D--the rotation rate of the missile--target line.

The Probability of Hitting the Circle of the Set Radius

With the known expectation y_0, z_0 and the mean square error σ_y, σ_z for the dispersion of the missile trajectories around the target and a normal law of SAM guidance errors, the probability P for the hitting of the missile in a circle of a set radius R is calculated in the following manner.

The first case. The systematic guidance errors are absent ($y_0 = z_0 = 0$) and the guidance errors are subordinate to a circular law ($\sigma_y = \sigma_z = \sigma$):

$$P(r \leqslant R) = 1 - e^{-n}, \qquad (6.74)$$

where

$$n = \frac{R^2}{2\sigma^2}.$$

The formula (6.74) also makes it possible to solve the inverse problems, that is, to determine the mean square error σ from the set probability of hitting the circle of a set radius.

Example. Let $y_0 = z_0 = 0$, $\sigma_y = \sigma_z = 10$ m. To determine the probability that in guiding the missile to the target it will deviate from the target by not more than 25 m.

Solution.

$$n = \frac{R^2}{2\sigma^2} = \frac{25^2}{2 \cdot 10^2} = 3,12;$$

$$P(r \leqslant 25) = 1 - e^{-n} = 1 - e^{-3,12} = 0,95.$$

Second case. The guidance of the missile to the target involves systematic errors ($y_0 \neq 0$ and $z_0 \neq 0$). The random errors are subordinate to a circular law ($\sigma_y = \sigma_z = \sigma$).

The solution to the problems related to the probability of hitting in a circle of a set radius is carried out by employing equal probability curves in the E/R and r_0/R coordinates as shown in Fig. 6.11.

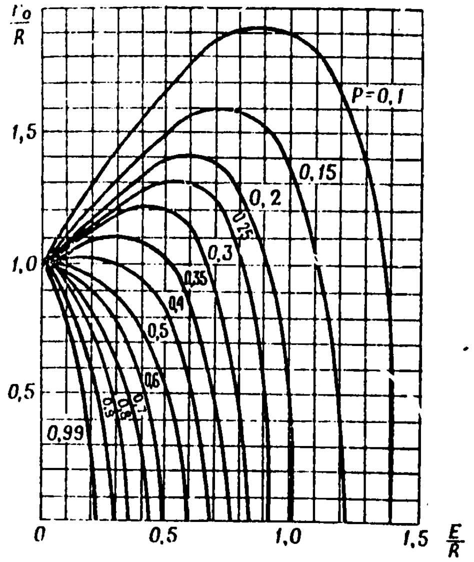


Fig. 6.11. Family of equal probability curves

They make it possible:

a) Using the known values of the systematic error of guidance to the target $r_0 = \sqrt{y_0^2 + z_0^2}$ and the mean error E, to determine the probability of the missile's hitting within a circle of a set radius R.

For obtaining an answer it is essential to calculate the E/R and r_0/R values and from the curves to find the probability value.

b) From the known values of the systematic error r_0, the mean error E and probability P, to determine the size of the radius for the circle in which the missile will hit.

For this the ratio is calculated:

$$\frac{r_0}{E} \text{ and the angle } \alpha = \text{arc tg } \frac{r_0}{E}.$$

From the origin of the coordinates, a line is drawn at angle α to the abscissa axis. The intersecting point of this line with the set probability curve determines the coordinates E/R and r_0/R. From the ratio E/R or r_0/R, the radius of the circle R is calculated within which the missile will hit with the set probability.

c) From the known values for the probability of the missile hitting in a circle with a radius R and for the values of the mean error E or the systematic error r_0, to find, respectively, r_0 or E.

The third case. Systematic guidance errors are absent ($y_0 = z_0 = 0$) and the random guidance errors are subordinate to an eliptical law ($\sigma_y = \sigma_z$).

The probability of the missile's hitting in a circle with a set radius is determined from Table 6.1. The inputs into the table are the values a and b calculated in the following manner:

$$1) \text{ with } E_y < E_z \quad a = \frac{R}{E_z}; \quad b = \sqrt{1 - \frac{E_y^2}{E_z^2}};$$

$$2) \text{ with } E_y > E_z \quad a = \frac{R}{E_y}; \quad b = \sqrt{1 - \frac{E_z^2}{E_y^2}}.$$

Example. Let $y_0 = z_0 = 0$; $E_y = 10$ m, $E_z = 15$ m. To determine the probability that the missile's miss in guiding it to the target will not exceed 30 m.

Solution. The inputs into the table:

$$a=\frac{R}{E_z}=\frac{30}{15}=2;\quad b=\sqrt{1-\frac{E_y^2}{E_z^2}}=\sqrt{1-\frac{10^2}{15^2}}=0{,}74.$$

From Table 6.1, P(r < 30) ≈ 0.72.

Table 6.1

a	b										
	0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1,00
0,1	0,0023	0,0023	0,0023	0,0024	0,0025	0,0026	0,0029	0,0032	0,0038	0,0052	0,0538
0,2	0,0091	0,0091	0,0092	0,0095	0,0099	0,0105	0,0113	0,0127	0,0150	0,0206	0,1073
0,3	0,0203	0,0204	0,0207	0,0212	0,0221	0,0234	0,0253	0,0283	0,0334	0,0455	0,1604
0,4	0,0357	0,0359	0,0365	0,0374	0,0389	0,0412	0,0444	0,0496	0,0586	0,0790	0,2127
0,5	0,0553	0,0556	0,0564	0,0579	0,0602	0,0635	0,0686	0,0764	0,0899	0,1196	0,2641
0,6	0,0786	0,0790	0,0802	0,0823	0,0855	0,0902	0,0972	0,1080	0,1265	0,1661	0,3143
0,7	0,1055	0,1060	0,1075	0,1103	0,1144	0,1207	0,1298	0,1439	0,1676	0,2168	0,3632
0,8	0,1355	0,1361	0,1381	0,1415	0,1468	0,1546	0,1660	0,1835	0,2124	0,2701	0,4105
0,9	0,1683	0,1690	0,1714	0,1756	0,1820	0,1911	0,2052	0,2260	0,2599	0,3247	0,4562
1,0	0,2034	0,2044	0,2072	0,2121	0,2197	0,2307	0,2467	0,2707	0,3091	0,3794	0,5000
1,1	0,2406	0,2417	0,2449	0,2506	0,2593	0,2719	0,2900	0,3170	0,3593	0,4329	0,5419
1,2	0,2793	0,2805	0,2842	0,2906	0,3003	0,3145	0,3346	0,3641	0,4095	0,4946	0,5817
1,3	0,3192	0,3205	0,3245	0,3316	0,3424	0,3578	0,3798	0,4115	0,4592	0,5338	0,6194
1,4	0,3597	0,3612	0,3656	0,3733	0,3849	0,4016	0,4250	0,4565	0,5075	0,5802	0,6550
1,5	0,4006	0,4021	0,4068	0,4151	0,4276	0,4452	0,4699	0,5046	0,5541	0,6234	0,6883
1,6	0,4414	0,4430	0,4460	0,4568	0,4698	0,4883	0,5139	0,5493	0,5984	0,6634	0,7195
1,7	0,4819	0,4835	0,4888	0,4978	0,5114	0,5305	0,5566	0,5922	0,6403	0,7002	0,7485
1,8	0,5215	0,5232	0,5287	0,5380	0,5520	0,5714	0,5978	0,6331	0,6794	0,7338	0,7753
1,9	0,5601	0,5619	0,5674	0,5770	0,5912	0,6108	0,6370	0,6716	0,7156	0,7645	0,8000
2,0	0,5975	0,5993	0,6049	0,6145	0,6288	0,6483	0,6742	0,7077	0,7488	0,7923	0,8227
2,1	0,6333	0,6331	0,6408	0,6504	0,6645	0,6838	0,7091	0,7410	0,7792	0,8174	0,8434
2,2	0,6675	0,6693	0,6749	0,6844	0,6984	0,7172	0,7415	0,7718	0,8068	0,8400	0,8622
2,3	0,6998	0,7016	0,7071	0,7165	0,7301	0,7483	0,7716	0,7999	0,8316	0,8602	0,8792
2,4	0,7303	0,7320	0,7374	0,7465	0,7596	0,7771	0,7991	0,8254	0,8538	0,8784	0,8945
2,5	0,7587	0,7604	0,7656	0,7744	0,7880	0,8036	0,8243	0,8434	0,8736	0,8945	0,9082
2,6	0,7852	0,7868	0,7918	0,8002	0,8122	0,8279	0,8470	0,8689	0,8910	0,9088	0,9205
2,7	0,8096	0,8111	0,8159	0,8239	0,8352	0,8498	0,8675	0,8872	0,9095	0,9215	0,9314
2,8	0,8320	0,8334	0,8380	0,8455	0,8561	0,8697	0,8858	0,9034	0,9201	0,9327	0,9410
2,9	0,8524	0,8538	0,8580	0,8651	0,8750	0,8874	0,9020	0,9176	0,9320	0,9425	0,9495
3,0	0,8709	0,8722	0,8762	0,8828	0,8918	0,9032	0,9164	0,9300	0,9423	0,9510	0,9570
3,2	0,9026	0,9038	0,9072	0,9127	0,9203	0,9296	0,9399	0,9502	0,9589	0,9645	0,9691
3,4	0,9279	0,9288	0,9316	0,9362	0,9424	0,9497	0,9576	0,9652	0,9712	0,9753	0,9782
3,6	0,9476	0,9483	0,9506	0,9543	0,9591	0,9648	0,9707	0,9760	0,9801	0,9828	0,9848
3,8	0,9626	0,9632	0,9650	0,9678	0,9716	0,9758	0,9800	0,9838	0,9865	0,9883	0,9893
4,0	0,9737	0,9742	0,9756	0,9778	0,9806	0,9837	0,9867	0,9892	0,9909	0,9921	0,9930
4,2	0,9819	0,9823	0,9833	0,9850	0,9870	0,9892	0,9912	0,9929	0,9940	0,9948	0,9954
4,4	0,9878	0,9880	0,9888	0,9900	0,9914	0,9930	0,9944	0,9954	0,9961	0,9966	0,9970
4,6	0,9919	0,9921	0,9926	0,9935	0,9945	0,9955	0,9964	0,9971	0,9975	0,9978	0,9981
4,8	0,9947	0,9948	0,9952	0,9958	0,9965	0,9972	0,9978	0,9982	0,9985	0,9987	0,9988
5,0	0,9966	0,9967	0,9970	0,9971	0,9978	0,9983	0,9986	0,9989	0,9991	0,9992	0,9993

Fourth case. The guidance of the missile to the target is accompanied by systematic errors ($y_0 \neq z_0 \neq 0$) while the random errors are subordinate to an eliptical law on a plane ($\sigma_y \neq \sigma_z \neq 0$).

The probability of hitting within a circle of a given radius, due to the complexity of the analytical calculations, can also be determined graphically using a circular dispersion grid.

6.2.3. The Coordinate Law for the Destruction of a Target

The Effect of the SAM Combat Equipment on the Target

In terms of the method of effect on the target, the SAM warheads are divided into high explosive, fragmentation and shaped-charge. In the foreign SAMS, the most widely employed are the nonisotropic fragmentation warheads.

In the exploding of the SAM, the target can be destroyed by: the destruction of the aircraft's structure; by knocking out its vitally important sections; by igniting the fuel on the aircraft and so forth.

The radius of the effective high explosive action of the SAM combat equipment depends primarily upon the weight of the explosive and the target's height. In terms of its amount it is relatively small.

The fragmentation action of a warhead can lead to the mechanical destruction of the aircraft's structure, to the damaging of vulnerable compartments, to the igniting of fuel and to the knocking out of crew members.

An indispensable condition for hitting a target is the blanketing or straddling of the target by warhead fragments. This condition with the set values of target and missile speed, the angle between them and the angle and velocity of fragmentation determines the moment for detonating the SAM warhead.

A contact element impacts with a target if at the moment of detonating the warhead the target is on a line coinciding with the relative velocity of this element $V_{rel\,re}$ (Fig. 6.12).

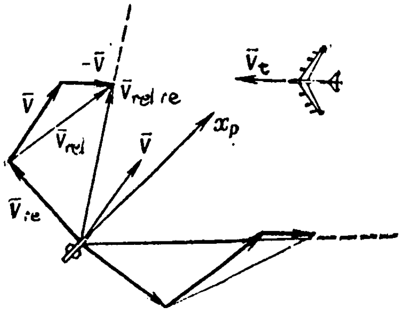


Fig. 6.12. Relative velocity of contact element

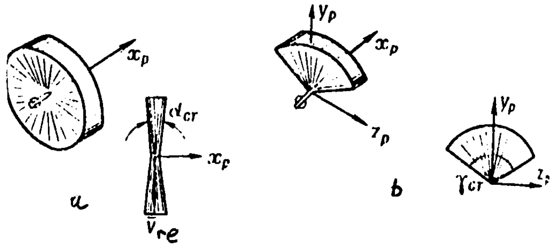


Fig. 6.13. Static fragmentation area of nonisotropic warhead (a--Symmetrical relative to the missile's longitudinal axis, b--Directed also in a radial plane)

If a target is within a certain area of space around a missile at the moment the missile's warhead is detonated and the target's vulnerable compartments are blanketed by the stream of fragments, this area of space is termed the area of a possible target kill.

The position of this area in firing does not remain constant. The speed of airborne targets changes within broad limits and the missile speed on the trajectory is also not constant. The angle of the missile's impact with the target (the angle between the directions of the target and missile velocity vectors) depends upon the coordinates and parameters of the target's movement and the initial SAM launch conditions. Consequently, choosing the moment for detinating the warhead should be done considering the specific conditions of the impacting of the missile with the target.

With a symmetrical static fragmentation area relative to the missile's longitudinal axis (Fig. 6.13a), the area of possible target kill is a volume bounded by two conical surfaces with the vertex at the warhead detonation point and with axes coinciding with the missile's relative velocity vector. The relative trajectories of the fragments are distributed within the given volume. Such a shape of the area of possible target kill makes it possible not to consider the direction of the missile's miss in selecting the moment for detonating the warhead.

If the static fragmentation area is characterized by an amount of the fragmentation angle relative to the missile longitudinal axis α_{ct} and an angle of fragmentation in a radial plane γ_{ct} (Fig. 6.13b), then in controlling the detonation of the warhead, one considers not only the amount and direction of the target and missile velocity vector but also the direction of the SAM miss. Prior to the detonation of the warhead, the missile turns on its longitudinal axis corresponding to the direction of the miss.

The detonation of a missile warhead in the area of the point of impact can be carried out by two methods: by the giving of the command to detonate the warhead from a ground control center when the missile is near the target and by a proximity fuze on the missile.

The first method in selecting the moment for detonating the warhead does not make it possible to consider the conditions of the missile's impacting with the target. In employing nonisotropic HE-fragmentation warheads on the missile, this method is employed in firing in special cases.

The second method is the basic one. Of all types of proximity fuzes in the SAMS of foreign armies, radar fuzes have become the most widespread.

By the radar fuze activation area one understands the spatial area around the missile determined by the geometric locus of the missile's hypothetical centers at the moment of activating the radar fuze, that is, the detonating of the missile warhead. The probability description of this area is the law of radar fuze activation $\omega(x, y, z)$. This describes the distribution of the warhead detonation coordinates in the area of the point of impact:

$$\omega(x, y, z) = f_1\left(\frac{x}{y, z}\right) f_2(y, z). \tag{6.75}$$

where $f_1(x/y, z)$--distribution density of coordinate x for activation of fuze with set guidance error y, z;

$f_2(y, z)$--probability of radar fuze activation against target depending upon guidance errors y, z.

The radar fuze activation area should coincide with the area of the possible target kill. If this area coincides, then it is said that the radar fuze is matched with the warhead. With the noncoinciding of these areas, one observes one or another degree of mismatching between the fuze and the warhead and a decline in the probability of a target kill with the set amount of miss.

Possible methods for matching the radar fuze and the missile warhead include:

a) A discrete or continuous change in the slant angle of the radar fuze directional pattern to the longitudinal axis of the missile depending upon the conditions of the impacting of the missile with the target (target speed, missile speed, position of point of impact and so forth);

b) Changing the angle of slant in the static fragmentation area relative to the missile's longitudinal axis depending upon target speed and firing conditions (this angle can be changed by choosing the appropriate points for triggering the warhead);

c) Selecting the moment of activating the radar fuze using Doppler velocity meters.

The detonating of the missile warhead occurs at ranges to the target corresponding to the amount of miss. A restriction on the operational range of a proximity fuze is imposed in order to exclude the possibility of its activation by a target not being fired on, that is, a target located outside the radius of effective action for the warhead's contact elements.

A Quantitative Representation of the Coordinate Law of Target Destruction

The hitting of a target as well as the damage caused to it in the detonating of the SAM warhead depend upon the following random aggregate of factors: the values of the coordinates for the SAM detonation point relative to the target, the degree of blanketing the target with a current of warhead contact elements, the mass and shape of the contact elements, the speed of the elements at the moment they hit the target and their density, the effectiveness of the high explosive action of the warhead, the vulnerability of the airborne target and the conditions of the impacting of the missile with the target (the height of the point of impact, the values and directions of the missile and target velocity vector and so forth).

With the given SAM combat equipment and the characteristics of the airborne target, the probability of hitting it depends basically upon the coordinates of the missile explosion point and the conditions for the impacting of the missile with the target.

An integral function G(x, y, z) determining the amount of the target kill probability depending upon the coordinates of the missile's point of explosion relative to the target is termed the coordinate law of target destruction.

The function G(y, z) determining the probability of target kill depending upon the errors in guiding the SAM to the target can be called the conditional coordinate law of destruction:

$$G(y,z)=\int_{-x_{\max}}^{+x_{\max}} G(x,y,z)\,f_1\left(\frac{x}{y,z}\right)dx, \qquad (6.76)$$

where the values $-x_{max}$, $+x_{max}$ determine the possible dispersion interval of the missile warhead detonation points along the trajectory ($|x_{max}| = 3\sigma_x$).

Graphically, the conditional coordinate law for the hitting of a target can be represented by a family of closed equal probability curves (Fig. 6.14) and these make it possible to determine the probability of target kill for any set values of y and z. In the general instance, these closed curves are not even circles, that is, the target kill probability depends not only upon the amount but also upon the direction of the missile miss.

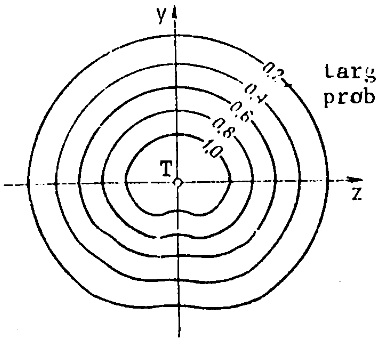


Fig. 6.14. Graphic image of conditional coordinate law for target destruction

With the given characteristics for the SAM combat equipment, the parameters of the conditional coordinate law of destruction depend upon target vulnerability and the conditions of the missile's impact with the target.

By the vulnerability of an airborne target one understands the degree of its sensitivity to destruction with the detonating of the missile warhead under the given conditions of impacting with the target. Assessing the vulnerability of enemy probable targets is done indirectly by a general analysis of their design and a comparison with the vulnerability of the standard sections of target aircraft.

Target vulnerability depends upon the conditions of its impacting with the SAM (the altitude, speed and orientation of the target relative to the point of the explosion and so forth).

The zone of certain target kill is directly adjacent to the aircraft. With the exploding of the SAM in this zone the aircraft is destroyed with virtual reliability as a consequence of the general destruction to the structure caused by the high-explosive effect of the warhead combined with the fragmentation action of the solid stream of contact elements.

With the detonating of the warhead outside the zone of certain target kill, the target is destroyed as a result of the fragmentation or incendiary action of the individual contact elements against the vulnerable sections of the aircraft. Target vulnerability in this instance is determined by the number of vulnerable sections of the first and second groups and by their area projected to a plane perpendicular to the vector of the relative shrapnel velocity.

In the sections of the first group one usually puts the elements of an airborne target the knocking out of which entails its destruction (pilot's cockpit, the engine of a single-engine aircraft, the bomb bay and so forth) and in the second group, the elements the knocking out of a certain number of which in a certain aggregate (a combination of damaged sections) leads to the destruction of the airborne target.

Analytically the conditional law of target destruction can be represented by a function which depends upon two independent variables: the size of the miss r and the direction of the miss ϕ. With the given characteristics of the missile's combat equipment, the density of fragments λ is determined by the amount of the miss r, while the reduced vulnerable area of the aircraft s_{vul} is determined by the direction of the miss ϕ and by the amount of the miss r:

$$G(r,\varphi) = 1 - e^{-\lambda(r)\, s_{vul}(r,\varphi)}. \tag{6.77}$$

With the experimental determination of the conditional law of target destruction, the dependence (6.77) is represented in the form:

$$G_0(r,\varphi) = 1 - e^{\frac{\delta_0^2(\varphi)}{r^2}}, \tag{6.78}$$

where $\delta_0(\phi)$--the parameter of the conditional law of target destruction depending with the given missile combat equipment upon the type of target, the firing conditions and the direction of miss.

With an approximate estimate of the effectiveness of SAM firing, a two-dimensional conditional law of target destruction is replaced by a circular conditional law of target destruction (Fig. 6.15). An approximation of the law is realized by an averaging of the parameter $\delta_0(\phi)$:

$$\delta_0 = \frac{1}{2\pi}\int_0^{2\pi} \delta_0(\varphi)\, d\varphi. \tag{6.79}$$

Then

$$G_0(r) = 1 - e^{-\frac{\delta_0^2}{r^2}}. \tag{6.80}$$

The parameter of the conditional law of target destruction δ_0 numerically equals the size of the miss r whereby the conditional probability of target kill is 0.632, since

$$G_0(r = \delta_0) = 1 - e^{-1} = 0{,}632.$$

Other approximations are also possible for the conditional law of target destruction, for example:

$$G_0(r) = e^{-\frac{r^2}{2R_0^2}}. \tag{6.81}$$

where R_0--parameter of the conditional law of destruction; it is numerically equal to the size of the miss whereby the conditional target kill probability is 0.606; $G_0(r = R_0) = e^{-0.5} = 0.606$.

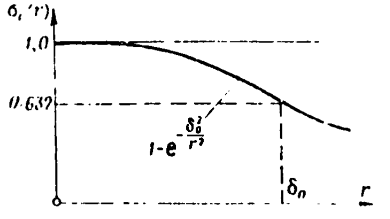


Fig. 6.15. Nature of dependence $G_0(r)$

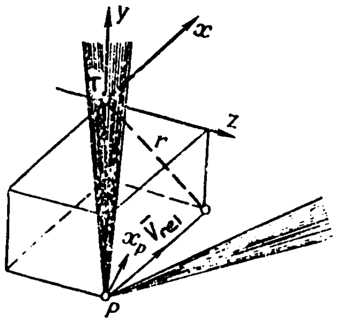


Fig. 6.16. On determining the target kill probability

6.2.4. Quantitative Indicators for the Effectiveness of SAM Firing

The Probability of Hitting a Single Target with One Missile

The hitting of a target by a SAM can be represented in the form of a complex random event consisting of two other random events occurring sequentially in time (Fig. 6.16).

The first random event consists in the fact that the missile warhead exploded precisely at the given point in space with coordinates x, y, z relative to the target. The probability of this event is determined by the law of errors f(x, y, z) accompanying the firing.

The second random event consists in having the contact elements of the missile warhead which has exploded precisely at the given point with the coordinates x, y, z, hit the target. The probability of this event is determined by the coordinate law of target destruction G(x, y, z).

Consequently, the probability of hitting a target with one missile is:

$$P_1 = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} f(x, y, z)\, G(x, y, z)\, dx\, dy\, dz. \tag{6.82}$$

The function f(x, y, z) differs from zero only in a certain (noninfinite) volume around the target. Integration also occurs in this volume.

The dependence (6.82) is represented in the form:

$$P_1 = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} f(y, z)\, f_2(y, z)\, G_0(y, z)\, dy\, dz, \tag{6.83}$$

where f(y, z)--the law of errors in guiding the missile to the target;
f_2(y, z)--the dependence of the probability of proximity fuze activation upon guidance errors;
G(y, z)--conditional coordinate law of target destruction.

The procedure for calculating the integral (6.83) depends upon the type of subintegral functions.

The first case. The guidance errors are subordinate to a circular law ($\sigma_y = \sigma_z = \sigma$), the dispersion center coincides with the target, that is, the density of the miss distribution probability is:

$$f(r)=\frac{r}{\sigma}e^{-\frac{r^2}{2\sigma^2}}. \qquad (6.84)$$

A circular-type law of target destruction is:

$$G_0(r)=1-e^{-\frac{\delta_0^2}{r^2}}. \qquad (6.85)$$

The radius for the activation of the proximity fuze surpasses the maximum value of the guidance error. Then

$$P_1=1-\frac{\sqrt{2}\delta_0}{\sigma}K_1\left(\frac{\sqrt{2}\delta_0}{\sigma}\right). \qquad (6.86)$$

where K_1--a function the values of which are given in Table 6.2.

Table 6.2

χ	$K_1(\chi)$	χ	$K_1(\chi)$	χ	$K_1(\chi)$	χ	$K_1(\chi)$
0,0		2,5	0,07389	5,0	0,004045	7,5	0,0002653
0,1	9,8538	2,6	0,06528	5,1	0,003619	7,6	0,0002383
0,2	4,7760	2,7	0,05774	5,2	0,003239	7,7	0,0002141
0,3	3,0560	2,8	0,05111	5,3	0,002900	7,8	0,0001924
0,4	2,1844	2,9	0,04529	5,4	0,002597	7,9	0,0001729
0,5	1,6564	3,0	0,04016	5,5	0,002326	8,0	0,0001554
0,6	1,3028	3,1	0,03563	5,6	0,002083	8,1	0,0001396
0,7	1,0503	3,2	0,03164	5,7	0,001866	8,2	0,0001255
0,8	0,8618	3,3	0,02812	5,8	0,001673	8,3	0,0001128
0,9	0,7165	3,4	0,02500	5,9	0,001499	8,4	0,0001014
1,0	0,6019	3,5	0,02224	6,0	0,001344	8,5	0,00009120
1,1	0,5098	3,6	0,01979	6,1	0,001205	8,6	0,00008200
1,2	0,4346	3,7	0,01763	6,2	0,001081	8,7	0,00007374
1,3	0,3725	3,8	0,01571	6,3	0,0009691	8,8	0,00006631
1,4	0,3208	3,9	0,01400	6,4	0,0008693	8,9	0,00005964
1,5	0,2774	4,0	0,01248	6,5	0,0007799	9,0	0,00005364
1,6	0,2406	4,1	0,01114	6,6	0,0006998	9,1	0,00004825
1,7	0,2094	4,2	0,009938	6,7	0,0006280	9,2	0,00004340
1,8	0,1826	4,3	0,008872	6,8	0,0005636	9,3	0,00003904
1,9	0,1597	4,4	0,007923	6,9	0,0005059	9,4	0,00003512
2,0	0,1399	4,5	0,007078	7,0	0,0004542	9,5	0,00003160
2,1	0,1227	4,6	0,006325	7,1	0,0004078	9,6	0,00002843
2,2	0,1079	4,7	0,005654	7,2	0,0003662	9,7	0,00002559
2,3	0,09498	4,8	0,005055	7,3	0,0003288	9,8	0,00002302
2,4	0,08372	4,9	0,004521	7,4	0,0002953	9,9	0,00002027
						10,0	0,00001865

The letter χ in Table 6.2 designates $\sqrt{2}\delta_0/\sigma$.

Example. To calculate the probability P_1, if $\sigma_y = \sigma_z = 10$ m and $\delta_0 = 25$ m.

Solution: $\chi = \sqrt{2}\cdot 25/10 = 3.54$.

According to the table $K_1(3.54) = 0.021$; $P_1 = 1 - 3.54\cdot 0.021 = 0.926$.

The second case. The laws of the guidance errors and the activation of the proximity fuze are the same as in the first case.

The target destruction law is described by a function of the type:

$$G(r) = e^{-\frac{r^2}{2R_0^2}}. \qquad (6.87)$$

Then

$$P_1 = \frac{1}{1+\left(\frac{\sigma}{R_0}\right)^2}. \qquad (6.88)$$

Example. To calculate the probability P_1, if $\sigma_y = \sigma_z = 10$ m, $R_0 = 30$ m.

Solution:

$$P_1 = \frac{1}{1+\frac{10}{30}} = 0.9.$$

The third case. The missile guidance errors are subordinate to a circular law ($\sigma_y = \sigma_z = \sigma$), the dispersion center does not coincide with the target ($y_0 \neq 0$ and $z_0 \neq 0$), that is, the probability density for the distribution of misses is:

$$f(r) = \frac{r}{\sigma} e^{-\frac{r^2+r_0^2}{2\sigma^2}} I_0\left(\frac{rr_0}{\sigma^2}\right). \qquad (6.89)$$

where

$$r_0 = \sqrt{y_0^2 + z_0^2}.$$

The target destruction law is described by the function:

$$G(r) = e^{-\frac{r^2}{2R_0^2}}.$$

The law for the activation of the proximity fuze is unlimited, hence

$$P_1 = \frac{R_0^2}{R_0^2+\sigma^2} e^{-\frac{r_0^2}{2\sigma^2}\left(1-\frac{R_0^2}{R_0^2+\sigma^2}\right)}. \qquad (6.90)$$

Example. To calculate the probability P_1, if $\sigma_y = \sigma_z = 10$ m, $R_0 = 30$ m, $r_0 = 15$ m.

Solution:

$$P_1 = \frac{30^2}{30^2+10^2} e^{-\frac{15^2}{2\cdot 10^2}\left(1-\frac{30^2}{30^2+10^2}\right)} = 0{,}80.$$

The fourth case. The laws of guidance errors and the activation of the proximity fuze are the same as in the third case.

The target destruction law is of a circular type:

$$G(r) = 1 - e^{-\frac{\delta_0^2}{r^2}}.$$

Hence

$$P_1 = \int_0^\infty \frac{r}{\sigma^2} e^{-\frac{r^2 + r_0^2}{2\sigma^2}} I_0\left(\frac{r_0 r}{\sigma^2}\right)\left(1 - e^{-\frac{\delta_0^2}{r^2}}\right) dr. \quad (6.91)$$

The dependence (6.91) is calculated by numerical integration methods.

The fifth case. The guidance errors are subordinate to an eliptical law ($\sigma_y < \sigma_z$), the dispersion center coincides with the target, that is, the probability density for the distribution of misses is:

$$f(r) = \frac{r}{\sigma_y \sigma_z} e^{-r^2 \frac{\left(\sigma_y^2 + \sigma_z^2\right)}{4\sigma_y^2 \sigma_z^2}} I_0\left(\frac{r^2\left(\sigma_y^2 - \sigma_z^2\right)}{4\sigma_y^2 \sigma_z^2}\right). \quad (6.92)$$

The target destruction law is of a circular type

$$G(r) = e^{-\frac{r^2}{2R_0^2}}.$$

The radius for the activation of the contact fuze is limited by the amount r_{max}.

Hence

$$P_1 = \frac{2a_1}{1 + a_1^2 + 2a_2^2} Je(K, \tau), \quad (6.93)$$

where

$$a_1 = \frac{\sigma_y}{\sigma}; \quad a_2 = \frac{\sigma_y}{R_0};$$

$$K = \frac{1 - a_1^2}{1 + a_1^2 + 2a_2^2};$$

$$\tau = \frac{1 + a_1^2 + 2a_2^2}{4\sigma_y^2} r_{max}^2;$$

$Je(K, \tau) = \int_0^\tau e^{-t} I_0(K, t)\, dt$ — tabular function given in Table 6.3.

Example. To calculate the target kill probability if $\sigma_y = 5$ m; $\sigma_z = 10$ m; $r_{max} = 20$ m; $R_0 = 30$ m.

Solution: $a_1 = 5/10 = 0.5$; $a_1^2 = 0.25$; $a_2 = 5/30 = 0.166$; $a_2^2 = 0.027$.

$$K = \frac{1 - 0{,}25}{1 + 0{,}25 + 2 \cdot 0{,}027} = 0{,}577;$$

$$\tau = \frac{1 + 0,25 + 2\cdot 0,027}{4\cdot 5^2}\cdot 20^2 = 5,216.$$

According to Table 6.3, $J_e = 1.175$, hence $P_1 = \frac{2\cdot 0.5}{1.304} = 1.175 \simeq 0.90$.

Table 6.3

τ	K values					
	0	0,2	0,4	0,6	0,8	1,0
0,0	0	0	0	0	0	0
0,2	0,1813	0,1813	0,1814	0,1815	0,1816	0,1818
0,4	0,3297	0,3298	0,3303	0,3311	0,3322	0,3337
0,6	0,4512	0,4517	0,4530	0,4554	0,4586	0,4629
0,8	0,5507	0,5516	0,5545	0,5593	0,5661	0,5749
1,0	0,6321	0,6337	0,6386	0,6468	0,6584	0,6736
1,2	0,6988	0,7012	0,7086	0,7209	0,7386	0,7620
1,4	0,7534	0,7567	0,7669	0,7841	0,8089	0,8422
1,6	0,7981	0,8025	0,8157	0,8383	0,8712	0,9157
1,8	0,8347	0,8401	0,8566	0,8850	0,9267	0,9839
2,0	0,8647	0,8712	0,8910	0,9255	0,9766	1,0426
2,2	0,8892	0,8968	0,9201	0,9607	1,0217	1,1025
2,4	0,9093	0,9179	0,9446	0,9916	1,0627	1,1642
2,6	0,9257	0,9354	0,9655	1,0186	1,1001	1,2183
2,8	0,9392	0,9499	0,9831	1,0424	1,1345	1,2699
3,0	0,9502	0,9618	0,9982	1,0635	1,1661	1,3195
3,2	0,9592	0,9718	1,0110	1,0822	1,1953	1,3672
3,4	0,9666	0,9800	1,0220	1,0988	1,2223	1,4132
3,6	0,9727	0,9868	1,0314	1,1136	1,2475	1,4578
3,8	0,9776	0,9925	1,0394	1,1268	1,2708	1,5010
4,0	0,9817	0,9971	1,0463	1,1386	1,2926	1,5430
4,2	0,9830	1,0010	1,0522	1,1492	1,3130	1,5839
4,4	0,9877	1,0043	1,0574	1,1587	1,3320	1,6237
4,6	0,9899	1,0070	1,0619	1,1679	1,3499	1,6625
4,8	0,9918	1,0092	1,0657	1,1749	1,3666	1,7005
5,0	0,9933	1,0111	1,0690	1,1818	1,3823	1,7376
5,4	0,9955	1,0140	1,0743	1,1937	1,4110	1,8025
5,8	0,9970	1,0160	1,0783	1,2034	1,4369	1,8686
6,2	0,9980	1,0174	1,0814	1,2114	1,4590	1,9452
6,6	0,9986	1,0183	1,0837	1,2180	1,4792	2,0097
7,0	0,9991	1,0190	1,0854	1,2237	1,4972	2,0722

The Probability of Hitting a Missile with n Missiles

In calculating the probability of hitting a target with n missiles, one must take into account the nature of the target from the viewpoint of the possibility of the accumulation of damage as it is successively fired on by SAM.

If there is no accumulation of damage and the probabilities for the hitting of the target by each missile are the same, then the probability of hitting the target by n missiles is:

$$P_n = 1-(1-P_1)^n. \qquad (6.94)$$

The amount of P_n, with the various values of P_1 and n is given in Table 6.4.

Table 6.4

P_1	P_n				
	$n=2$	$n=3$	$n=4$	$n=5$	$n=6$
0,10	0,19	0,27	0,35	0,41	0,47
0,15	0,28	0,39	0,48	0,56	0,62
0,20	0,36	0,49	0,59	0,67	0,74
0,25	0,44	0,58	0,68	0,76	0,82
0,30	0,51	0,66	0,76	0,83	0,88
0,35	0,58	0,72	0,82	0,88	0,92
0,40	0,64	0,78	0,87	0,92	0,95
0,45	0,70	0,83	0,91	0,95	0,97
0,50	0,75	0,87	0,94	0,97	0,98
0,55	0,80	0,91	0,96	0,98	0,99
0,60	0,84	0,94	0,97	0,99	0,995
0,65	0,877	0,967	0,985	0,995	0,998
0,70	0,910	0,973	0,992	0,998	0,999
0,75	0,937	0,984	0,996	0,999	0,9998
0,80	0,960	0,992	0,998	0,9997	
0,85	0,977	0,997	0,999		
0,90	0,990	0,999			
0,95	0,997	0,9999			

From the table it can be seen that, for example, with $P_1 = 0.7$, the launch of a second missile increases the target kill probability by 21 percent, for the third missile by 6.3 percent, and for the fourth missile by just 0.1 percent.

The number of missiles ensuring the set target kill probability P_n is calculated by the formula:

$$n = \frac{\lg(1 - P_n)}{\lg(1 - P_1)}. \tag{6.95}$$

With the accumulation of damage

$$P_{1,n} > P_{1,n-1} > \ldots > P_{1,2} > P_{1,1}$$

(the second figure below the P_1 index designates the sequence of the missile launch).

Hence

$$P_n = 1 - (1 - P_{1,1})(1 - P_{1,2}) \ldots (1 - P_{1,n}). \tag{6.96}$$

It is very difficult to determine with sufficient accuracy the value of the probabilities $P_{1,2} \ldots P_{1,n}$ for the given type of targets and firing conditions. In calculating the target kill probability by using n missiles, as a rule, formula (6.94) is employed and the accumulation of damage is considered by correction factors.

The probability of the normal functioning of the missile system for carrying out its combat mission (in firing) is usually termed the coefficient of combat work reliability K_{cw}.

Considering this coefficient:

$$P_n = K_{cw\ tot}[1-(1-K_{cw\ rc}P_1)^n], \tag{6.97}$$

where $K_{cw\ tot}$ and $K_{cw\ rc}$--the probability of normal functioning, during the firing, of the general-channel systems of the missile system and the elements of one missile channel, respectively.

The number of missiles which determine the given target kill probability is:

$$n = \frac{\lg\left(1 - \frac{P_n}{K_{cw\,tot}}\right)}{\lg(1 - K_{cw\,rc} P_1)}. \tag{6.98}$$

Example. Given: $P_1 = 0.8$; $K_{cw\ tot} = 0.98$; $K_{cw\ rc} = 0.96$. To determine the number of missiles for hitting a target with a probability $P_d = 0.95$.

Solution:

$$n = \frac{\lg\left(1 - \frac{0.95}{0.98}\right)}{\lg(1 - 0.96 \cdot 0.8)} = 2.4 \approx 3 \text{ missiles.}$$

Mathematical Expectation of Number of Hit Targets

In firing at a group of individual targets, the mathematical expectation of the number of destroyed air attack weapons equals the total of the kill probabilities of the individual targets fired on:

$$M_c = \sum_{i=1}^{N_t} P_i. \tag{6.99}$$

If the kill probabilities P_1 are the same, then

$$M_c = N_t P_1 \tag{6.100}$$

An assessment of the kill probability of at least m or precisely m out of N_t individual targets comes down to calculating:

With the same target kill probabilities--the corresponding terms of the binomial factorization

$$P(j = m) = C_{N_t}^m P^m (1 - P)^{N_t - m}; \tag{6.101}$$

$$P(j \geqslant m) = \sum_{j=m}^{N_t} C_{N_t}^m P^m (1 - P)^{N_t - m} \tag{6.102}$$

or

$$P(j \geqslant m) = 1 - \sum_{j=0}^{m-1} C_{N_t}^m P^m (1 - P)^{N_t - m}; \tag{6.103}$$

With different target kill probabilities--coefficients for a generating function of the type:

$$\prod_{i=1}^{N_t} [(1 - P_i) + P_i Z] = \sum_{j=0}^{N} P_j Z^j. \tag{6.104}$$

Example. The number of targets fired on $N_t = 3$. The probability of hitting the first target $P_1 = 0.7$, the second target $P_2 = 0.5$ and the third target $P_3 = 0.9$.

To determine the probability of destroying exactly two and no less than two targets.

Solution: $[(1-P_1)+P_1Z][(1-P_2)+P_2Z][(1-P_3)+P_3Z] = (0.3+0.7Z)(0.5+0.5Z)(0.1+0.9Z) = 0.015+0.185Z+0.485Z^2+0.315Z^3$; $P(j=2) = 0.485$; $P(j \geqslant 2) = 0.485+0.315 = 0.8$.

In firing at a group target, that is, a group of aircraft observed on a radar indicator in the form of a single blip under the condition that the lock-on by the tracking radar or the GSN for one or another aircraft in the group is equally probable and with the detonating of a SAM near the given aircraft the destruction of other aircraft in the group is excluded:

$$M_c = N\left[1-\left(1-\frac{P_1}{N}\right)^n\right]. \tag{6.105}$$

Example. If $N = 3$, $n = 6$, $P_1 = 0.9$, then $M_c = 3[1-(1-0.9/3)^6] = 2.64$.

On Estimating Firing Effectiveness with Countermeasures from the Airborne Target

Firing effectiveness with countermeasures by the airborne target (electronic jamming, maneuvering) can be reduced as a consequence of:

a) Increased guidance errors and reduced effectiveness of the SAM combat equipment:

$$P_1^* = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} f^*(y, z)\, f_2^*(y, z)\, G^*(y, z)\, dy\, dz \tag{6.106}$$

(the asterisk designates the corresponding laws under the conditions of target countermeasures);

b) A disruption of the normal functioning of the missile system's elements (the halt in the reception of information on the coordinates and parameters of the target's movement in the guidance loop, the breaking of the SAM guidance loop, the false activating of the radar fuze and so forth); the probability P_f of the system's normal functioning:

$$P_f = 1 - \prod_{i=1}^{K} (P_{org} P_{re} P_m)_i, \tag{6.107}$$

where K--the number of channels exposed to the effect of electronic jamming in the guidance and detonating of the SAM by the target;
P_{org}--probability that interference will be organized;
P_{re}--the probability that interference will be received by the receiver in the SAM channel to be neutralized;
P_m--the probability that the power of the jamming will be sufficient to disrupt the normal functioning of the guidance loop;

c) The leaving of the impact zone by the target by the time of the missile's arrival.

Assessing the target kill probability by n missiles is carried out considering all the above-listed factors

6.2.5. Impact and Launch Zones, the Capabilities of SAMS to Successively Fire on Targets

The SAMS Impact Zone

The impact zone of a SAMS is the name given to an area of space within which an airborne target is hit with a set probability. Considering the effectiveness of firing, it determines the missile system's range for altitude, distance and the heading parameter. The impact zone is displayed in the parametric system of coordinates and is characterized by the position of the far, near, upper and lower limits. A typical sectioning of the impact zone by a vertical bisector plane and a horizontal plane with forward firing is shown in Fig. 6.17.

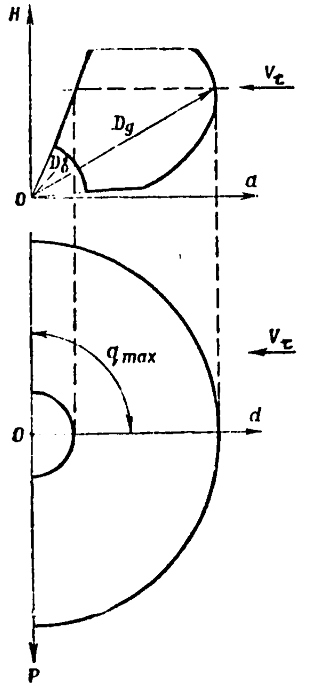


Fig. 6.17. An impact zone

The position of the limits of an impact zone is determined by a large number of factors related to the technical performance of the individual SAMS elements and the control loop as a whole; by the firing conditions and by the characteristics and parameters of the air target's movement. For the given SAMS, the dimensions of this zone depend upon target speed, its radar cross-section, the firing conditions (the presence of electronic jamming, maneuvering by the target) as well as upon the selected guidance method, the type of SAM and so forth.

The position of the far limit of the impact zone predetermines the required range for the operation of the target tracking radar

$$d_{req\ d} = d_f + V_t(t_{re} + t_f), \qquad (6.108)$$

where d_f--horizontal distance to far limit of impact zone;
t_{re}--the firing preparatory time;
t_f--the flight time of the SAM to the far limit of the impact zone.

If with any values of the radar cross-section, target speed and altitude the realized operating range of the radar is less than the required ($d_{ra} < d_{req\ d}$), then this leads to a reduction in the computed impact zone of a SAMS, that is, to a reduction in the maximum firing range.

The position of the realizable far and lower limits of the SAMS impact zone can also depend upon terrain. Fig. 6.18 shows that the maximum firing range for a low-flying target (under the condition of its limitation by the D value) is a function of the target's altitude and speed, the position's coverage angle and the firing preparatory time. Obviously the lower the altitude of the target the shorter the range at which it can be fired on.

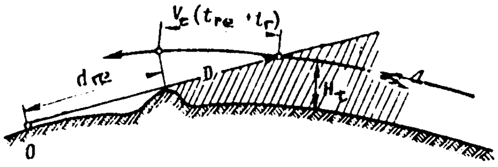


Fig. 6.18. Maximum firing range with limited radar operating range

Selecting the SAM Launch Moment

In order for a missile to impact with the target in the impact zone, the missile must be launched ahead of time considering the target and missile flight times to the point of impact.

The launch zone is the name given to an area of space through which the target passes at the moment of launching the SAM and the missile will impact with the target in the impact zone. For determining the limits of the launch zone from each point of the impact zone it is essential to lay off in a direction inverse to the target's course a segment equal to the product of the target's speed V_t by the missile's flight time to the given point. In Fig. 6.19 the most characteristic points of the launch zone are respectively designated by a', b', c', d' and e'.

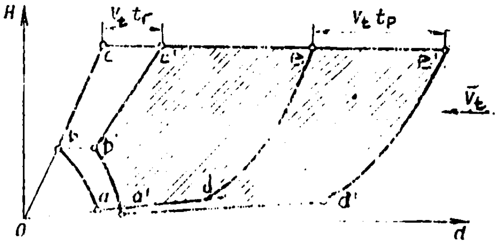


Fig. 6.19. The launch zone

The guaranteed launch zone is the name given to an area of space within which the target remains at the moment of the missile launch and the missile impacts with the target in the impact zone with any missile-evasion maneuver by the target. The boundaries of this zone are determined by the condition $t_i = t_{t\ req}$, where t_i--the flight time to the point of impact; $t_{t\ req}$--the time required for the target to escape by an abrupt maneuver outside the limits of the impact zone.

For each point of the guaranteed launch zone $t_i \leqslant t_{t\ req}$.

SAMS Capability for Successive Firing on Targets

The capability of a SAMS to successively fire on targets entering its launch zone is determined by the duration of the firing cycle and by the time required to reload the launchers and ready the missiles to launch.

The firing cycle is characterized by the time occupied by the target channel of the system in carrying out one firing at a target with the designated number of missiles. The time T_c includes the firing preparatory time T_p and the time necessary for firing on the target T_f:

$$\left.\begin{aligned} T_c &= T_p + T_f, \\ T_f &= t_i + t_n + t_{ev}, \end{aligned}\right\} \qquad (6.109)$$

where t_n--the total of the time intervals between the missile launches in the series;
t_{ev}--the evaluation time of the firing results.

The time of loading and readying the missiles for the launch T_{1d} influences the capability of the target channel for the successive firing on a target, if

$$T_{1d} \geqslant \frac{N_p}{n_p} T_c, \tag{6.110}$$

where N_p--the number of missiles per launcher for the given specific channel;
n_p--the number of missiles in a series in firing on the targets.

The capability of a SAMS target channel for refiring at the same target with n missiles is determined by the condition

$$T_f + t_n \geqslant T_{1z}, \tag{6.111}$$

where T_{1z}--the time the target remains in the launch zone.

The time T_{1z} is a function of the target's altitude H_t, the course parameter P_t and its speed V_t. It exceeds the time the target remains in the impact zone T_{iz} by the difference of the missile's flight times to the far and near limits of the impact zone:

$$T_{1z} = T_{iz} + (t_f - t_n). \tag{6.112}$$

The shifting of fire to the second target is possible if the time interval between the targets being fired on (Fig. 6.20) is:

$$\Delta t_{1,2} \geqslant \Delta t_{1,2\,\mathrm{min}} = (T_{0,1} + T_{p,2} + t_{c,2}) - T_{iz2}. \tag{6.113}$$

6.2.6. Basic Concepts of Firing Rules

Firing rules determine the procedure for preparing and conducting fire at airborne targets under various situational conditions. The recommendations of the firing rules, as a rule, include the procedure for assessing the air enemy, one's own weapons and the choice of targets to be destroyed, the choice of the method and procedure for preparing the initial data, the combat conditions, the guidance methods, the error compensation laws, the choice of the type of fire, the purpose for using the missiles, the determining of the methods for firing on the targets and the SAM launch moments, evaluating the firing results and so forth.

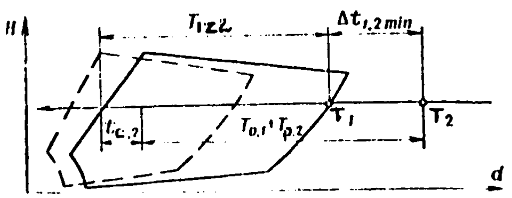


Fig. 6.20. On determining the capability of a single shift of fire

The working out of the given recommendations is done on a basis of assessing firing effectiveness at an airborne target with different variations of combat work. The variation which ensures the greatest reliability and economy of firing is considered the optimum variation.

The classification of airborne targets in the firing of SAM is carried out by a number of features: according to type such as bomber, fighter bomber or air-to-surface missile; by altitude such as low-flying and high altitude; for speed and so forth. Airborne targets are also divided by the nature of their blips observed on the radar indicator screens.

Radar targets are divided into individual and group targets as well as groups of targets.

An individual target is an aircraft or other air attack weapon observed on the indicator screen in the form of an individual blip.

By a group target one understands a group of aircraft (air attack weapons) which cannot be resolved by the radar and are observed on the indicator screens in the form of a single moving blip. The ability to distinguish group targets from individual ones is achieved by operator experience and by the characteristic features of the target blips. Characteristic of a group target is an increased fluctuation and increased dimensions of the blip, an unique type of blip fluctuation, an increased detection range and so forth.

A group of targets is the name given to several aircraft or other air attack weapons observed on the radar indicator screen in the form of individual blips.

The basic means of countering SAM firing is to jam the radars as well as other electronic equipment of the SAMS and execute an evasive maneuver.

An evasive maneuver by a target in terms of the time and place of execution is usually divided into a maneuver against control and a maneuver against firing.

A maneuver against control is carried out prior to the launching of the SAM with the task of complicating fire control by the SAMS as well as the direct preparations for firing by the subunits, thereby reducing the number of firings at the airborne targets and their effectiveness. This type of maneuver can be executed both by individual targets and particularly by a group of aircraft the actions of which are synchronized in time.

A maneuver against firing is executed after the launching of the SAM in the task of avoiding it and reducing firing effectiveness.

The type of target, its composition, the coordinates and parameters of movement, the counterprocedures and their effectiveness predetermine the choice of combat operating conditions for the SAMS as well as the method of target tracking, the guidance method, the type of fire, the number of missiles to be used and the choice of the SAM launch moment.

In the destroying of a target by a SAM, two types of fire are possible: with individual missiles and with a series of missiles.

The firing of individual missiles is a type of fire whereby the launch of each successive missile against the target is done after assessing the firing results of the previous missile. This can be employed if the target remains long in the launch zone and there is no need to shift fire to another target.

The firing of a series of missiles is a type of fire when the firing on the target is done by a designated number of missiles with a set pace. The missile launch pace excludes the possibility of a preliminary assessment of the firing results by each missile.

The time a target remains in the impact zone of a SAMS is extremely limited. For this reason the airborne target should be dependably destroyed with the first series of missiles.

Firing effectiveness depends substantially upon the degree to which the procedure for its preparation and execution conforms to the situational conditions, that is, the ability to apply the basic recommendations of the firing rules in destroying the air enemy.

6.3. Tactics of Antiaircraft Missiles Subunits

6.3.1. Principles in the Combat Employment of Antiaircraft Missile Subunits

Combat Tasks of Subunits

The combat task of antiaircraft missile subunits is to destroy the air enemy in the aim of protecting the defended installations, covering the troops and preventing the air attack weapons from flying through the fire zone. They carry out their tasks by combat.

Combat is the organized repelling of an enemy air strike and the basic content of this is firing to destroy the air attack weapon in the aim of carrying out the combat task. Combat is conducted with the wide employment of the maneuvering of fire and resources. Combat is exceptionally rapid, dynamic and decisive. It starts with the moment of opening fire against the air enemy and terminates by the enemy's destruction or by the ceasing of fire.

The carrying out of the task of not preventing the enemy to attack the defended object is achieved by destroying the airborne targets on the approaches to the installation before the mission accomplished line.

By the mission accomplished line (MAL) one understands a line having reached which the air enemy can hit the installation with weapons not destroyed by the antiaircraft missile subunits. The distance of the MAL from the boundaries of the installation is (Fig. 6.21)

$$L_{mal} = R_{we} + A, \qquad (6.114)$$

where R_{we}--the radius of effective action for the weapons employed by the enemy against the installation;

A--bomb drift (the launch range of a missile not destroyed by the SAM and the required range for destroying a cruise missile).

The amount of bomb drift depends upon the height and speed of the aircraft as well as upon the ballistic properties of the bomb itself. Within the range of possible altitudes for modern aircraft, the amount of bomb drift varies widely. The bomb

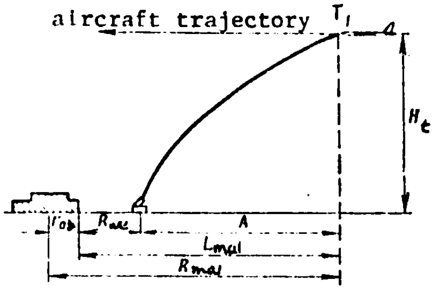


Fig. 6.21. On determining the mission accomplished line

drift for a certain characteristic time (the time of the bomb's falling from a certain altitude at a certain speed) is shown in Table 6.5.

The System of Antiaircraft Missile Fire

The strength of defenses is determined primarily by a skillfully organized fire system.

By a system of antiaircraft missile fire one understands the combined firing of the antiaircraft missile subunits which has been planned and organized for carrying out the combat task under various situational conditions. The fire system should consider the possible variant actions of the air enemy, the particular features of the defended installation, the area of combat operations and the terrain, the casks and capabilities of the cooperating men and equipment.

Table 6.5

H, м	V_t, м/с										
	280	350	420	490	555	625	695	765	835	905	975
1 000	3,45	4,05	4,35	—	—	—	—	—	—	—	—
2 000	4,70	5,35	5,70	6,20	—	—	—	—	—	—	—
3 000	5,56	6,35	6,85	7,35	7,60	—	—	—	—	—	—
4 000	6,35	7,15	7,75	8,35	8,65	—	—	—	—	—	—
5 000	7,00	7,95	8,60	9,15	9,60	—	—	—	—	—	—
6 000	7,65	8,55	9,35	9,70	10,35	—	—	—	—	—	—
7 000	8,30	9,20	10,00	10,70	11,20	—	—	—	—	—	—
8 000	8,80	9,80	10,65	11,50	11,90	—	—	—	—	—	—
9 000	9,25	10,35	11,25	12,10	12,70	13,30	—	—	—	—	—
10 000	10,10	10,90	11,90	12,90	13,45	14,00	14,70	—	—	—	—
15 000	11,90	14,85	15,65	17,15	18,45	19,10	20,80	21,60	—	—	—
20 000	14,30	17,00	19,90	22,10	24,20	26,20	27,90	29,90	31,80	—	—
22 000	15,70	18,75	22,00	25,00	27,20	29,60	31,80	34,10	36,50	38,9	—
25 000	—	—	—	—	—	—	—	—	41,60	44,2	46,7
30 000	—	—	—	—	—	—	—	—	—	54,7	57,9

The creation of a fire system is achieved by deploying the subunits on the terrain, by carrying out a range of jobs to ensure effective firing by each of them and by organizing fire control of the subunits.

The basic characteristics of the fire system are the dimensions of the zone of antiaircraft missile fire, the amount of overlapping in the realized impact zones μ, fire density D_{fi}, the number of firings up to the designated lines N_{ctp} and the effectiveness of the firings P_n.

The fire zone is the name given to an area of space within which the subunits deployed in battle formation can hit the airborne targets. The dimensions of the fire zone are predetermined by the dimensions of the SAM impact zones and their reciprocal position. For a graphic determination of the dimensions of the antiaircraft missile fire zone, for the given altitude it is essential to plot the impact zone realizable by each SAMS and fit them into a common external and internal configuration (Fig. 6.22).

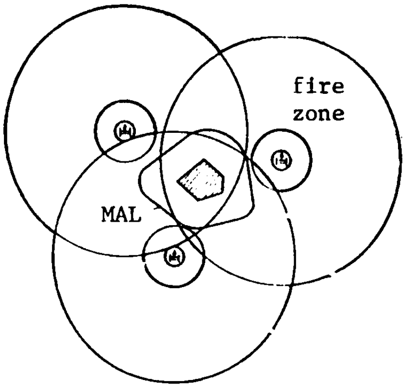


Fig. 6.22. A zone of antiaircraft missile fire

The overlapping factor of the realized impact zones describes the capability of concentrating antiaircraft missile fire for destroying airborne targets at one or another point of the fire zone.

The density of antiaircraft missile fire is the number of firings per minute which can be carried out by the subunits in repelling an enemy air attack.

This is calculated for directions and altitudes:

$$D_{fi} = \sum_{i=1}^{K_{pa}} c\, D_{fil}, \qquad (6.115)$$

where D_{fi}--fire density created by the SAMS;
D_{fil}--fire density of SAMS i;
K_{pa}--the number of SAMS participating in repelling the enemy air attack from the given direction in the given range of altitudes.

The number of firings to the set lines is assessed in terms of directions and altitudes:

$$N_{\text{стр}} = \sum_{i=1}^{K_{pa}} N_{\text{стр}\,i}, \qquad (6.116)$$

where $N_{ctp\ i}$--the number of firings conducted up to a set line by subunit i.

With the entry of the targets into the fire zone simultaneously, the number of firings is a function of the depth of shifting the impact zone of the SAMS beyond the given line h_i, of the firing cycle T_c and target speed.

The missile's flight time and, consequently, the time of the firing cycle depend upon the position of the point of impact of the SAM with the target in the impact zone. A second firing by subunit i against a target is possible (Fig. 6.23) if the flight time of the target in the impact zone up to the given line is $\frac{h_i}{V_t} \geqslant T_{ti,2}$, and a third firing is possible if $\frac{h_i}{V_t} > T_{ci,2} + T_{ci,3}$,

where $T_{ci,2} = t_{re\ i} + t_{i,2}$;

$T_{ci,3} = t_{re\ i} + t_{i,3}$;

t_{re}--the firing preparatory time (the work time of subunit i);

$t_{i,2}$, $t_{i,3}$--the missile flight time to the point of impact in carrying out second and third firings, respectively.

With an overflight length $t_o > 0$, the number of firings is:

$$N_{\text{стр}\,i} = \left(1 + \frac{t_o + T_{sti}}{T_{ci}}\right) \leqslant \frac{Q_i}{n_p}, \tag{6.117}$$

where T_{sti}--the time the targets remain in the SAMS launch zone;

Q_i--the number of rockets which can be used by the subunit in repelling the attack;

n_p--the consumption of missiles in one firing;

T_{ci}--the average value of the firing cycle.

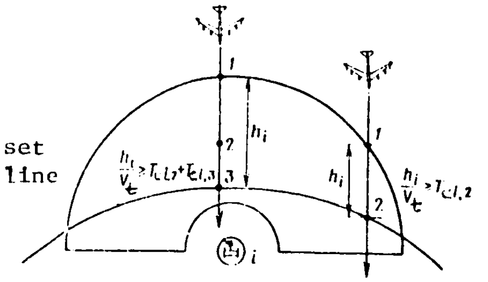


Fig. 6.23. On determining the number of firings N_{ctpi}

Firing effectiveness describes the reliability of destroying the airborne target and is determined by the probability of hitting the target during the diring under various situational conditions. Its value is a function of the probability of the hitting of the target with one missile and missile consumption in the firing.

With a graphic representation of a system of antiaircraft missile fire, on a map (diagram) one plots the expected routes of flight for the air enemy, the location of the subunits and their realizable impact zones; in terms of each route one establishes and visibly depicts the subunits which can participate in repelling the attack as well as their total fire densities and number of firings. Other data characterizing the fire system are also plotted on the map (diagram).

Indicators for the Combat Capabilities of Subunits

By combat capabilities of a subunit (unit) one understands the ability of the subunit (unit) to carry out the combat tasks under various situational conditions.

Combat capabilities are determined by the composition and manning levels of the subunit (unit), by the tactical-technical performance and combat properties of the weapons, by the level of political, combat and moral-psychological training of the personnel and by the quality of measures to support the combat operations.

Combat capabilities are determined by an aggregate of indicators: by fire capability, by cover capabilities, by the time capabilities for preparing for combat, by maneuvering capabilities and so forth.

Fire capabilities are the ability of a subunit deployed in battle formation and ready for combat to destroy the air enemy under various situational conditions. A generalized indicators of fire capabilities is the expectation of the number of destroyed air attack weapons during an overflight of a given length M_{fc}, while the particular indicators are the number of firings and their effectiveness:

$$M_{fc} = \sum_{j=1}^{N_{\text{стр.}t}} P_{nj}, \qquad (6.118)$$

where $N_{ctp\ t}$--the number of air attack weapons which can be fired on by the subunit (unit);

P_{nj}--the probability of fitting the air attack weapon in the firing.

The amount M_{fc} is calculated for directions and altitudes and depends upon the number of SAMS involved in repelling the attack and their fire productivity.

With a given variation of an attack by an air enemy, the number of firings $N_{ctp\ t}$ and the mathematical expectation of the number of destroyed air attack weapons M_{fc} are determined by "drawing" the target routes through the zone of antiaircraft missile firing in evaluating the possibility of the subunits firing on them sequentially in time.

Fire capabilities characterize the potential capabilities of a subunit (unit) to destroy airborne targets. The degree of realizing these capabilities depends upon the quality of the effective activities by the commander and staff in organizing and conducting combat operations.

Thus, an assessment of the fire capabilities of subunits (units) includes a determining of their potential values and the degree of possible realization under various situational conditions.

The amount of losses caused to the air enemy is:

$$M_t = K_p M_{fc}. \qquad (6.119)$$

Cover capabilities is the name given to the ability of a subunit in deploying into battle formation to create a solid zone of antiaircraft missile fire with one or another overlap factor for the kill zones.

As an indicator of cover capability one may employ the maximum value of the cover sector of an installation up to a given line ψ of the length of the solid cover line L_{co}.

The maximum value of the cover sector is:

$$\psi = \frac{K_s' 2\varphi_{max}}{\mu}. \qquad (6.120)$$

where K_S'--the number of SAMS in the subunit (the SAMS are usually considered as single-channel for a target);

μ--the overlap factor of the impact zones;

$2\phi_{max}$--maximum cover sector of an installation by one SAMS.

The amount of the angle $2\phi_{max}$ is a function of the spatial dimensions of the SAMS impact zone and the distance of the designated line from the installation (the radius R_{mal} and the depth of shifting the impact zone beyond this line h).

A completely definite distance of the SAMS position from the center of the installation R_{cs}^* corresponds to the value of the angle $2\phi_{max}$. The angle $2\phi_{max}$ can be calculated using the following dependences.

The first case. Horizontal distance to the far limit of the impact zone is greater than the radius of the mission accomplished line: $d_f \geqslant R_{mal} + r_{ob}$, where r_{ob}--the radius of the installation. Hence a SAMS located around the limits of the installation is capable of destroying airborne targets up to the set line with enemy attacks against the installation from any direction, that is, $2\phi_{max} = 360°$. This is illustrated by Fig. 6.24 in which the SAMS impact zones and their extension beyond the MAL are shown for overflight directions 1 and 2.

The second case. The horizontal distance d_f is less than the radius of R_{mal} but greater than a certain amount equal to $R_{mal} \cos q_{max}$, that is, $R_{mal} \cos q_{max} \leqslant d_f < R_{mal}$.

Hence the maximum amount of the cover sector is achieved in locating the SAMS on the middle of a chord $2d_f$ long in a circle with a radius R_{mal} (Fig. 6.25). Consequently,

$$2\varphi_{max} = 2\arcsin\frac{d_f}{R_{PB3}}. \qquad (6.121)$$

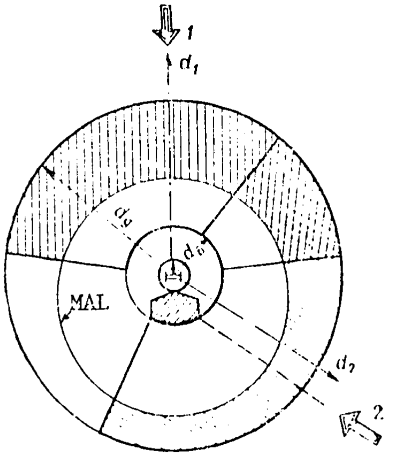


Fig. 6.24. $2\phi_{max} = 360°$ with $d_f \geqslant R_{mal} + r_{ob}$

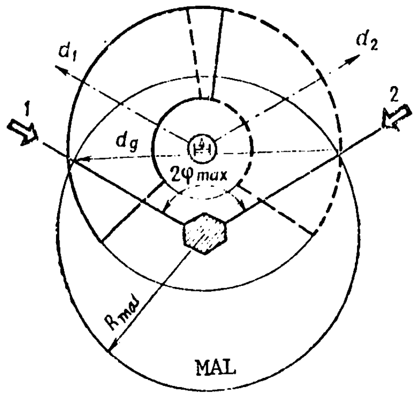


Fig. 6.25. Value of angle $2\phi_{max}$ with $R_{mal} \cos q_{max} \leqslant d_f < R_{mal}$

Here

$$R^{*}_{cs} = \sqrt{R^{2}_{mal} - d^{2}_{f}}. \tag{6.122}$$

The third case. The horizontal distance $d_f < R_{mal} \cos q_{max}$. Hence for the overflight direction 1 (Fig. 6.26) at point a (the intersection of the target's course with the MAL) it is essential to lay off the angle q_{max} and on this straight line the segment ao equal to d_f. Point o determines the position of the SAMS and the leg ob--the maximum parameter of the impact zone.

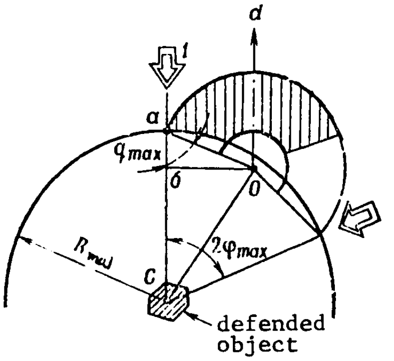


Fig. 6.26. Upon determining $2\phi_{max}$ with $d_f < R_{mal} \cos q_{max}$

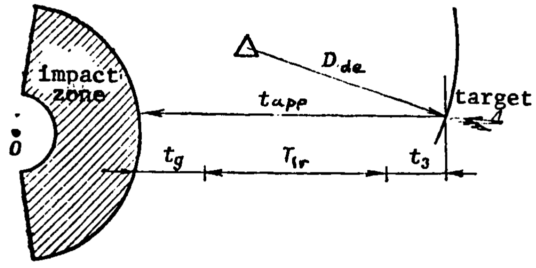


Fig. 6.27. Conditions for firing on a target according to the balance of time

From the geometric ratios:

$$\varphi_{max} = \operatorname{arcctg}\left(\frac{R_{PB3}}{d_f \sin q_{max}} - \operatorname{ctg} q_{max}\right); \tag{6.123}$$

$$R^{*}_{cs} = \frac{d_f \sin q_{max}}{\sin \varphi_{max}}. \tag{6.124}$$

The procedure for assessing the maximum cover angle will not change if a certain condition is imposed on the minimum amount of extending the impact zone beyond the mission accomplished line. In this instance in the calculation formulas the amount of the radius R_{mal} must be increased by the corresponding amount.

With a different configuration of the battle formation, the length of the solid cover line is:

$$L_{co} = \sum_{i=1}^{K_s} 2P_{for}. \tag{6.125}$$

With an increase in the overlap factor of the impact zones (with $\mu > 1$), the length of this line L_{co} will correspondingly shorten.

The fire and cover capabilities of a subunit (unit) in their aggregate determine the capability of creating a system of antiaircraft missile fire.

Time capabilities for preparing for combat characterize the time required for a subunit to move from a given state of combat readiness to readiness to launch the missiles T_{1r}.

The condition necessary for firing on a target at the far limit of the impact zone (Fig. 6.27) is:

$$T_{1r} + t_f \leqslant t_{app} - t_{de}, \tag{6.126}$$

where t_{app}--the approach time of the air enemy (the flight time of an airborne target up to the far limit of the SAMS impact zone from the moment of its detection by the forward radars);

t_{de}--the time lag in transmitting data on the detection of an airborne target to the subunit.

Maneuvering capabilities of a subunit are characterized by the time required to prepare for a march formation, to carry out the march, to deploy in combat status at the new position and prepare for firing. These are determined by the technical specifications of the SAMS and the transport as well as by the training of the crews, the position and the march conditions.

Battle Formations of Subunits

For carrying out combat tasks, the antiaircraft missile subunits are deployed in a battle formation.

A battle formation is the configuration of the subunit on the terrain for conducting combat.

The battle formation of an antiaircraft missile subunit should ensure:

a) The complete employment of the technical capability and combat properties of the weapons in repelling enemy air strikes from any direction;

b) The best employment of the terrain, concealment of the position and engineer organization and camouflage of the position in the aim of maintaining the battleworthiness of the subunit and personnel, the weapons and equipment;

c) The possibility of maneuvering.

The position of an antiaircraft missile subunit is usually called a launch position.

The battle formations of antiaircraft missile subunits comprise the basis of a unit's battle formation and the basic parameters of this are the distance of the launch positions from the defended installation and the intervals between them.

The destruction of the enemy at the approaches to the installation before reaching the mission accomplished line is achieved by so deploying the antiaircraft missile subunit relative to the installation's limits that the destruction of the enemy is ensured before reaching the designated limits.

The intervals between the launch positions I are chosen considering the creation of the designated fire density and other demands on the battle formation.

The calculation formulas for the values of I are:

For the condition of creating the required fire density $D_{fi\ re}$:

$$I = 2P_{for} \frac{D_{fil}}{D_{fi\ re}}, \qquad (6.127)$$

where D_{fil}--average fire density up to the MAL by one antiaircraft missile subunit;

For the condition of reciprocal fire cover of the subunit:

$$I = d_f - (R'_{mal} + V_t\tau), \qquad (6.128)$$

where R'_{mal}--the distance of the mission accomplished line with the distance of the enemy in terms of the launch position;
τ--the time required for firing the designated number of missiles against the target.

6.3.2. The Elaboration and Adoption of a Decision by the Commander for Combat Operations

The preparation of combat operations includes: the elaboration and adoption by the commander of a decision for combat operations; planning, the issuing of combat tasks to the subunits; the creating of a fire plan, the organizing of reconnaissance and control; the organizing of cooperation; organizing support for combat operations; exercising control and providing aid to the subunits in preparing for combat operations.

The process of elaborating a decision or plan is organized in the following sequence: analyzing the given task; calculating the time and issuing preliminary orders; evaluating the situation; working out an overall concept for the decision for combat operations; carrying out tactical calculations and analyzing possible variations of the antiaircraft missile fire plan; the taking of a preliminary decision using a map; reconnaissance of the terrain; adopting the decision.

By an analysis of the set task one understands an analysis of the overall concept of the senior commander's decision and one's own task and determining the role and place of one's own subunit in the combat operations as organized by the senior commander. As a result of analyzing the task, one establishes: what should be done by what time and what results must be achieved by one's subunit.

Assessing the situation includes an assessment of the air and ground enemy, the defended installation, the terrain and area of combat operations, the condition and capabilities of one's own subunits and cooperating resources as well as other elements which can influence the carrying out of the combat task.

An air enemy is assessed by analyzing the data received from the superior staff; by studying the effective strength, basing and combat capabilities of the opposing enemy; by analyzing its tactics.

As a result of assessing the air enemy and other elements in the combat situation, the following are determined: the possible effective strength of the resources which the enemy can employ for attacking the defended installation as well as the battle formation; the basic directions and possible configuration of the attacks; the speed and altitude of the air attack weapons; the most probable routes of attack at low and maximum low altitudes; the expected densities; approach time; possible counteractions and their effectiveness.

The conclusions from the assessment of the situation can also contain a forecast of the most probable variations of the air enemy's attack against the defended installation.

Assessing a ground (sea) enemy is carried out in anticipating the possibility of a direct contact with it, firing against the battle formations as well as the landing of airborne (amphibious) parties or sabotage groups.

As a result of assessing the ground (sea) enemy, measures are outlined to prevent a surprise attack, to repel enemy strikes, to increase the survivability of the subunits and to protect and defend the positions and command posts.

Assessing the defended installation includes determining the nature and dimensions of the installation, its vulnerability to attack by various weapons, the relative importance of the various elements of the installation, the position of the defended installation relative to other installations and so forth.

As a result of assessing the installation, the most probable methods of enemy actions are determined along with where the concentrating of enemy efforts is possible and what weapons might be employed against the installation. In assessing the terrain and area of combat operations, the commander studies the presence and condition of roads, the conditions for the deployment of the subunit into battle formation, engineer organization and camouflage, the influence of the terrain on organizing the fire plan, the organizing of reconnaissance as well as ground defenses, the possible actions of an air enemy at low and maximum low altitudes and so forth.

As a result of assessing the given situational element, it is determined to what degree the terrain features and the area of combat operations influence the carrying out of the combat task and what measures must be carried out to fully utilize the combat capabilities of the subunits.

Assessing the state and capabilities of one's own subunits consists in clarifying the composition, manning level and training level of the combat crews and determining the capability for creating a fire plan, organizing reconnaissance and control, ensuring the survival of the battle formations and the maneuvering of resources.

As a result of assessing his own subunits, the commander outlines measures which should be carried out in the aim of most effectively carrying out the set combat task.

In assessing cooperating forces it is determined to what degree the adjacent subunits and units will contribute to carrying out the set combat task and what measures must be carried out to organize cooperation with them.

Having analyzed the set combat task and having assessed the situation, the commander determines the possible nature of the air enemy's operations, the overall concept for combat operations, the possible variations for the configuration of the fire plan and the measures to support combat operations.

The overall concept is the main part of the decision or plan which determines the goal of combat operations and the basic idea for carrying it out; this is a decision expressed in the most general outline.

The overall concept determines the installations and sectors where the basic efforts are to be concentrated for defense, the overall nature of the fire plan and, consequently, the subunit's battle formation; the most characteristic variations of conducting combat and the measures to support combat operations.

The carrying out of tactical calculations is done in the aim of ensuring the feasibility and clarifying the overall concept as well as for selecting the most rational variation of the antiaircraft missile fire system and for organizing reconnaissance and control.

The commander's decision for combat operations includes the overall concept of combat operations; the battle formation, the combat tasks for the subunits and the times they are to be ready; the organization of reconnaissance and control; measures to restore the fire and control system and so forth.

The preliminary decision which determines the subunit's battle formation is adjusted in the process of reconnoitering the terrain and the elements of the battle formation.

Reconnaissance is conducted by a reconnaissance group (groups), the composition and tasks of which are determined depending upon the reconnaissance goals and the availability of time.

Having clarified the decision for organizing and conducting combat operations in the field, the commander reports it to the senior commander for confirmation after which he issues instructions to the chief of staff for working out the operational documents.

6.3.3. Support of Combat Operations

Support of combat operations is a range of measures conducted by the commanders and staffs in the aim of preventing an enemy surprise attack and providing an opportunity for the subunits in a prompt and organized manner to go into combat and carry out the task under any conditions.

The basic types of support for combat operations are: combat, special, technical and rear.

Combat Support

Combat support includes: reconnaissance and warning, camouflage, protection against weapons of mass destruction, ECM, engineer support, self-defense and security and so forth.

For the antiaircraft missile subunits, the most important component of reconnaissance is reconnaissance of the air enemy.

Reconnaissance of the air enemy ensures control of the subunits and firing in destroying the air enemy.

The basic demands on reconnaissance of the air enemy are:

1. Detection of airborne targets at ranges which ensure their firing on by the antiaircraft missile subunits at the far limit of the impact zone:

$$d_{re} = d_f + V_t(T_{c\ max} + T_{cp}), \tag{6.129}$$

where $T_{c\ max}$--maximum firing cycle of the SAMS;
t_{cp}--the working time of the command post which controls the fire of the subunits.

2. Determining the coordinates and parameters for the movement of the air targets with an accuracy ensuring the effective carrying out of the fire control problems of the subunits and firing against the air enemy.

3. The availability in the information of data on the overall air situation in the area of the subunits' combat operations making it possible to determine the number and type of targets, their composition, intervals and distance between them, battle formation, the countermeasures as well as to discover the overall plan of actions of the air enemy.

4. Reliability of the reconnaissance data, including in determining the nationality of the aircraft.

Identification of the aircraft is the most important task of the reconnaissance equipment and the promptness and reliability of carrying out this task determines the flight safety of friendly aircraft and the possibility of cooperating with fighters.

The organization of reconnaissance of an air enemy includes: the selection and preparation of positions for the reconnaissance equipment, organizing the obtaining of data on the air enemy and organizing control over the reconnaissance resources.

The positions of the reconnaissance and target designation stations are chosen on the basis of a careful analysis of visibility zones using a map and directly in the field in conducting reconnaissance and taking up positions. For adjusting the visibility zones the radars are overflown by friendly aircraft.

The data of radar reconnaissance are supplemented by other types of reconnaissance.

The organization of control of the reconnaissance resources consists in determining the procedures for conducting reconnaissance and transmitting data on the air enemy to the command post under various conditions, as well as in organizing control and cooperation communications.

Camouflage is one of the most important measures relating to the combat support of the subunits. This is carried out in the aim of concealing from the enemy the true position and actions of the subunits and to confuse it on their combat formation, state and tasks being carried out.

Camouflage should ensure surprise antiaircraft missile firing and impede the enemy in organizing and carrying out countermeasures against the control of the SAM firing.

Defense against weapons of mass destruction is organized in order to exclude or maximally reduce the exposure of the subunits to nuclear, chemical and biological weapons and to keep them ready to carry out the combat task.

Electronic countermeasures is a range of measures carried out in the preparations for and during combat to ensure antijamming capability in the fire and control system with enemy electronic countermeasures. The most important among these measures are: the correct choice of the elements of the battle formation and the position of one's equipment on the terrain, the observance of the requirements of radioelectronic camouflage, improving the skills of the combat crews in working under jamming conditions as well as destroying enemy radioelectronic equipment.

Engineer support for the combat operations of antiaircraft missile subunits include the engineer organization of the battle formation with shelters for the personnel and materiel, camouflage work to shelter the battle formations using available and regulation camouflage gear, simple work to repair roads and reinforce bridges using available equipment in the area, equipping the elements of ground defense and the immediate cover, carrying out fire safety measures, eliminating the consequences of an enemy attack and so forth.

The scope of these measures is predetermined by the tasks to be carried out by the subunits and by the conditions.

Self-defense and security are organized under any situation (with the location of the subunit at its position, on the march or at rest) and are aimed at excluding an enemy surprise attack, preventing its reconnaissance and sabotage groups from penetrating into the subunit's position and to ensure the prompt engagement of the subunits and the repelling of the enemy.

The ground defenses of a position are based upon the early organized fire plan consisting of firearms and various obstacles. The fire plan is so organized that there are no areas of terrain which cannot be seen or fired on in the approaches to the position. When necessary weapons and observers are moved forward beyond the limits of the position's territory. In the most dangerous sectors, machine gun fire is planned for; in the remaining sectors, fire from submachine guns and carbines. The antiaircraft machine guns are readied beforehand for firing both at air and ground targets.

Trenches are built for each weapon and shelters for the personnel.

Special and Technical Support

The most important types of special and technical support for the antiaircraft missile subunits are topographic and engineer-missile.

Topographic support is a system of measures to provide the combat operations of the subunits with the necessary data for fire control and for firing at airborne targets as well as for studying, evaluating and using the terrain in the interests of carrying out the combat mission.

Engineer-missile support is a system of measures to maintain the weapons in constant readiness for combat employment and to ensure the full utilization of their combat capability in the course of battle.

The requirement and supply of a subunit for missiles are figured in units of fire.

A unit of fire is the number of missiles per weapon unit (per antiaircraft missile system).

6.3.4. Principles in Controlling the Fire of Subunits in Combat

The Essence of Control

Control over the fire of the antiaircraft subunits is a most important component in the control of their combat operations. Fire control includes: analyzing the received task to destroy the air targets, assessing the situation, taking a decision to destroy the air enemy, assigning the fire tasks to the subunits, supervising the fulfillment of the set fire tasks and assessing the results of combat.

Antiaircraft missile combat is exceptionally rapid and dynamic. For this reason, fire control is carried out under the conditions of extremely limited time and can be organized by combining centralization and independent firing of the subunits.

By analyzing the set task one understands an analysis of the overall concept of the senior commander's decision to repel the enemy air strike, one's fire tasks and role in the combat operations.

As a result of analyzing the task it is possible to establish what airborne targets must be destroyed independently and in cooperation with other AD resources.

An assessment of the situation in fire control includes an assessment of the air situation (the air enemy and the actions of friendly aircraft), the condition and capability of one's own subunits, cooperating forces and the firing conditions.

An assessment of the air enemy includes, in the first place, determining its overall character and attack plan; the possible duration, effective fighting strength, basic sectors of the attack, the missions to be carried out and, secondly, an assessment of each air attack weapon as a target for the antiaircraft missile subunits, including: the composition of the target, its importance, altitude and speed, the heading parameters relative to the launch position, the approach time and the methods for parameters relative to the launch position, the approach time and the methods for countering control and firing.

An assessment of the state and capabilities of one's own subunits is made by analyzing information continuously received from them (reports and briefings) on the condition and combat activities based upon the commander's profound knowledge of the combat capabilities and performance of the weapons under various conditions and the combat crew training level.

An assessment of cooperating forces is made by analyzing information received from the superior command post, from adjacent subunits and one's own intelligence.

The firing conditions (the firing season and time of day, meteorological conditions, the presence of natural and artificial interference and so forth) are assessed from the viewpoint of their effect on firing effectiveness, the position of the feasible limits of the impact zones, the possible firing density of the subunits and the methods for firing on airborne targets.

The decision to destroy the air enemy is taken by the commander on the basis of analyzing the set task and assessing the situation. To take a decision means to determine the importance of the airborne targets and the overall concept of the engagement, to solve the problem of allocating fire to the targets, to clarify the methods of cooperation with other AD resources and particularly with the fighters and to outline measures to support the subunit's combat operations.

The choice of the variation for allocating the fire of the subunits to the airborne targets is the basis of the decision in fire control.

By the setting of fire tasks the commander's decision is given to the subunits. A fire task can include target designation (determining the target's location in space), the command to destroy the target and instructions on the procedure for firing. A maximum reduction in the time for transmitting the commander's decisions to the subunits can be achieved by employing signals or brief instructions for giving the fire tasks and by maximum utilization of automation.

In supervising the execution of the given fire tasks, it is essential to make certain that the lock-on of the SAMS assigned to destroy the targets has been correct. This can be achieved by comparing the target designation coordinates and the coordinates of the target detected and tracked by the system at the command post.

The assessing of the situation, the taking of the decision and the giving of fire tasks to the subunits in repelling an enemy air attack, as a rule, are carried out continuously and simultaneously for various air targets and in terms of the particular features of antiaircraft missile combat at one or another moment in time.

Demands Placed on Fire Control

Effectiveness is the basic demand on the control of fire by the subunits. Control should ensure the carrying out of the combat task by causing maximum losses to the air enemy considering the importance of the targets.

A general indicator of the effectiveness of fire control can be considered the ratio of the number of destroyed air attack weapons N_{dest} in repelling an enemy air attack to the number of air attack weapons N_{max} which could be destroyed in making maximum use of the fire capabilities of the subunits considering the importance of the targets:

$$K_d = \frac{N_{dest}}{N_{max}} . \qquad (6.130)$$

The importance of the targets is taken into account by weight factors.

The effectiveness of centralized fire control is predetermined by the following: the optimality of the adopted variation of allocating fire against the airborne targets, by the accuracy of issuing target designations and by the promptness of giving the fire tasks to the subunits (the efficiency of control).

The optimum variation of allocating fire is the one which ensures the highest effectiveness in carrying out a combat task.

The optimality of the distribution of fire is characterized by the coefficient K_{ca} which is the ratio of the correctly allocated air attack weapons N_{ca} to the number of correctly allocated air attack weapons N_{opt} which could be with the complete utilization of the fire capability of the subunits:

$$K_{ca} = \frac{N_{ca}}{N_{opt}}. \qquad (6.131)$$

A target is considered correctly allocated if it is fired on by the SAMS in the impact zone, if its importance is taken into account and the capabilities of the subunit assigned to destroy the target most fully conform to its characteristics and parameters of motion.

Formula (6.131) can also be represented in the following form:

$$K_{ca} = \frac{N_{opt} - n_1 - an_2}{N_{opt}} , \qquad (6.132)$$

where n_1--the number of air attack weapons not fired on by the subunits due to the non-optimality of fire distribution from the command post;
n_2--the number of air attack weapons fired on by the subunits with the incomplete utilization of their fire capabilities due to the same reasons;
α--weight coefficient.

The accuracy of giving the target designation predetermines the probability of immediate detection of the target assigned to the given SAMS for destruction. If the value of this probability is close to one, then from the target designation data the target is detected without a search and the working time of the subunit is determined by the time needed to prepare for firing. This also excludes the possibility of the confusing of targets by the subunits.

When it is necessary to search for the target, the time spent on its detection depends upon the search capability of the target tracking radar.

The directness of fire control describes the promptness of decision taking and issuing the fire tasks to the subunits, that is, the possibility of carrying out the tasks in terms of the available time.

The demand of the directness of fire control determines the positions of the extreme lines for setting fire tasks for the subunits (the target designation lines). The distance of this line from the subunit's position equals (Fig. 6.28):

for engaging the target at the far limit of the impact zone

$$d_{tdf} = d_f + V_t(t_{wk} + t_f); \qquad (6.133)$$

for engaging the target at the near limit of the impact zone

$$d_{tdn} = d_n + V_t(t_{wk} + t_n), \qquad (6.134)$$

where $d_t(d_b)$--distance to the far (near) limit of the impact zone;
t_{wk}--working time of subunit;
$t_f(t_n)$--flight time to far (near) limit of impact zone.

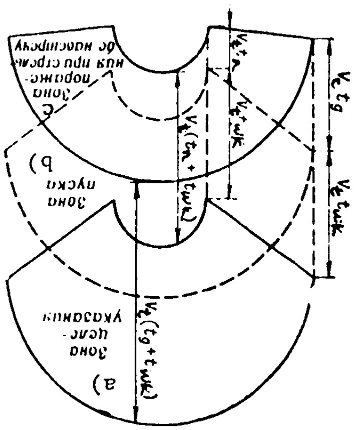


Fig. 6.28. Target designation zone

Key: a--Target designation zone; b--Launch zone; c--Impact zone with forward firing

The directness of fire control is achieved by creating the required depth of radar reconnaissance; by the correct organization, smooth and precise work of the command post crew whereby minimum time is spent on the control cycle; by reducing the working time of the SAMS by raising the accuracy of target designation from the command post and by increasing crew skills.

The required distance of target radar reconnaissance is

$$d_{req} = d_{td} + V_t(t_{lag} + t_{cp}), \qquad (6.135)$$

where t_{cp}--working time of command post which controls fire of subunit;
t_{lag}--time lag in target information (time from the moment of detecting the station by the reconnaissance and target designation station to the moment of displaying the information at the command post).

The requirement of directness of control does not mean the advisability of the premature issuing of fire tasks to the subunits. The giving of fire tasks to the subunits beforehand increases the possibility of counteractions by the airborne targets to control and firing (maneuvers, jamming and so forth).

Solving the Problems of Distributing Fire to the Airborne Targets

The distributing of fire against an air enemy comprises the basis of the commander's decision to destroy the enemy. This should correspond to the degree of importance of the airborne targets.

In distributing fire, calculation methods are employed for assessing the situation and solving the target allocation problem as well as previously elaborated principles and particular rules of fire control, the logical thinking, experience and intuition of the commander. The use of electronic computers for working out recommendations for the commander provides a significant effect in solving the fire distribution problem.

The algorithm of target distribution in all instances includes an evaluation of the following:

1. The possibilities of the entry of each target into the impact zone of each SAMS, that is, the determining of the subunits which could fire effectively against one or another airborne target.

The engagement of target i by SAMS j is possible if:

$$P_{ti} \leqslant P_{for\ j} \text{ and } H_{min\ j} \leqslant H_{ti} \leqslant H_{max\ j}. \qquad (6.136)$$

The fulfilling of the condition in (6.136) is determined by comparing the altitude and heading parameter of the target's movement with the maximum values of the impact zones of the antiaircraft missile complexes or by looking to sea what lead target route crosses the flat zones of what SAMS at the given altitude.

2. The possibilities of engaging the target considering its speed characteristics. The effective engaging of a target by a given SAMS is possible if:

$$V_{ti} \leqslant V_{max\ j},$$

where $V_{max\ j}$--the maximum capabilities of the SAMS in terms of target speed.

3. The possibilities of engaging the target by the given subunit in terms of available time. Engagement is possible if:

$$T_{app\ ij} \geqslant t_{td\ ij} + t_{wk\ j} + t_{n\ j}, \qquad (6.137)$$

where $T_{app\ ij}$--approach time of target i to near limit of impact zone of SAMS j;
$T_{td\ ij}$--time for giving fire task for target i to SAMS j.

4. The combat readiness of the subunit assigned to engage the target and the non-engagement in carrying out a combat task against another target.

If it is assumed that subunit i is to be involved in destroying target j with a shift in fire, then the possibility of such combat work is varified in terms of the time balance.

Having information on which of the targets can enter the impact zones of what subunits and in what sequence, it is essential to find the optimum variation for distributing fire against the airborne targets.

In taking the decision consideration is given to the condition of the subunits, the availability of missiles and the training level of the combat crews.

The Setting of Fire Tasks for the Subunits

A fire task includes target designation, the order to destroy the target and, when necessary, an instruction on the firing procedure.

Possible methods of target designation (TD).

Automatic beam guidance (bisectrix of the sector of view) from the guidance station for the missiles to the target assigned for destruction.

The method provides for the giving of target designation without time losses and with high accuracy. The accuracy of giving the TD is determined by errors in measuring target coordinates by the radars, by the errors of their reading and feeding into the control system.

By grid squares. Target designation is provided by transmitting the number of the square in which the target's projection is at a given moment. A grid is plotted on the plotting boards and indicators of the sender and receiver of the target designation. The grid squares are numbered in a certain manner. The accuracy of giving TD for indicators is limited by the value of the small square and for plotting boards depends also upon the time lag as well as the accuracy of depicting the air situation data on them.

By transmitting the azimuth, range and altitude of the target. The transformation of the target designation data, as a rule, is carried out by the receiver of the TD.

By fixing a uniform number to the air target blip on the indicators of the transmitter and receiver of the target designation or by giving a code sign to the indicator of the receiver of the TD.

The method is employed if the corresponding display and data transmission equipment is available.

From the reciprocal position of targets. The method comes down to indicating the position of the given target's blip relative to the blips of other targets observed on the indicator screens. Confusion of targets is dependably excluded only with a relatively short distance between the transmitter and receiver of the TD or in considering this distance in the display of the air situation.

6.4. Antiaircraft Artillery

6.4.1. The Essence of Firing at an Airborne Target and the General Characteristics of Antiaircraft Artillery Systems (Mounts)

Basic Concepts of Antiaircraft Artillery Firing

The essence of antiaircraft artillery firing at airborne targets comes down to solving the problem of the meeting of the projectile and a rapidly moving target at a certain point of space and at a certain moment of time and consists in sending off rounds (salvoes) each at new initial settings for a new target lead position calculating on hitting and destroying the target.

The gun is aimed not at point A_b (Fig. 6.29) where the target is at the moment of the round but rather at the lead A_y at which, according to the calculations, the shell should encounter the target. The triangle $0A_bA_y$ is called the azimuth prediction triangle in which the path of the target A_bA_y equals the target's velocity by the shell's flight time (prediction interval), $S = V_t t$, D_b and D_y--the slant ranges to the present position (the point where the target is at the moment of the round) and to the future position, respectively.

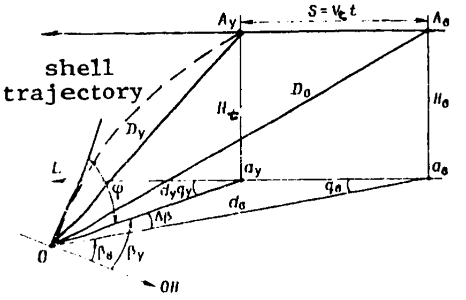


Fig. 6.29. Diagram for solving the prediction problem

In modern antiaircraft artillery systems (mounts), the prediction problem (determining the settings for firing) is solved continuously and virtually instantaneously by computers or the vertical aim-off mechanisms.

For solving the prediction problem, the following should be set: the geometric coordinates of the present position; the parameters of the target's movement; the hypothesis on the target's movement; the gun system, the shell and the fuze.

The preparation of the rounds includes:

1. Determining the coordinates of the target's present position and its parameters.

2. Determining the target's position at the moment of the round.

3. Solving the prediction problem which consists in determining the coordinates of the future position and the gun and fuze settings, in transmitting and receiving the settings (aiming the gun), in loading and getting off the round.

The present coordinates of a target which has been detected and assigned for destruction are determined as a result of its tracking by the fire control radar (FCR) or optical instruments. Determining the amount and direction of the target velocity vector, solving the prediction problem and determining the gun and fuze settings are carried out continuously by the antiaircraft fire control system (AAFCS) instruments. The obtained settings--the future bearing, the elevation and the number of fuze marks (for medium and large-caliber antiaircraft artillery)--are transmitted continuously by synchrotransmission to the guns which thus are always aimed at the future position. The guns are loaded and the rounds gotten off.

In the firing of medium- and large-caliber batteries, the target is destroyed by being struck by fragments of the projectile which explodes when the fuze is activated. The fuze setting conforms to the coordinates of the future position on the target's course. A hit can be achieved with an entire shell (percussion action) or by its blast effect, but the probability of a direct hit on the target and the exploding of the shell directly next to the aircraft is slight.

In the firing of small-caliber batteries, the target is hit, as a rule, as a result of the direct impacting of the shell in the target (percussion effect).

Hypotheses on the movement of an air target after a round.

The general hypothesis: over the prediction interval the target will move as it had prior to the round.

Particular hypotheses: 1) over the prediction interval a target moves rectilinearly, steadily and horizontally; 2) over the prediction interval a target moves rectilinearly and evenly in any plane; 3) over the prediction interval a target moves rectilinearly in an inclined plane with constant acceleration; 4) over the prediction interval a target moves at a fixed speed horizontally along a circular arc.

The choice of the hypothesis is determined by the technical performance of the AAFCS and by the actions of the airborne target. Other particular hypotheses are also possible.

Each hypothesis involves error since the actual movement of a target may not coincide with the assumed or hypothetical. The mistakes will be greater the longer the prediction interval.

The solving of the prediction problem comes down to finding the geometric coordinates of the future position and consists in matching in time t the path of the target and the shell with their various velocities.

The geometric coordinates of the future position are found by the combined solution to a number of dependences between the elements of the azimuth prediction triangle in an inclined or horizontal plane.

From $\triangle oa_b a_y$ (Fig. 6.29), it can be seen that the future horizontal range is:

$$d_y = \sqrt{d_n^2 + (V_t t)^2 - 2d_n V_t t \cos q_n}; \tag{6.138}$$

the aim-off into the azimuth is:

$$\sin \Delta\beta = \frac{V_t t \sin q_n}{d_y}; \tag{6.139}$$

the future bearing is:

$$\beta_y = \beta_n \pm \Delta\beta. \tag{6.140}$$

The shell's time of flight t is a function of the future range and altitude, that is:

$$t = f(d_y, H_y). \tag{6.141}$$

The dependences (6.138) and (6.141) together cannot be solved by ordinary procedures since d_y and t cannot be expressed one relative to the other. For this reason the solution to the prediction problem in the AAFCS and automatic sights is carried out by the successive approximation method.

In a number of instances (the preparation of barrage fire, theoretical research and so forth), the inverse problem can be solved, that is, from the set coordinates of the future position and the parameters of the target's movement to determine the present position. In this instance, from the coordinates of the future position it is possible to immediately find the time of flight t and the aim-off A_bA_y.

Gun laying is the name for giving the barrel the required position for firing. Laying for deflection and laying for elevation are done separately and independently of one another, although simultaneously.

Direct and indirect laying are employed in antiaircraft artillery.

Indirect laying consists in giving the gun the necessary direction for azimuth and elevation on the basis of data determined in the AAFCS or by calculation. The amount of the future bearing β_y is read off relative to the oriented stationary part of the gun, while the elevation ϕ is read relative to the stationary leveled part of the gun.

Direct laying is the name given to laying whereby the gun is aimed using the sight gear by direct sighting to the target.

With direct laying the target itself is the aiming point and the barrel is given a certain position relative to the target's line (considering the gun elevation σ and the lateral lead angle $\Delta\beta$) by setting the slant range to the target and the parameters of its movement on the sight.

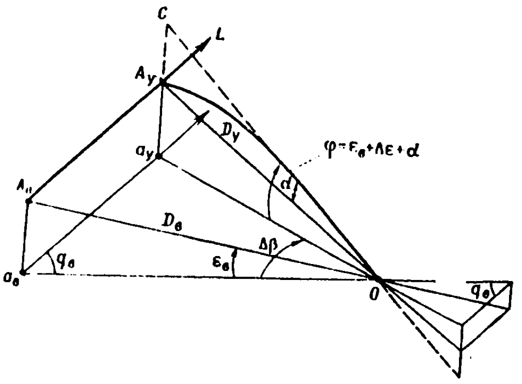


Fig. 6.30. Solving the prediction problem with a sight

In aiming the crosshairs of the collimators at the target and in feeding the input data into the sight for firing, in space two triangles are constructed (Fig. 6.30): the azimuth prediction triangle OA_bA_y and the ballistic triangle OCA_y. The axis of the bore is lined up along the line OC. Here consideration is given not only to the location of the future position relative to the present position but also the shell's decline in flight under the effect of the force of gravity:

$$\varphi = \varepsilon_{в} + \Delta\varepsilon + \alpha = \varepsilon_{в} + \sigma.$$

Artillery systems (mounts) have various sight gear and firing with direct laying requires consideration of the particular features of their design.

Antiaircraft Artillery Weapons

Many armies are armed with antiaircraft artillery systems and multibarrel rapid firing antiaircraft mounts predominantly on self-propelled chassis (ZSU) as well as antiaircraft machine guns (ZPU).

An antiaircraft artillery system includes antiaircraft cannons, a fire control radar (FCR), AAFCS equipment and power units.

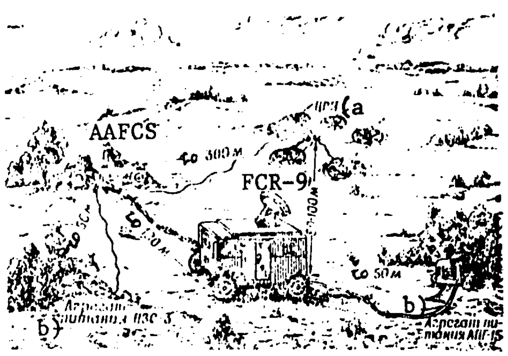


Fig. 6.31. Composition of an antiaircraft artillery system (for a 57-mm battery)

Key: a--Central distribution box;
b--Power unit

The antiaircraft cannon is designed for hitting airborne targets with shells within given altitude and range limits as well as ground and surface targets. Firing at airborne targets by large- and medium-caliber antiaircraft cannons is carried out with a small-caliber time-fused HE shell, as a rule, with projectiles having a percussion fuze. The system includes several guns of 1 caliber (from 4 to 8).

The fire control radar is used for detecting airborne targets, determining the coordinates of the target selected for engagement and transmitting these to the AAFCS.

The AAFCS, using data received from the FCR solves the prediction problem. The prediction problem is solved in terms of the selected hypothesis on the movement of the airborne target after the round. In coming out of the AAFCS the lead coordinates are sent to the cannons and they are automatically aimed at the future position.

The FCR and AAFCS together are called a radar instrument system (RIS).

In 1945-1954, 100-, 57- and 130-mm antiaircraft artillery systems were developed and introduced.

The composition and disposition of a 57-mm antiaircraft artillery system are shown in Fig. 6.31.

Antiaircraft guns and mounts include automated small-caliber antiaircraft cannons and autonomous radars and computers. These provide effective fire at a halt and in motion under any weather conditions.

The basic characteristics of certain models of such AA guns and mounts are given in Table 6.6.

6.4.2. Firing at an Airborne Target

The tasks in the firing of antiaircraft artillery include:

a) Destroying the aircraft, cruise missiles, helicopters and targets dropped on parachutes;

b) Destroying tanks, armored vehicles, sslf-propelled artillery mounts, infantry and other ground targets;

c) Destroying landing personnel, launches, pontoons, barges and other surface targets in coastal areas.

Table 6.6

state	model	shell weight kg	muzzle vel. m/s	maximum range, m		rate of fire, rpm
				alt.	dist.	
USA	20-мм 6-barrel AAC Vulcan	0,12	1050	2,0	5,4	3000
	40-мм coupled self-prop. AAC M-42	0.96	875	4.8	9.9	240
U.K.	20-мм AAC Мк20	0,12	1100	2,0	7,0	2000
France	40-мм AAC M39/53	0,9	825	3,2	10,0	120
	30-мм coupled self-prop. AAC AMX-51	0,39	1080	3,0	10,2	1300
FRG	35-мм coupled self-prop. AAC Gepard	0,55	1175	5,5	11,0	1100

Antiaircraft artillery can also fire, as a rule, for self-defense at ground and surface targets.

Zones of Antiaircraft Guns

For a gun with any elevation there is a certain limit range of fire. Each gun cannot fire accurately at near vertical angles, it has a maximum elevation and as a consequence of this an inner zone is formed called the dead zone.

The impact zone of a gun is the space within which a given gun can throw a projectile. It is limited by the gun's range curve, the dead zone and horizon. The range curve is the geometric locus of points corresponding to the maximum slant ranges with different elevations.

The engagement zone is the name given to the portion of the impact zone within which a proximity burst or direct hit is possible (in the firing of small-caliber antiaircraft artillery, the impact fuzes for ensuring the safety of friendly troops and installations on the ground are equipped with self-destruction devices).

The flat engagement zone [engagement zone related to height of attack] is a circular zone obtained as a result of sectioning the engagement zone by a horizontal plane at a certain altitude (Fig. 6.32). The dimensions of the flat engagement zone are characterized by the radius R which with an increase in altitude is reduced, as well as by the dead zone radius r which increases with an increase in altitude.

The dimensions of the flat engagement zones of a 57-mm antiaircraft cannon are given in Table 6.7.

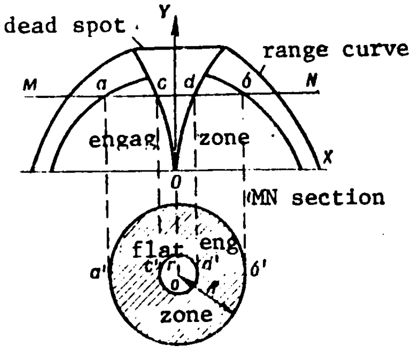


Fig. 6.32. Zones of antiaircraft guns

Table 6.7

alt., m	r, м	R, м
500	25	6500
1000	50	6500
1500	75	6400
2000	100	6200
2500	125	6000
3000	150	5800
3500	175	5500
4000	200	5200
4500	230	4700
5000	260	4200
5500	300	3600
6000	340	2600

For opening fire at the far limit of the engagement zone, the required target detection range for the FCR is:

$$d_{req} \geqslant R + V_t(t_{fcr} + t_{bat} + t_f), \qquad (6.142)$$

where t_{fcr}--the time for detection, identification and taking up the target for tracking by the FCR;

t_{bat}--the time for readying the battery to open fire after the taking up of the target for tracking by the FCR;

t_f--the shell's time of flight to the far limit of the engagement zone.

Preparation of Firing

Preparation of firing is divided into the calculation of initial errors and direct preparations.

The calculation of initial errors for firing using a AAFCS is carried out prior to receiving the target designation or before detection of the target at the battery and includes determining the deviations of firing conditions from the tables, the calculating of the total corrections and the considering in the AAFCS of those corrections (deviations) the incorporation of which does not depend upon the target's flight conditions.

Direct preparations are carried out after the obtaining of the target designation or after the target has been detected at the battery and includes the following:

a) The search, detection and identification of the target;

b) The choice of the method for determining the firing data using the AAFCS (for example, according to the data of the FCR, the data of the rangefinder, the FCR and rangefinder);

c) Setting on the AAFCS the data for considering the base depending upon the chosen method for determining the firing data;

d) Determining and assigning target altitude;

e) Setting on the AAFCS the data for considering ballistic and meteorological conditions (after determining target altitude);

f) Setting on the AAFCS the observing interval, that is, the time for evaluating the parameters of the target's movement for determining its extrapolated trajectory in accord with the assumed hypothesis on the movement of the air target after the round;

g) Designating the type of fire.

Firing Methods, Types and Conditions of Fire

Depending upon the situation, the particular features of the target, the conditions of its observation and the capabilities of the antiaircraft artillery systems (mounts), the following methods of firing are employed: with a AAFCS (RIS), with a sight (an optical sighting collimator), for routes and with barrage fire.

Firing with a AAFCS (RIS) is the basic firing method, it ensures greatest effectiveness and is employed both against visible and invisible airborne targets.

Depending upon the method of fire, the particular features of the target selected for engagement, the firing range, the capability and condition of the equipment of the guns (machine guns) and the availability of ammunition, the following types of fire are employed: single round, volley fire, rapid fire, short bursts, long bursts and continuous fire.

6.4.3. Combat Employment of Antiaircraft Artillery

Operational-Tactical Principles for the Combat Employment of Antiaircraft Artillery in the Great Patriotic War

The combat tasks carried out by the AD antiaircraft artillery can be reduced to the following groups:

a) Antiaircraft artillery defense of major administrative-economic centers;

b) Antiaircraft artillery defense of important industrial centers, cities and installations (large power plants and so forth);

c) Defense of the lines of communications and, primarily, railroad stations, bridges, ports, piers and crossings;

d) Defense of other important installations, such as: military dumps and depots, airfields of long-range aviation, communications centers, hydraulic engineering projects, individual towns and population points which had temporarily assumed important military significance.

The grouping of the antiaircraft artillery in defending a large installation of the nation was organized according to the principle of all-round cover with reinforcing of the sectors for the most probable enemy raids. The grouping was also to satisfy the demand of causing decisive damage to the enemy which had broken through to the near approaches to the installation before the enemy had reached the probable bombing line (PBL), that is, before it carried out its combat mission. For this reason the basic portion of the medium-caliber antiaircraft artillery batteries (and in the postwar period the large-caliber ones) was deployed in a ring in front of the PBL, on the so-called firing line. Internal firing lines were created to combat enemy aviation which had broken through the basic firing line.

In the course of the entire war, the principle of all-round defense and defense echeloned in depth remained unchanged. In keeping with the quantitative growth of antiaircraft artillery, only the density of antiaircraft fire was increased by shortening the intervals and distances between the batteries. The qualitative development of aviation moved the question of the combined employment of different-caliber batteries to the forefront.

During the various periods of the war, from 13 to 32.4 percent of the medium-caliber antiaircraft artillery, from 24.4 to 54.3 percent of the small-caliber antiaircraft artillery and 27.6-60.6 percent of the antiaircraft machine guns were employed for antiaircraft defense of the lines of communications. The most important railroad junctions and bridges were covered and in the combat zone all stations without exception.

For escorting troop trains on the move use was made of mobile antiaircraft groups (small-caliber antiaircraft artillery and machine guns) mounted on railroad flatcars as well as armored trains. Armored trains escorted the troop trains in a full consist or with individual armored flatcars. Here platoons of antiaircraft artillery were located at the head and tail end of the train and a machine gun platoon was in the middle of the train.

Combat Employment of Modern Antiaircraft Artillery

Small-caliber antiaircraft artillery with its mobility, simplicity of maintenance and reliability in combat remains a weapon against low-altitude airborne targets. Such subunits can fire at the air enemy while on the move or from brief halts and carry out combat tasks related to AD of the troops on the march, on an offensive, on the defensive, while remaining in their battle formations.

In addition to covering the troops, these subunits are employed for antiaircraft defense against low-altitude enemy air strikes against friendly air bases, ammunition and fuel dumps, bridges across rivers, railroad stations, control centers and other installations.

The commander of an antiaircraft subunit, having received the task of air defense of an installation, conducts reconnaissance and selects the firing position. Upon arriving in the area of the installation to be defended, he clarifies the missions, the position and the degree of its vulnerability, he studies the terrain, he determines the possible and most probable routes of concealed approach for the aviation to attack the installation and after this plans the battle formation of his subunit.

The choice of alternate positions is made in such a manner that the moving of the subunits to these positions would not reduce their fire capability in the most probable sectors of air operations against the installation.

7. CONTROL SYSTEMS

7.1. General Characteristics of Control Systems and the Process of Control

7.1.1. Definition, Structure and Classification of Control Systems

The Definition of a System

For carrying out the given combat tasks by the units and subunits of the branches of the AD Troops, control systems are created and organized on the appropriate levels of control. In the general instance military control systems reflect the TOE structure of the troops.

A control system in the broad sense is a systematized aggregate of interrelated and interacting subsystems (elements) which naturally form a single whole with the task of achieving the set result in the process of operation.

Any control system consists of subsystems and is in turn a subsystem of the higher-level system encompassing it.

A subsystem is a portion of a control system which has been isolated according to certain features (properties or functions) and performs one or several functions inherent to the given system.

For example, in the control system created in a unit of the ZRV [Antiaircraft Missile Troops], it is possible to isolate several subsystems which perform various functions: the reconnaissance subsystem, the communications subsystem, the missile support subsystem and so forth. In being viewed on a different, lower level of control, a subsystem can be seen as an independent system solving a strictly determined problem.

A system element may or may not possess relative independence (as, for example, a subsystem), but it performs one of the system's functions independently or in an aggregate with other heterogeneous elements of the given control system.

A control system from the viewpoint of its operation consists of the controlling subsystem (the controlling organ) and the controlled subsystem (the controlled object or objects). There should be one controlling organ in a system but, as a rule, there can be several controlled objects.

An overall diagram of a control system is shown in Fig. 7.1.

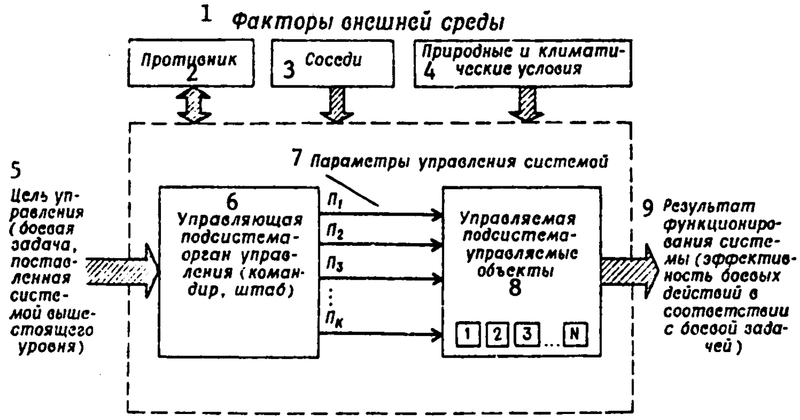


Fig. 7.1. General diagram of a control system

Key: 1--External factor; 2--Enemy; 3--Adjacent units; 4--Natural and climatic conditions; 5--Aim of control (combat task set by higher-level system; 6--Controlling subsystem or control body (commander, staff); 7--System control parameters; 8--Controlled subsystem or controlled objects; 9--Result of system's functioning (effectiveness of combat operations in accord with the combat task)

The controlling organ is that part of the control system where information is collected, processed and generalized on the internal state of the system as a whole and on the external state and on this basis control actions (commands, instructions) are produced which are transmitted to the controlled subsystem.

The controlled subsystem is that part of a control system where the control actions are actually implemented for achieving the basic goal set for the system as a whole.

In terms of units of the branches of AD Troops (ZRV, IA [fighter aviation] and RTV [Radar Troops]), the controlling organ is the headquarters (the deputies, staff or services) of the unit headed by the commander while the controlled objects are the subordinate TOE and attached subunits headed by their commanders.

For the quartering of controlling organs, command posts are organized and equipped and from here the unit commanders in the branches of the AD Troops control the combat activities of the troops.

Common features of control systems. Inherent to control systems are a number of features which are common to all varieties and levels of systems having any nature and complexity.

The most essential of such features are: a specific set, that is, the system's purpose for carrying out one task or a group of defined tasks; the organized nature of the system, that is, the presence of a certain structure; complexity; the presence of the control act (the process of control); dynamicness; the presence of controlling parameters inherent to the given system; the presence of the system's amplification properties.

Distinguishing features of AD Troop control systems. The control systems employed in the AD Troops, in comparison with the other military-end systems, have a number of characteristic features:

a) A large number of multifunction controlled objects (or an aggregate of controlled subsystems) of varying nature and complexity as well as broad purpose which, in turn, gives rise to intensive flows of information which is diverse and heterogeneous in terms of composition and encoding methods;

b) The high speed of such systems which derives from the demand of maintaining the systems in constant combat readiness to repel massed, surprise and brief attacks by an air enemy;

c) A broad range of change in the system's states in maintaining the given structure and the great dynamicness of the change in these states;

d) The systems operate on a real time scale and over large spatial scales;

e) The AD control systems are in the category of variable-structure systems;

f) In the AD control systems, as a rule, there is the simultaneous solving of a set of combat tasks in a certain spatial volume (the guiding of fighter-interceptors, the firing of the SAMS, the firing of antiaircraft artillery and so forth), utilizing the automation of these systems.

Types of links in the control system. In each normally operating control system, there is a material, energy and information exchange between its control organ and controlled objects. In accord with this in a system there really exists the following types of links: material (the exchange of material); energy (the exchange of energy); information (the exchange of information).

In the AD Troop control systems, extensive use is made of all types of links, as a rule, in their aggregate but the information links comprise a significantly larger amount. The primacy of one or another type of link in the system is determined by the system's purpose and by the scale of the tasks carried out by it, that is, by the system's level.

The Structure of a System

The structure of a system is a stable order of internal links between its subsystems (elements) determining its functional purpose and interaction with the external environment. The structure is the material foundation of the system, its basis, within which the control process is carried out.

The inner basis on which the system's operation is organized is its structure reflecting its organizational form.

In essence a control system is an organizational form which unifies the principles, equipment, procedures and methods of control as well as the personnel taking decisions on the scale of the given system and in accord with the overall aim confronting the system.

The structure of the AD Troop control systems is determined by their purpose, by the nature and scale of the tasks carried out, by external factors and so forth.

The structure of troop control systems (TCS) reflects the TOE structure of the troops (the units and subunits of the branches of troops), while the structure of the weapons control systems (WCS) shows the structure and particular features in the organization of weapons systems.

The characteristic features which influence the structure of control systems are: the overall number of same or different-type subsystems (elements); the qualitative characteristics of each subsystem from the view of the functions performed; the interaction between the elements (subsystems) in the process of operating; the separateness of the individual subsystems or groups of elements and their influence on the overall effectiveness of the system; the spatial reciprocal positioning of the subsystems (elements) in the given control system considering their internal and external links.

Among the typical structures of control organs in control systems are: patriarchal, line or linear, functional; line-staff (line-functional) and committee.

The structure of control organs in control systems is shown in Fig. 7.2.

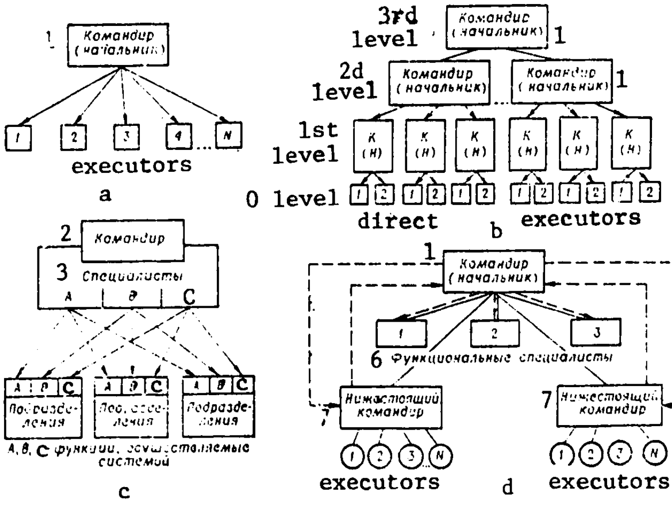


Fig. 7.2. Typical structures of a control organ in a control system; a--patriarchal; b--line; c--functional; d--line-staff with centralized leadership

Key: 1--Commander (chief); 2--Commander; 3--Specialists; 4--Subunit; 5--A, B, C--Functions carried out by system; 6--Functional specialists; 7--Inferior commander

In the AD Troop control systems, as in a majority of the military-purpose control systems, an important place is held by the line-staff structure of control organs. This is a combination of elements of the line and functional structures whereby all control is exercised in parallel by the line (commander, chief) and staff apparatus (staff, functional services).

The given structure provides the following: the realization of the principle of one-man leadership; the control of complicated systems (elements) of varying nature (heterogeneous in terms of their functions) with a large number of problems in employing specialists (specialist groups) of the staff apparatus; a rather high effectiveness of control on any level of command.

There are two varieties of the line-staff structure;

The line-staff structure with centralized leadership whereby the giving of all commands and instructions through any communications channels to the controlled objects is carried out only through the line leaders while the functional specialists of the control organ are just the assistants (experts) of the line leader for the corresponding function of control;

The line-staff structure with limited functionalism whereby the individual functional specialists (groups) are given the right to issue instructions to the controlled objects for certain control functions in bypassing the line leadership.

The last variety with the correct and rational organizing of the system's control organ ensures higher effectiveness of control in complex multilevel hierarchical systems, particularly with the requirement of the system's high speed.

Principles. The principles of the creation and operation of control systems are in the category of specific principles and do not contradict the basic principles of military art.

Among such specific principles of control, one might put the following: goal-oriented (the principle of a system's goal); centralization of control; feedback; integrated solving of problems in the system (the system of interaction); adaptation (the combining of centralized control with the granting of the right of independence to the controlled objects); variability (the capacity of the system to alter or reorganize its structure in the process of operation); a unified information field (base); a step-by-step nature; new problems (the principle of prospectiveness); the necessary diversity of both the control organ as well as the controlled objects in the system in solving control problems; the functional linking of the given control systems with other systems of the same or different levels; effectiveness.

The Classification of Control Systems

Control systems including those employed in the AD Troops can be classified by various, most characteristic features which largely influence the realization of troop combat capability with the use of the given system. Naturally any classification in a certain sense is of a hypothetical nature.

Control systems are divided as follows:

a) In terms of the nature of the object of control--into weapons control systems (WCS) and troop control systems (TCS);

b) According to interaction with the external environment--into open and closed control systems;

c) According to the scale and nature of the problems solved--into single-purpose and multipurpose control systems;

d) According to the particular features of the control processes occurring in the systems--into probability and determined;

e) According to the degree of automating the control process--into unautomated, automated and automatic control systems;

f) According to the nature of the processing and utilization of information on the system's output--into information, information-control and combined;

g) According to mobility--into stationary and mobile control systems.

A weapons control system is a system in which the aggregate of subsystems (elements) provides direct control of weapons in using them against enemy installations with the task of knocking out or fully destroying these installations.

WCS are characteristic for such tactical fire subunits as a SAM battalion or a SAM battery of the AD antiaircraft missile troops. A classic example of a WCS is the control system created in a SAM battery which is armed with an antiaircraft missile system or an antiaircraft artillery system. Analogous WCS are also created for guiding fight-interceptors to airborne targets. The WCS are organically part of the troop control systems and are their subsystems or elements. In being examined in terms of the level of the hierarchy, the WCS hold the lowest level of control.

A troop control system is a system in which all the subsystems and elements comprising it are unified by a common overall plan and carry out combat tasks in coordinating actions from a single center (control organ) in the interests of the overall combat task with maximum effectiveness in employing the troops and weapons.

Depending upon the scale of the combat tasks to be carried out, the TOE structure of the AD Troops and the level of command, the TCS have a definite hierarchical structure. The lowest level in this structure of the TCS is the system created on the scale of a unit of a branch of the AD troops for controlling subordinate subunits in combat.

The TCS and WCS can be open, probability, single-purpose and integrated. They can also be mobile and stationary. The WCS can be automatic and automated while the TCS, as a rule, are automated.

7.1.2. The Control Process and Its Characteristics

The presence of the control process in a system is its chief property and the basic condition of its existence. The control process is a continuous technical organizational process carried out with the aim of various methods and equipment for achieving certain results in the course of the system's operation with its given internal state and external conditions.

A control process in a system represents a natural, successive and continuous change in the system's states over time, that is, a transition of it from one state to another in accord with the system's aim and program.

Any control in any dynamic system represents a process of converting information on the state and operating conditions of the objects into signals (commands) which provide either for maintaining the state of the objects or bringing them into a condition in accord with the system's set goal and program.

In the control systems employed in the AD Troops, along with physical and energy exchange, information exchange predominates on all levels of control and this is determined by the specific features of preparing and carrying out combat operations by the subunits and units of the branches of AD Troops. For this reason, in such systems the control process can be characterized as an information process in which the collection, processing, storage and transmission of the information comprise an exceptionally important place.

Control in an organized control system can consist of: a change in the system's structure; a change in the operating modes of the elements, subsystems and the system as a whole; a reallocation of functions between the elements and subsystems within the system itself; the using of the system's reserve capacity.

The essence of control within a TCS consists in the continuous collection, processing and analyzing of data on the situation in the system's control organ (the inner state of the entire system and the external factors) and in producing control actions (signals, commands or instructions) for the controlled subsystem in the aim of achieving maximum effectiveness in troop combat operations under the given situational conditions and in accord with the combat task received from a superior level of command.

In a TCS a control process can be divided into several phases (stages) in each of which a certain particular control problem is solved:

a) The collection, processing and generalization of data on the inner state of the control system and the external factors (the air, ground or sea enemy; natural, climatic and meteorological conditions and so forth);

b) The receiving and analysis of the combat task from the control organ of the superior level of command;

c) Assessing the situation, that is, an analysis and synthesis of the generalized information and the preparation of data for taking a decision in the control organ of the control system;

d) The taking of the decision to employ the weapons and the combat operations of the troops in accord with the overall plan for combat operations coming from a superior commander (defining and formulating the specific combat tasks for each controlled object and for the subsystems of the given control system);

e) The giving of combat tasks to all the elements and subsystems in accord with the adopted decision;

f) Supervising the carrying out of the given tasks and when necessary the correction and adjustment of a previously adopted decision;

g) A report to the control organ of the superior control system on the results of combat operations.

A typical scheme of the control process in a TCS is shown in Fig. 7.3.

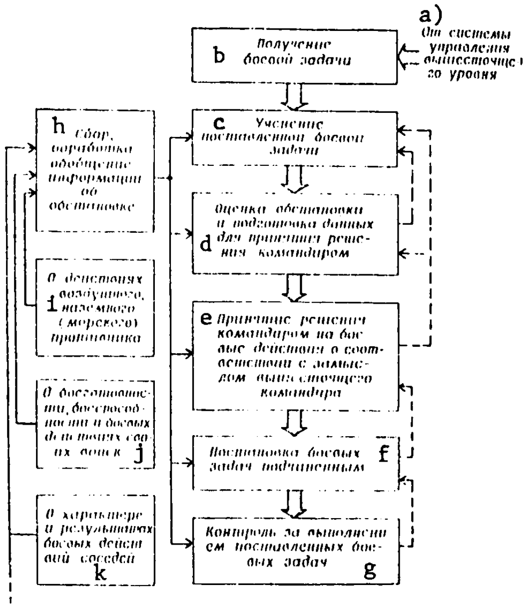


Fig. 7.3. Typical diagram of control process carried out in troop control systems

Key: a--From the superior level control system; b--Receiving of combat task; c--Analysis of received combat task; c--Evaluation of situation and preparation of data for the taking of a decision by the commander; e--Taking of decision by commander for combat actions in accord with overall plan of superior commander; f--giving combat tasks to subordinates; g--Supervision of carrying out of received combat tasks; h--Collection, processing and generalization of situational data; i--On the actions of the air, ground (sea) enemy; j--On the combat readiness, combat capability and combat actions of one's own troops; k--On the nature and results of combat operations by adjacent units.

The procedure and sequence of solving these problems are characteristic for any troop control system including for a TCS of the AD Troops.

A control cycle. The control process in control systems with a closed process cycle always has a cyclical nature and for this reason the entire course of the process on a time scale can be described by a control cycle.

A control cycle is an interval of time during which control tasks are successively carried out from the moment of receiving the combat task in the control organ until its complete execution within the given control system.

Generally speaking, this consists of the following components:

$$T_{cc} = t_{ex\ pr} + t_{pro} + t_{sev} + t_{dt} + T_{wc} + t_{ev}, \tag{7.1}$$

where T_{cc}--duration of control cycle;

$t_{ex\ pr}$--the time during which the combat task is received from the superior commander and it is analyzed in the system's control organ;

t_{pro}--the time during which information is collected, processed and generalized on the situation from various sources and needed for carrying out the given combat task;

t_{sev}--the time needed by the commander (combat crew, staff) for evaluating the situation and preparing data for taking a decision;

t_{dt}--the time spent by the commander on taking a decision (an operational plan) with the formulating of specific combat tasks for the troops (units, subunits) comprising the given control system;

T_{wc}--the duration of the cycle of the effect of a certain type of weapons in their carrying out of combat tasks;

t_{ev}--the time during which the commander (combat crew) evaluates the results of the action of the weapons against the enemy in their carrying out of the combat task.

Usually the aggregate of components in the control cycle, without the time of the cycle of the action of the weapons T_{wc}, is termed the operating time of the system's control organ.

Information used in control systems of any sort should possess two basic properties: it should be tailored to solve a certain range of problems characteristic for the given type of control system; it should have certain sources and corresponding consumers with a unified encoding system.

By information one should understand the aggregate of data needed for forming the system's goal and program and for characterizing the states of the controlled objects and the external environment.

Information is the actual carrier of all the transformations carried out in the system and without it the control process is impossible.

The classification of information employed in the TCS and WCS of the AD Troops can be made according to the aggregate of distinguishing features depending upon the particular features of the receipt, processing and purpose of the information.

The most essential features by which information can be classified are the following (Fig. 7.4): the nature of the change; the sources of receipt; the purpose and procedure of use; the presentation (display) of information; composition; quality; value; the state of the system's controlled objects; the degree of priority; the nature of employing the information and others.

The information support of the TCS and WCS is the aggregate of measures aimed at acquiring and generalizing information on the situation from diverse sources of its acquisition by the given system and other systems and the providing of this information to the users.

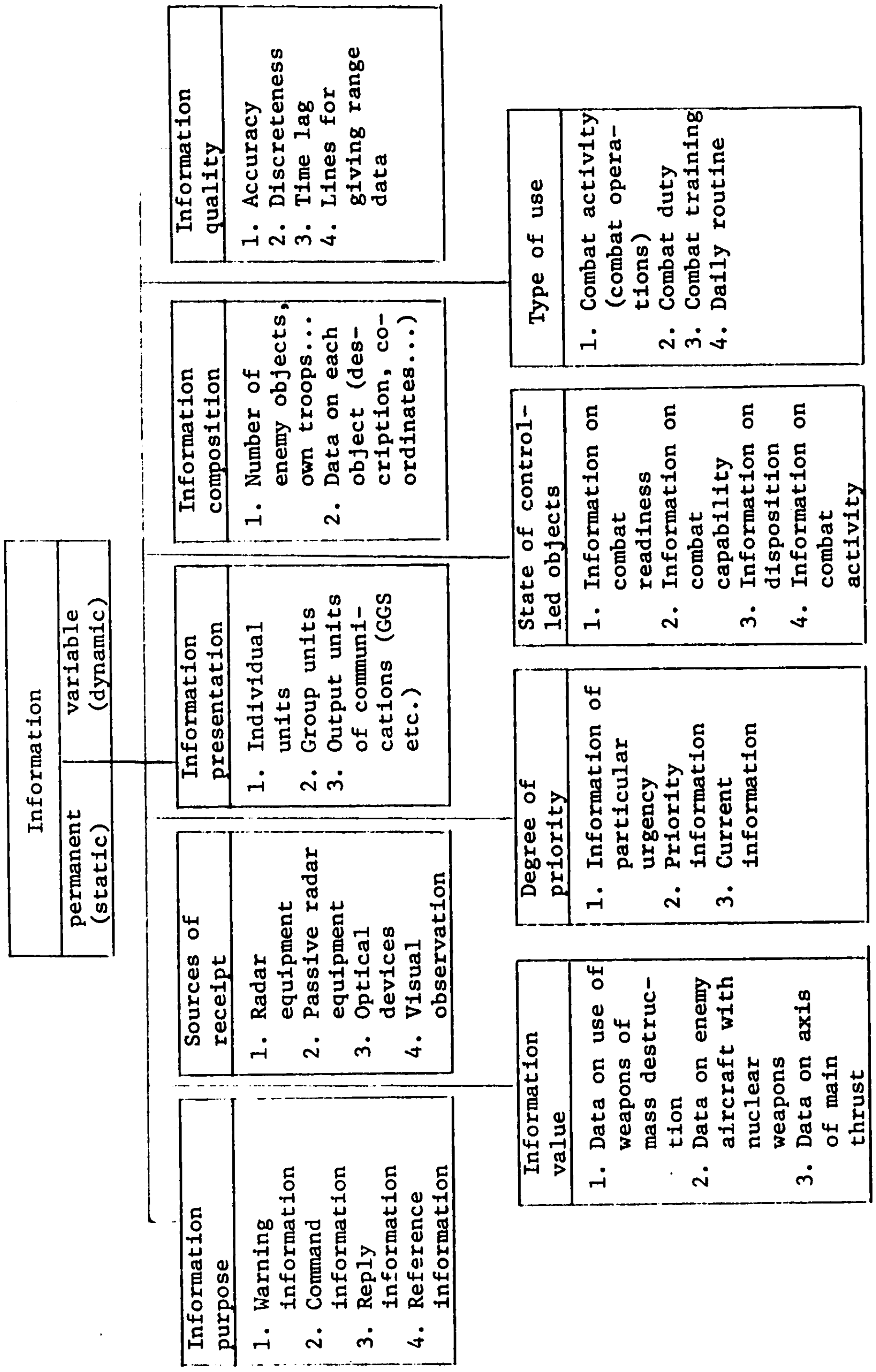


Fig. 7.4. Classification of information used in AD Troop control systems

In a control system the information sources can be: all types and purposes of radars, the data of visual observation as located on all the elements of the system, the air reconnaissance data of other systems and so forth. The basic sources of information on the situation are radar reconnaissance equipment which possesses high information capability for scanning the air space in minimum short times and the providing of information to the system. For this reason the obtaining of information from all types of radar reconnaissance equipment is termed radar support of the control system.

The basic demands placed upon information circulating in the AD control systems are: promptness and continuity of receipt, updating with an established discreteness, providing a high accuracy in taking and receiving the information, the completeness of data in terms of composition, simplicity of encoding, the possibility of processing by various methods and equipment of the given system and other systems, a short time lag and so forth.

The degree to which the information satisfies the designated requirements determines its quality as a whole and has a decisive impact on the effectiveness of troop (weapons) control in the given system.

7.2. Automated Control Systems

7.2.1. ACS Elements

An automated troop (or weapons) control system is a man-machine system which provides the automated collection, processing and display of information needed to optimize troop (weapons) control in the aim of their most effective employment.

The ACS can include the following elements:

a) Information sources (radar reconnaissance equipment; connecting equipment; connecting equipment for other ACS to exchange information and so forth);

b) The system's set of automated equipment (SAE) located at the position of the command post (control organ);

c) Connecting equipment for the controlled objects.

A structural diagram of an ACS is shown in Fig. 7.5.

Among the data sources in an ACS are diverse equipment but the basic role is played by various types of radars located at all command posts comprising the system and transmitting information on the situation to the corresponding command posts of the given system or to the command posts of another adjacent ACS. In addition, information can be received at the system's command post (control organ) from superior and adjacent command posts also equipped with SAE over the automatic communications channels. The connecting equipment provides the functional connecting of the sources with all the system's elements and with the other ACS.

The set of automated equipment is an aggregate of equipment ensuring the collection, processing, display and output of recommendations to the combat crew of the command

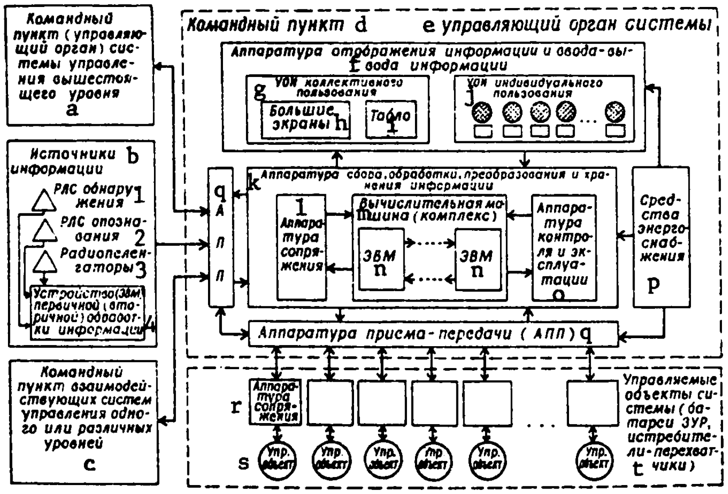


Fig. 7.5. Structural diagram of an automated control system

Key: a--Command post (control organ) of higher-level control system; b--Information sources; b_1--Detection radar; b_2--Identification radar; b_3--Radio direction finder; b_4--Primary (secondary) data processing device (computer); c--Command post of cooperating control systems of the same or different levels; d--Command post; e--System control organ; f--Equipment for data display and data input-output; g--Group displays; h--Large screens; i--Boards; j--Individual displays; k--Information for the collection, processing, conversion and storage of information; 1--Connecting equipment; m--Computer (installation); n--Computer; o--Monitoring and operating equipment; p--Power supply equipment; q--Receiving and sending equipment; r--Connecting equipment; s--Controlled object; t--Controlled objects of system (SAM batteries, fighter-interceptors)

post in accord with the established control algorithm and the issuing of combat tasks to the controlled objects (troops) on the scale of the given system.

The SAE includes: an electronic computer or computer installation consisting of two or more computers; data display equipment; receiving and sending equipment (RSE); power supply equipment. The basic portion of the SAE is located at the system's command post while its individual elements can be located at the inferior command posts of the given system.

The equipment for data display and data input-output is designed for the visual presentation of information to the combat crew at the command post in solving the problems of troop (weapon) control. The basis of the equipment is the data display units (DDU) and the units (panels) which provide for the inputting of control commands into the computer (computer installation) from the work areas of the operators (the men of the combat crew).

The data receiving and sending equipment (RSE) is used for the automatic sending and receiving of information both within the system between its elements and also for exchanging information between other systems with which the given ACS is functionally connected. Various means of communications are employed for the exchange of information between the elements.

The power supply equipment is used to ensure a source of power for the entire SAE of the system's control organ.

The connecting equipment for the controlled objects is designed to ensure the functional connecting with the automated equipment of the controlled objects. This equipment is located, as a rule, at the positions of the given objects.

The electronic computer as the basic part of the control system's SAE is an electronic device (an aggregate of devices) designed to automate data processing and calculating according to a certain algorithm. With the aid of a computer the SAE equipment can elaborate certain recommendations within the limits of the designated conditions on the combat employment of the weapons (troops) controlled from the system's command post.

All existing computers can be classified according to the following basic features: according to the method of solving problems; according to the form of processing the submitted data; according to computer capacity; according to the degree of universality of data processing; according to the circuitry and structure of the computer.

According to the problem solving method, a distinction is made between computers with an analogue solving method, program-controlled and combined.

The analogue method is based on the theory of mathematical modeling which in turn is based upon the similarity of the mathematical descriptions of the object and its model.

The program controlled solution method is based upon the employment of numerical methods of mathematical analysis and consists in the fact that for a certain mathematical dependence there is a corresponding definite sequence of performing simple arithmetic operations or the computation algorithm achieved as a result of the interrelationship of the individual units and devices which changes in the course of the solution.

Both these methods in a certain combination are employed with the combined problem solving method.

In terms of the form of processing the submitted information, computers are divided into three types: continuously operating computers or analogue computers (AC) which process data submitted in an analogue (continuous) form; discrete-action computers or digital computers (DC) which process data submitted in a digital (discrete) form; hybrid computers which process the information partially in a discrete and partially in a continuous form.

Digital computers have been most widely employed in the WCS and the TCS.

The structural diagram of a digital computer is shown in Fig. 7.6.

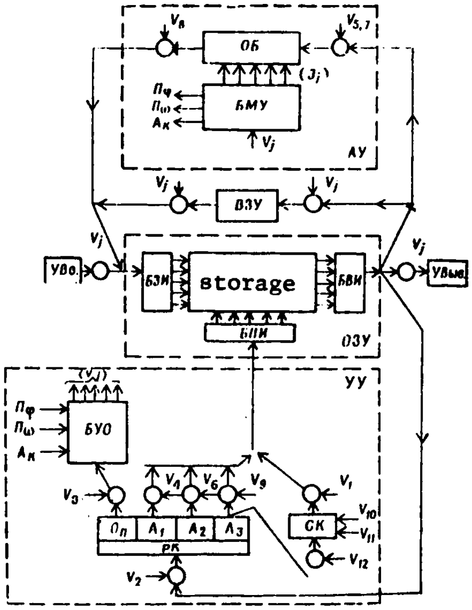


Fig. 7.6. Simplified structural and functional diagram of a digital computer

АУ--arithmetic unit; ОЗУ--main memory; УУ--control unit; Units: ОБ--operating unit; БМУ--local control unit; ВЗУ--external memory; УВв.--input unit; УВыв.--output unit; БЗИ (БВИ)--data writer (reproducer); БПИ--data retrieval unit; БУО--operations control unit; РК--command register; СК--command counter. Signals: V_j--control pulses; J_j--control signals to operations unit; $П_φ$--overflow signal; $П_ω$--conditional transfer signal; A_K--operation end signal; $V_{1,2,3}$ ...--signals for completing three-address command with direct addressing.

In terms of computer power, digital computers are hypothetically divided into large, medium and small.

Large digital computers possess high speed (from several hundred thousand to several million operations per second) and a large storage capacity (up to a million bytes in the working storage and up to several million bytes in the external storage). These also have the capacity of operating under multiprogramming conditions and (or) under time-sharing conditions in serving several users simultaneously. There are also superpowerful digital computers which have a speed on the order of scores of millions and even hundreds of millions of operations per second (the Illiac-IV in the United States).

The medium-sized digital computers possess a speed on the order of several tens of thousands of operations per second and a storage capacity of tens of thousands of bytes and in the external storage millions of bytes. The given class of digital computers are most widely employed in the TCS and WCS.

Small-sized digital computers have a speed of hundreds and thousands of operations per second and a working storage capacity of several tens of thousands of bytes. The small digital computers operate according to a single program and serve one user. The given type of digital computer is employed in the WCS.

In terms of the degree of data processing universality, all digital computers are divided into universal and specialized.

Universal digital computers are general-purpose computers which are designed to solve a broad range of problems and have a diversified operational system, a hierarchical memory structure and a developed data input-output system.

Specialized digital computers are designed to solve one problem or a comparatively narrow range of problems. The specialization of digital computers rigidly defines their structure and makes it possible to consider the particular features of solving the given type of problems. This sharply increases the effective use of the digital computers (the simplifying of design, the reduced problem solving time, increased speed and accuracy, better serviceability, that is, the simplicity of operating the machine for a human, display and presentation of data, reduced cost of the digital computer, simplified software and input (output) units for the digital computers and so forth).

The specialized digital computers in terms of the particular features of employment are often divided into control and simulating or modeling. Control specialized digital computers are employed in the TCS and WCS. As a rule, these operate on a real time scale in a closed loop with the object (objects) of control (control over the guidance of the fighter-interceptors, fire control of the SAM batteries, control of the radar data sources and so forth).

In terms of the structure and circuitry of computers, they are conditionally divided into several generations: first generation with vacuum tubes and a speed on the order of tens of thousands of operations per second; second generation or the transistorized or solid-state computers with a speed on the order of hundreds of thousands of operations per second; third generation or computers with integrated circuits and computer installations with a speed on the order of millions of operations per second; fourth generation or multiprocessors employing large integrated circuits with a speed on the order of tens of millions of operations per second and more.

Data display equipment in an ACS includes: data display units (DDU), devices (panels) for operator input or output of information to the computers or computer installation, equipment for connecting the DDU to other elements of the system.

Data display units are the basic elements in the display equipment. They are set up at the AD command posts on any level of command.

Devices (panels) for inputting and outputting data into the computer (installation) provide for the data inputting (outputting) for display on the appropriate units (indicators).

The equipment for connecting the DDU with other system elements provides for normal operation of all the data display equipment under combat conditions.

All the DDU of the ACS in terms of design and engineering are subdivided into three basic types: projection, panel and CRT indicator DDU.

The projection DDU are designed for obtaining an oversize image. These operate according to the principle of projecting the image onto a screen for general viewing. Such DDU include an input unit, a sign generator, a recorder, a projector and a screen.

Panel DDU are designed to display information on a matrix screen of specific size using electroluminescent, opticomechanical or gas-filled elements. The panel DDU are employed both for group and individual use.

The CRT indicator DDU are designed to display a more detailed situation in receiving data directly from the sources (radar reconnaissance and other) as well as in employing information over the communications channels within the given control system or from other ACS.

In terms of the use and particular features of data display on the screens, all DDU are divided as follows: by purpose, by the type of displayed information and in terms of the methods of forming the signs on the DDU screens.

A classification of DDU is shown in Fig. 7.7.

In terms of purpose, DDU are divided into group and individual devices.

The group DDU are designed for reproducing an information model of the general air (ground) situation within a certain area of combat operations, the state of combat readiness of one's troops and so forth. On the basis of such a model a quantitative evaluation of the situation is made and data are prepared for the commander to take a decision.

Among the group DDU are large screens and electronic boards which are designed to provide information for the entire combat crew.

The large screens display dynamic and status information on the general situation, on the nature and directions of air enemy operations, on the disposition of one's troops, the terrain, geographic markers and so forth. All the information is displayed on a definite scale. The dimensions of the screens can reach several meters.

Electronic boards are designed to display information on the combat state of the troops, their combat capabilities, the course of combat operations at the given moment of time, on the results of combat operations and so forth. The boards serve as a complement to the large screens and they display information with a certain degree of detailing for individual questions.

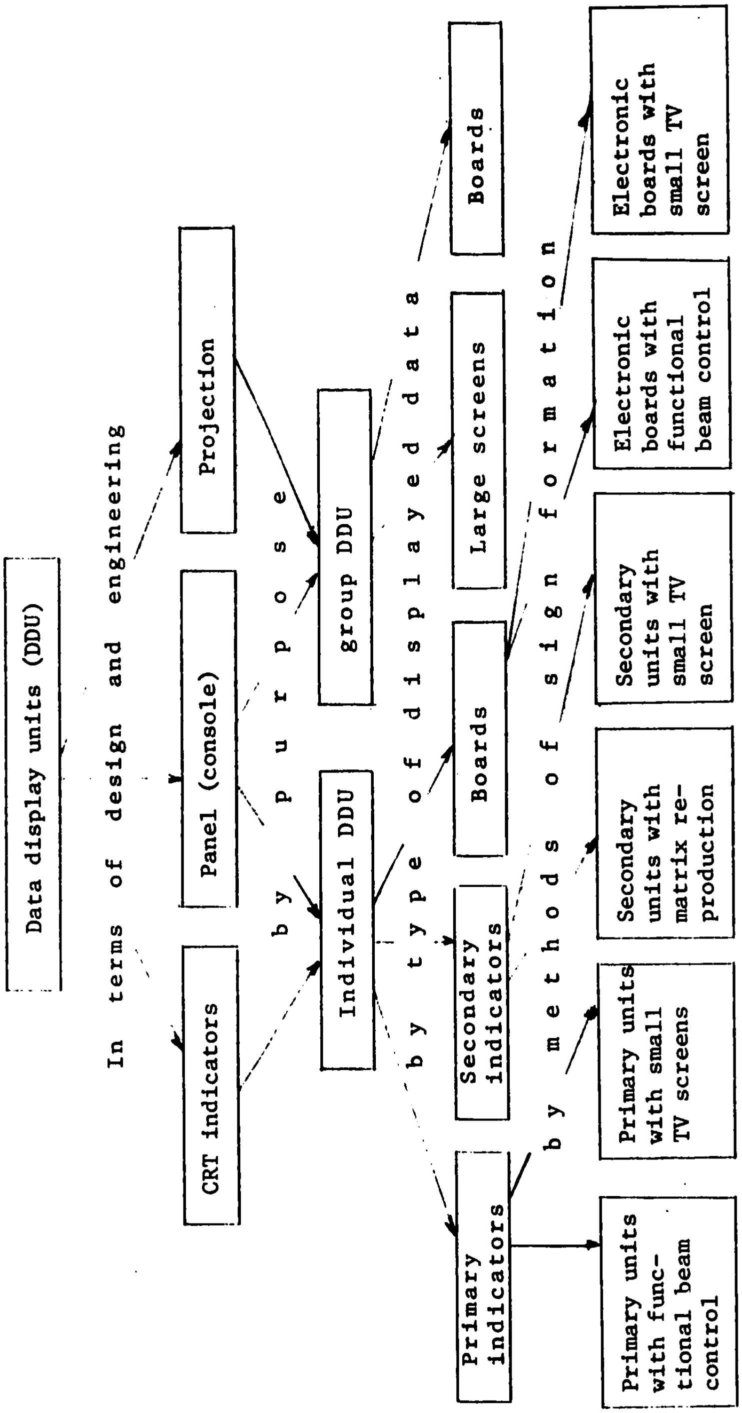


Fig. 7.7. Classification of data display units in a WCS

Individual DDU are designed for more detailed and complete display of data in a certain area in receiving the data from the primary (radar reconnaissance) and secondary (ACS) data sources. Among the individual DDU are the primary and secondary indicators and boards which selectively display information designed for certain members of the combat crew. Here the primary indicators display the information received directly from the system's radars while the secondary indicators give data from the ACS data processing equipment in a converted form. In individual instances indicators can be employed which simultaneously display both primary and secondary information received from several sources (combined or integrated information).

The displaying of information on the screens of the DDU indicators is formed from two types of elements: sign groups made up from digits, letters and standard (special) symbols; lines of nonstandard length (the image of the configuration of the troop positions, the terrain, the specific position of troops, characteristic lines and zones and so forth).

Sign presentation or display assumes the creation of definite systems of symbols in the form of different geometric shapes, figures and letters.

The aggregate of these symbols reduced into certain groups characterizing the state and change of the state of one or another object (or several objects) is termed the data form. Using the data forms it is possible to display on the DDU screens the data on airborne targets, data on one's own fighter interceptors, data on the state and combat operations of the SAM or antiaircraft artillery batteries (battalions) and so forth.

The position of the data form on the DDU screen is strictly determined and describes the position of the objects (one's own and the enemy's) and their state.

Thus, in the American Sage ACS the target data form consists of nine signs (three lines with three signs in each). In other ACS the image is given only in a symbolic form (the U.S. Missile Monitor ACS).

For depicting information in a symbolic form, most often geometric shapes of a simple and complicated configuration are employed.

The triangle, rhombus, rectangle, circle and square possess the greatest ease and accuracy of perception.

Moreover, it is possible to employ typical and specialized symbols which have mnemonic and associative significance (a bomber or fighter, a command post, SAMS and others).

The requirements for the DDU are determined by the factors of three basic groups: technical factors which describe the display system, the unit and methods of display; information factors which reflect the nature and particular features of the information to be processed; psychophysiological factors which consider the capabilities of the human operator in handling the DDU.

The first two groups of factors describe the display system as a whole from the technical viewpoint while the third group involves the operator or group of operators (the combat crew).

The basic demands made upon the DDU are: promptness in the display and presentation of information to the control system's combat crew at a pace equal to or less than the pace of combat operations; ease of viewing; completeness; accuracy; contrast and brightness of the image.

For evaluating the operating qualities of the DDU, it is possible to employ the following indicators: information capacity, information content or specific information capacity; the data display rate; resolution; operating reliability and durability.

The information capacity of a DDU characterizes the maximum quantity which can be displayed on the screen. The information capacity of a DDU depends upon the number of sign positions on the indicator screen and upon the number of signs in the alphabet of the sign generator. The larger the number of sign positions and the larger the alphabet of the sign generator the greater the information capacity of the DDU indicator screen.

Information content or the specific information capacity of an indicator is the amount of information per sign position. Information content is determined solely by the alphabet of the sign generator.

The data display rate is characterized by the amount of information displayed on an indicator screen per unit of time. Naturally the planned data display rate should not exceed the psychophysiological capability of the operator to read it.

The full data reset time T_{fr} is the interval of time during which all the sign positions on the DDU indicator screen are filled. This depends upon the method of forming the signs and the method of filling the sign positions. With the sequential or parallel filling of the sign places, respectively,

$$\left.\begin{aligned} T_{fr} &= N_{sp}T_{rs}; \\ T_{fr} &= \frac{N_{sp}}{m}T_{rs}, \end{aligned}\right\} \qquad (7.2)$$

where N_{sp}--number of sign positions on indicator screen;
T_{rs}--write speed of one sign;
m--number of simultaneously filled sign positions.

Generally speaking, the maximum data display rate is directly proportional to the information content of the indicator and inversely proportional to the sign forming rate in the display system.

The reliability of data display characterizes the degree to which the perceived signs correspond to the signs which actually should be displayed.

Quantitatively data display reliability can be judged by the probability of the correct perception of the sign's information P_c or the probability of the incorrect reading of a sign P_w.

With a certain degree of approximation, the data display reliability can be expressed by the average value of the probability of correct or incorrect reading:

$$\left.\begin{aligned} P_c &= \frac{1}{K_{sp}} \sum_{i=1}^{K_{sp}} p_c(x_i); \\ P_w &= \frac{1}{K_{sp}} \sum_{i=1}^{K_{sp}} p_w(x_i), \end{aligned}\right\} \qquad (7.3)$$

where $p_c(x_i)$, $p_w(x_i)$--the probability of the correct and incorrect reading of sign x_i.

Generally speaking, the probabilities of the correct (incorrect) reading of different signs vary and depend upon the shape of the signs and the methods of forming them.

The resolution of a DDU is one of the basic indicators for the effectiveness of its operation. This is viewed together with the physiological capabilities of the human operator. As a rule, the resolution of a DDU is set proceeding from the resolution of normal human vision and is determined by the dimensions of the signs (linear or angular) and their distance to the viewer's eye:

$$S_{sn} = 2r_{sn}\,\mathrm{tg}\frac{\alpha}{2}, \qquad (7.4)$$

where S_{sn}--the linear size of the sign;
r_{sn}--the distance to the sign;
α--angular dimension of sign.

The optimum size of a sign which ensures the most rapid and accurate reading equals 40 min (for height). With larger signs the rate and accuracy of reading virtually do not change. The least permissible sign size is 20 min.

After determining the size of the sign for height it is also possible to determine the other sign dimensions (width, boldness of face, distance between signs).

The most preferred ratios between these sign parameters are approximately as follows (light signs against a dark background): width--3/5 the sign's height; thickness--12 percent of height; distance between signs--1/2 the sign width.

Operating reliability characterizes the degree of operating efficiency of the DDU and is assessed by the probability of dependable work over a determined service life or average service life.

In determining the dimensions of the operations rooms of the AD command posts where they intend to place group DDU (large screens or boards), consideration is given to the distance between operators and the viewed surface of the screens:

$$r = \frac{W}{2\,\mathrm{tg}\,\frac{\varphi}{2}}, \qquad (7.5)$$

where r--distance to the screen;

W--screen width;

ϕ--angle of view (in the calculations it is usually set within the limits of 50-60°; the maximum value of the angle should not be over 90° and here ϕ in the vertical plane is taken approximately equal to one-half the angle in the horizontal plane).

Quality characteristics of ACS operations indicate the degree of the given system's efficiency for effectively solving the control problems. Among such characteristic one should put the following: combat readiness, efficiency, throughput capacity, antijamming capability, capacity, invulnerability, mobility, effectiveness and others.

The combat readiness of an ACS is assessed by the time required to convert the system's automation equipment from one degree of readiness to another, higher one. Using the given characteristics one can assess the system's adaptation in terms of the time of solving control problems under various combat conditions.

Since the TCP and WCP are designed to increase the effectiveness of troop combat operations and the effectiveness of the combat employment of weapons, the time of converting the ACS to combat conditions should not exceed the time for converting the weapons (SAMS, fighter-interceptor, antiaircraft artillery) to readiness for combat and the converting of the troops (ZRV, IA, RTV and so forth) to a higher degree of readiness.

The efficiency of the ACS describes its speed, that is, the system's capacity to respond to a change in the combat situation. Quantitatively a system's efficiency can be assessed by the time outlays of the system's combat crew in solving a control problem (working time). The less time a commander (combat crew) needs for effectively solving control problems the higher the efficiency the system possesses. This time depends upon the degree to which the solving of control problems has been automated. It should not exceed the time the air targets are in the weapons impact (intercept) zones or in the fire control (guidance) zones of these weapons.

The quality of solving control problems characterizes the ability of the ACS to solve the set control problems with the required accuracy. Quantitatively it can be assessed by the amount of errors in solving specific problems or by the probability of a correct solution of a certain problem. For example, the quality of radar data processing in an ACS is characterized by the mean square errors of tracking the target trajectory while the quality of solving the target designation problem for the weapons is assessed by the probability of the immediate lock-on of the target by the weapons guidance radars.

The throughput capacity of an ACS characterizes its information capability and can be assessed by the maximum number of tracked and processed targets information about which can be received, processed and presented to the users (fighter-interceptors, SAM batteries and so forth) in a unit of time with a set discreteness and accuracy.

The antijamming capability of an ACS characterizes the ability of the system to effectively solve troop (weapons) control problems under the conditions of interference, as the presence of various interference can complicate the system's operating conditions and lead to a decline in its throughput capacity. The system's antijamming capability is determined by the jam-proofness of the radar information sources and the means of communications and by the quality of the data processing algorithms in the system.

The capacity of a system characterizes the maximum capability of the ACS to solve control problems. It can be assessed by various criteria for the individual, specific control problems.

For example, the capacity of an ACS in data processing is characterized by the maximum number of targets for which the information can be received, processed and transmitted. The capacity of an ACS can be assessed by the maximum number of guidance channels or by the number of SAM batteries to which a task can be given automatically.

The invulnerability of an ACS is determined by its capacity to carry out the control problems assigned to it under the conditions of enemy fire in conducting combat operations. This is composed of combat stability and operating reliability. The invulnerability of an ACS is determined by the invulnerability of the most vulnerable elements in the system, for example, the data transmission equipment or the reconnaissance radars.

Combat stability characterizes the capacity of the system to resist enemy fire and is assessed by the probability of the uninterrupted operating of the system with the failure of its individual elements.

Operating reliability of an ACS is assessed by the probability of the system's dependable operation over a certain (set) interval of time under typical conditions.

The mobility of a system is characterized by its ability to be transported by all types of transport: motor vehicle, rail and air. The existing foreign models of ACS are mounted on truck-pulled or self-propelled chassis and also can be placed in special containers.

The effectiveness of a system is determined by the increase in the indicator of troop combat effectiveness (the effectiveness of weapons employment) in using the given ACS. In general terms this is determined by the expression

$$E_{acs} = \frac{E_{acs} - E^*}{E_{acs}} \cdot 100\%, \qquad (7.6)$$

where E_{acs}--effectiveness indicator characterizing the realization of the combat capabilities of the troops (weapons) in employing the given ACS;
E^*--effectiveness indicator characterizing the realization of the combat capabilities of the troops (weapons) in the absence of the given ACS.

In utilizing the above-indicated characteristics it is possible to evaluate the ACS for any level of command and purpose.

7.2.2. Controlling SAMS Fire Using an ACS

The AD system of individual installations is an aggregate of the groupings of different branches of troops deployed in battle formations. The composition of the groupings is determined by the scale of the tasks to be carried out, by the nature of enemy air operations, by the combat capabilities of the weapons systems, the control systems and the support of the troops (SAMS, ARKP [abbreviation unknown], ACS, radar and so forth) and by the particular features of organizing and providing cooperation with adjacent units (subunits) of the various branches of the AD Troops.

The SAMS fire control system reflects the TOE structure of the antiaircraft missile troops. Fire control is carried out on a level of the created SAMS grouping consisting of the battle formations of the SAM batteries, the SAM battalions and the artillery.

The SAMS groupings can be of the same type (for example, just the Improved Hawk or SAM-D or other SAMS) or mixed (different types of SAMS).

The ACS used for controlling troop combat operations in terms of the particular features of combat employment can be single-purpose (Missile Master, Missile Monitor, Missile Mentor, Missile Minder and others) for controlling SAMS fire in mixed groupings and multipurpose or integrated (Florida and others) for controlling the combat operations of the SAMS and fighter-interceptors.

A single-purpose ACS of the Missile Monitor type is designed for controlling the SAMS fire of an artillery group (brigade) which is part of a field army in the theater of war (United States).

In terms of structure this is a three-tier hierarchical control system in which there are three command posts: the command post of the system (one), the command posts of the SAM battalions (for the number of battalions comprising the group) and the command posts of the SAM batteries (for the number of SAM batteries comprising the SAM battalion). Each of the command posts solves the control problems inherent to its functions in the general control system of the SAMS grouping.

The most general problems (coordinating the basic efforts of the SAMS grouping in the main sector of the enemy's air attack, cooperation with the fighter aviation and other AD resources) are solved at the system's command post. The problems of direct fire control of the SAM batteries under the given battalion are solved at the battalion command post. At the command posts of the SAM batteries firing is carried out against one target (the Nike Hercules SAMS), against two targets (the Hawk SAMS) or six targets (SAM-D).

In considering the expected nature of enemy air operations, the capabilities of the reconnaissance equipment of the control system as a whole and the particular features of controlling the fire of the SAMS under the most complicated conditions of the air situation, it can be pointed out that the most effective fire control can be provided from the command post of the SAM battalion which may include several SAM batteries.

A structural diagram for the SAMS fire control in the Missile Monitor ACS is shown in Fig. 7.8.

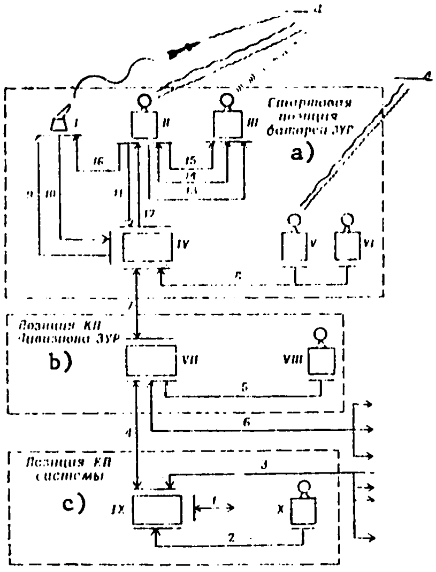


Fig. 7.8. Structural diagram for controlling the fire of the Hawk SAMS in the Missile Monitor ACS

Located at the launching position of the SAM battery are: I--the launcher; II--illuminating radar (AN/MPQ-23); III--radio rangefinder; IV--hut with equipment for controlling the fire of the SAM battery; V--radar for detecting low-flying targets (AN/MPQ-34 or AN/MPQ-51); VI--radar for detecting high altitude targets (AN/MPQ-35). Located at the position of the SAM battalion command post are: VII--equipment for controlling the fire of the SAM battery (AN/MSQ-18); VIII--radar of the SAM battalion command post (AN/TPS-1G).

Located at the position of the system's command post are: IX--equipment for data processing and controlling (coordinating) the fire of the SAM battalions, for the functional connecting and transmission of data in the system created in the form of two centers (the radar data processing center and the fire control center); X--a three-dimensional radar of the Freescanner type (AN/MPS-23).

In the system there are the following links between the elements: 1--the exchange of information between the system's command post and the superior and adjacent command posts; 2--data on the air situation from the radars of the system's command posts; 3 and 4--the exchange of information between the battalion command posts and the system command post; 5--data on the air situation from the radar of the battalion command post; 6--the exchange of information of the battalion command post with the command posts of adjacent SAM battalions and battery; 7--exchange of information of the SAM battalion command post and the SAM battery command post; 8--data on target detection by the reconnaissance radars of the SAM battery command post; 9--command to

[Fig. 7.8 continued]

launch the SAM; 10--data on the state of readiness of the SAM on the launcher; 11--data on target tracking; 12--target designation to the illuminating radar from the battery command post; 13--data on the target's azimuth; 14--data on the precise range to the target; 15--request for precise range to target; 16--signal that the missiles are ready to launch.

Key: a--Launching position of SAM battery; b--Position of SAM battalion command post; c--Position of system command post

The SAMS groupings of the Missile Monitor type of ACS provide the solving of the following control problems:

a) The receiving, processing, displaying, storage, converting and transmitting of data on the situation received from various sources both within the system among its elements as well as between other systems of different levels;

b) Analysis, generalization and selective presentation to the command post crew (the system or SAM battalion) of the essential information for taking sound decisions on the combat employment of the SAMS;

c) Controlling the fire of the SAM batteries from the SAM battalion command post (coordinating the fire of the SAM battalions with the system command post) while they maintain the right to independently choose the targets for destruction in certain sectors or within the range of altitudes within the limits of their SAMS impact zone;

d) Centralized warning of all the SAM batteries on the actions of the air enemy and on the combat activities of the SAM batteries (on the scale of the SAM battalion) or the entire system;

e) Monitoring the combat activities of the SAM batteries from the battalion command post or the system command post.

The automated equipment of the command post in the Missile Monitor system makes it possible to coordinate the fire of 32-35 SAM batteries (through the battalion command posts) armed with Hawk SAMS or others with a simultaneous attack by up to 130-160 enemy aircraft (missiles) from different directions.

Controlling the fire of the SAM batteries is carried out from certain lines and within certain zones and here in each zone a specific particular control problem is solved aimed at destroying the enemy aircraft (missiles) within the SAM battalion fire zone.

Fig. 7.9 shows the reciprocal position of the control zones and lines on the scale of a Hawk SAM battalion.

The control lines and zones are directly related to the tasks carried out by the SAM battalion command post in controlling the fire of the SAM batteries. Such tasks involving the use of the SAE of the ACS can be: the collection and processing of incoming information and the information logical problems, the encoding and decoding

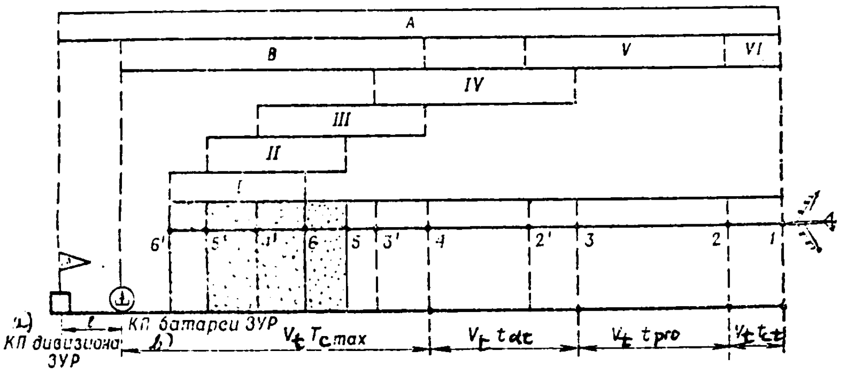


Fig. 7.9. Control lines and zones in a SAM battalion in controlling the fire of the Hawk SAM batteries

Zones: A--the zone of action of the SAM battalion with centralized control from the system command post; B-- zone of action of SAM battery with centralized fire control from the battalion command post; I--impact zone of SAMS; II--launch zone of SAMS; III--zone of giving missions to SAM battery; IV--zone of evaluating situation and taking decision to destroy target at SAM battalion command post; V--zone of detecting the targets by the battalion reconnaissance equipment and processing information for taking a decision using the automation equipment of the SAM battalion command post; VI--zone of receiving combat task from the system command post to repel air enemy attack

Lines: 1--line for receiving combat task from the system command post; 2(2')--far (near) line for detecting targets and processing information on them using automation equipment; 3(3')--far (near) line for allocating the fire of the battalion's SAM batteries against the airborne target; 4(4')--far (near) line for setting tasks for SAM batteries to destroy targets; 5(5')--far (near) limit of SAMS launch zone; 6(6')--far (near) limit of SAMS impact zone; a--SAM battalion command post; b--SAM battery command post

of information, the storing of it in a converted form and preparation for use in solving various problems; assessing the combat state and combat capabilities of the SAM batteries and the particular features of their employment under the given specific situational conditions; solving the problems of target allocation, that is, the most rational allocation of fire by the SAM batteries against the airborne targets considering their importance with the maximum realization of battery fire capability under the given situational conditions; the giving of the combat tasks to the SAM batteries for destroying the targets in providing target designation and other additional data on the situation; monitoring the fulfillment of the set combat task and when necessary adjusting the decision within the zone of setting the tasks.

In examining the control process on a time scale there is a repetition of actions by the commander (crew) of the command post in working on each next airborne target. The control problems solved for one target (flow of targets) and expressed continuously and successively in time can be characterized by a control cycle.

The control cycle of the SAM battalion command post is the interval of time during which the commander (crew) carries out all the tasks of controlling the fire of the SAM batteries from the moment of detecting the given target by the reconnaissance equipment up to the moment of destroying it:

$$T_{cc} = t_{cp} + T_c, \qquad (7.7)$$

where T_{cc}--time of control cycle, seconds;
t_{cp}--working time of SAM battalion command post, seconds;
T_c--firing cycle time of SAM battery against given target, seconds.

The components of the control cycle are shown in Fig. 7.10.

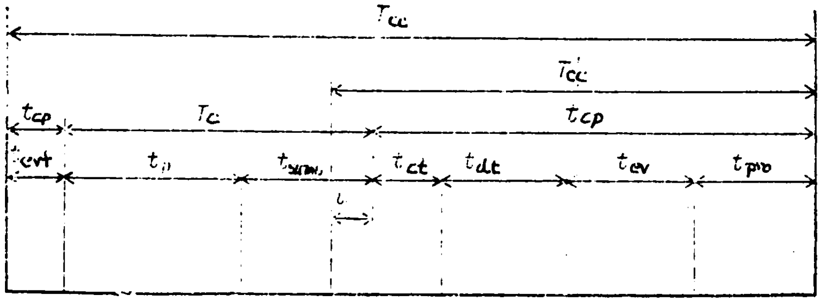


Fig. 7.10. Control cycle and its components

The working time of a command post is the interval of time from the moment of detecting the target by the equipment of the battalion (or SAM battery) command post to the moment of setting the task for the SAM batteries to destroy it considering reports on the firing results at it under the condition that all the operations (with the exception of the last) are carried out continuously and successively:

$$t_{cp} = t_{pro} + t_{ev} + t_{dt} + t_{ct} + t_{evf} \qquad (7.8)$$

where t_{pro}--the time required to detect the target by the reconnaissance equipment and to process the data on it at the battalion command post, seconds;
t_{ev}--the time spent by the commander (fire control officer) on analyzing the task and evaluating the situation, seconds;
t_{dt}--the time needed by the commander (fire control officer) to take a decision to destroy the given target (with the obligatory solving of the problem of fire allocation for the SAM batteries), seconds;
t_{ct}--the time needed by the commander (fire control officer) to set the combat tasks for the SAM batteries, seconds;
t_{evf}--the time needed by the commander (fire control officer or other members of the crew) to evaluate the firing results at the given target, seconds.

The detection and processing of information on the targets can be carried out by automated or automatic methods by several members of the command post crew and for this reason does not have a significant influence on increasing the working time of the command post.

The The most complicated and labor-intensive operations are evaluating the situation and taking the decision and a large portion of the time is spent on this. In determining the maximum throughput capacity of a command post it is advisable to consider only these two components. The time spent on giving the tasks to the SAM batteries is insignificant and this operation can be carried out by the commander and several crew members simultaneously.

The time spent on evaluating the firing results may not be considered in carrying out the calculations for the lines, as this evaluation is always made in the firing zone of the SAM batteries or even after the targets have left this zone.

In using the components of the command post working time it is possible to calculate the lines and zones for controlling the SAM battery fire relative to the positions of the SAM batteries and their zones of impact.

Thus, the line for setting the tasks for the SAM batteries for a given altitude (or range of altitudes) is calculated from the formula

$$d_{1st\ f(n)} = d_{f(n)} + V_t \cdot T_{c\ max(min)}. \qquad (7.9)$$

where $d_{f(n)}$--horizontal range to the far (near) limit of the impact zone, km;
V_t--calculated speed of target, km/sec.
$T_{c\ max(min)}$--maximum (minimum) firing cycle of SAM battery, seconds.

The distance equal to the difference of the far and near limits is called the depth of the task setting zone. The depth of the zone to a significant degree depends upon the configuration of the SAMS impact zone in space as well as upon the speed and altitude of the targets.

With low values of the distances to the far limit of the SAMS impact zone and with values of target altitude (from several km and higher) it is advisable to determine the slant range to the task setting line:

$$d_{1st\ f(n)} = \sqrt{(d_{f(n)} + V_t \cdot T_{c\ max(min)})^2 + H_t^2}. \qquad (7.10)$$

where H_t--calculated target altitude, km.

The line for allocating the fire of the SAM batteries against airborne targets is determined considering the expenditure of time needed by the commander (fire control officer or other crew member) on evaluating the situation and taking a decision to destroy the airborne target. This is calculated relative to the task setting line

$$d_{fa\ f(n)} = d_{1st\ f(n)} + V_t(t_{ev} + t_{dt} + t_{ct}). \qquad (7.11)$$

The value $(t_{ev} + t_{dt} + t_{ct})$ is a variable amount and depends upon a large number of factors. For this reason for the specific ACS, these time components are determined experimentally and are set as a time standard characteristic for certain conditions. Within the limits of the fire allocation zone bounded by its near and far lines, the commander has an opportunity to soundly take a decision, to adjust or adopt a new decision to destroy the targets under the difficult situational conditions.

The required target detection line for the reconnaissance equipment of the SAM batteries (or the SAM battalion) is calculated relative to the fire allocation line:

$$d_{de\ req} = d_{faf} + V_t\ t_{pro}, \qquad (7.12)$$

The aggregate of the required target detection zone for the reconnaissance equipment, the zone for situation evaluation and decision taking (the fire allocation zone) and the zone for setting the tasks for the SAM batteries is determined as a whole as the fire control zone of the SAM batteries from the SAM battalion command post.

The spatial dimensions of the control zone are substantially influenced by the components of the command post working time. For this reason the greatest possible reduction in the working time in maintaining high quality control is one of the ways for increasing the effectiveness of control.

8. ELECTRONIC COUNTERMEASURES

8.1. Equipment and Methods for Conducting Electronic Countermeasures

Electronic Countermeasures

Electronic countermeasures (ECM) are a group of measures conducted in the purposes of reconnaissance and subsequent electronic neutralization of enemy radio electronic equipment (REE) and systems as well as the radio electronic defense (RED) of one's own REE and systems. The ECM measures are conducted together with the destruction of the REE, particularly radiation-homing weapons.

In the armies of many capitalist nations new systems have appeared which include signals intelligence, jamming, false targets and weapons against the REE. Jamming equipment is being developed to neutralize the operation of all types of REE, including radar, laser and infrared, satellite communications and radionavigation.

Radio electronic neutralization includes measures and actions by the troops to detect, identify and prevent the operation of enemy REE. For carrying out these tasks, in the opinion of foreign specialists, the following methods can be employed: the development of active and passive jamming of the REE, the use of false targets and decoys, reducing the radar, thermal and optical contrast of one's objects, changing the electrical properties of the medium and the conditions for the propagation of electromagnetic waves and transmitting false information for the enemy reconnaissance equipment.

The objects of radio electronic neutralization are radars, radio communications, radionavigation and other REE comprising the basis of modern control and reconnaissance systems. Radio electronic neutralization was widely employed in World War II and in subsequent local wars.

Radio electronic defense is a group of organizational and technical measures to ensure the concealment and dependable operation of the REE and control systems of one's troops and weapons.

The radio electronic defense measures envisage defense against being hit by weapons which home on sources of electromagnetic waves, defense against electronic jamming and ensuring electromagnetic compatibility.

The basic methods of radio electronic defense, as foreign specialists feel, can be the integrated use of REE, rigid regulation of radiation, the maneuvering of frequencies and the use of protective equipment against enemy electronic jamming and homing weapons.

Electrical intelligence (ELINT) is intelligence carried out by special REE in the aim of obtaining data on the type, purpose and position of enemy REE. ELINT is carried out using special equipment located at ground installations, on ships and aircraft.

The tasks of signals intelligence include the intercepting and analysis of signals sent by enemy REE. This makes it possible to determine the parameters of the signals being sent, the type of modulation, the spatial characteristics and operating conditions of the REE.

Among the parameters of the emitted signals are: carrier frequency (the frequency of the high frequency oscillations) f_c and sending power P_p. The type and parameters of modulation characterize the structure of the emitted signals and this provides an opportunity to determine the purpose of the REE and the content of the transmitted information. Modulation of the carrier oscillations can be amplitude, frequency and phase.

With pulse-amplitude modulation, the signals intelligence equipment can determine the repetition rate F_r and the duration τ_i of the pulses, the structure of the pulse series and their shape. In the case of amplitude modulation by harmonic oscillations the law of change in the modulating signals can be determined.

With the frequency (phase) modulation of the carrier oscillations, the frequency F_m and the form of the modulating oscillations and the deviation ΔF_m of the carrier frequency are determined.

Among the spatial characteristics of the REE are the direction of propagation and polarization of the radio waves, the shape and width of the antenna directional pattern and the method of scanning space. The opeating conditions of the REE are characterized by the type of carrier oscillations, by the duration of work in time and so forth.

For conducting signals intelligence it is possible to employ ground, surface and onboard (aircraft) equipment. Earth satellites (for example, the U.S. Ferret) can be employed for this same purpose.

ECM Equipment

A typical signals intelligence installation (Fig. 8.1) has a wide-band channel for receiving and analyzing the signals and a REE direction finding channel. The signals received by the broad-band antenna A_1 pass through the broad-band antenna amplifiers 1 and through the antenna switch 2 to the receivers 3 which have certain frequency selectivity. As a result frequency selection of the signals is provided and their isolation against the background of obstructing signals. After amplification and preliminary conversion the signals from the output of the receivers can go to the channel separation, demodulation and decoding equipment 4, to the analysis equipment 5 and to the indicators 6.

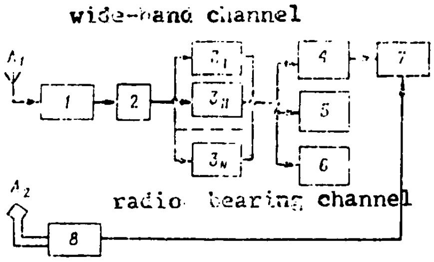


Fig. 8.1. Structural diagram of a typical signals intelligence installation

The channel separating, demodulation and decoding equipment provides the separation of one or several channels of multichannel REE and converts the signal into a form convenient for recording. After this the signal goes to the recording device 7 for recording.

The analysis equipment provides the analysis and separating out of the content of useful information. It can include spectrum analyzers for the oscillations emitted by the REE and this makes it possible to determine the values of the carrier and modulating frequencies and the sending power.

Indicators are used to convert the electrical signals into sound of visual ones and this makes it possible to establish their presence and determine certain parameters. The converted signals can be recorded on photographic or magnetic tape or directly viewed by an operator.

Recording equipment provides for a documentary recording of the intercepted signals and thereby an opportunity is created to reproduce their content for subsequent analysis.

The direction finding channel contains a high-directional antenna A_1 and a radio receiver 8 which form the radio direction finder. The signals of the REE are picked up by the antenna, they pass through the receiver and go to the recorder. The equipment of the direction finder provides an opportunity to determine the direction to the source of radiation. With two or more direction finders it is possible to determine the point coordinates of the REE.

Directing Finding Methods

The maximum method is a method whereby the direction to the source of emission is determined from the maximum signal on the output of the intercept receiver corresponding to the direction of its antenna to the source of transmission. This method is employed in the bands of centimeter and decimeter waves using high-directional antennas. The accuracy of direction finding is:

$$\Delta\theta_d = (0.1 - 0.25)\theta_a^{\circ} , \quad (8.1)$$

where θ_a°--width of directional pattern in receiver antenna.

The minimum method makes it possible to determine the direction to the source of transmission from the minimum signal on the receiver output. Here the antenna directional pattern has two lobes which are placed at a certain angle. Such a method is employed for direction finding of powerful sources of radiation in all the radio wave bands. This provides high accuracy of direction finding, however the operating range of the direction finder is less than with the maximum method.

The equisignal method provides accurate determining of direction to the radiating source by the equal amplitude of signals received by the antennas forming an equisignal direction. For this two antennas are used which form two overlapping beams with the directions of their maximums spread at a certain angle apart. The method possesses high direction finding accuracy with comparatively long operating ranges of the receiver.

With the phase method, determining the direction to a radiating source is achieved from the equality of the signal phases on the receiver output. In realizing the method two antennas are employed located on a certain base and forming two beams with the directions of their maximums parallel to the equisignal direction. The method provides high accuracy of direction finding.

The scan methods in direction finding can be circular and sector.

With circular scanning, the receiver antenna directional pattern turns in a circle at a rate:

$$\omega_a \leqslant \frac{\theta_a^\circ F_r}{n_{i\,\min}}, \tag{8.2}$$

where θ_a°--width of directional pattern in receiver antenna;
F_r--pulse repetition rate of intersected REE;
$n_{i\ \min}$--minimum number of pulses needed to analyze the signals transmitted by the REE.

With the operating of the intercepted REE under continuous sending conditions:

$$\omega_a \leqslant \frac{\theta_a^\circ}{t_n}, \tag{8.3}$$

where t_n--the necessary time for observing the signal whereby its amount on the receiver output reaches a set amount:

$$t_n \geqslant -\ln\left(\frac{u_{in} - u_{ou}}{u_{in}}\right)\frac{1}{\pi\Delta F_{re}}, \tag{8.4}$$

where u_{in}, u_{ou}--amounts of input and output voltages;
ΔF_{re}--width of receiver pass band.

The probability of detecting a signal in n turns of the antenna is:

$$P_n = 1 - e^{-np_1}, \tag{8.5}$$

where p_1--the probability of signal detection with one turn of the antenna.

With sector scanning, the directional pattern of the receiver antenna moves at a fixed speed in a certain sector. Here its angular velocity should not exceed an amount determined from the expressions (8.2), (8.3).

In intercept stations having antennas with a circular directional pattern, nonscan reconnaissance methods are employed. These provide the receiving of signals from any direction and instantaneously determine the bearing.

The range of ELINT in the USW band (not considering the attenuation of radio wave energy in the atmosphere) is:

$$D_{int} = \frac{\lambda}{4\pi}\sqrt{\frac{P_d G_c G_p}{n P_{re\,min}}\gamma_p}, \qquad (8.6)$$

where P_d, λ--radiating power and wave length of intercepted REE;

$P_{re\ min}$--sensitivity of receiver of intercept station;

G_c, G_p--coefficients for directional action of antenna in receiving and transmitting signals at angles θ_c, θ_p relative to the maximum;

γ_p--coefficient considering the wave polarization misalignment of the signal and the receiving antenna;

n--coefficient for the excess of the signal over noise.

The maximum possible intercept range in receiving the transmitted signals of the REE (Fig. 8.2) does not exceed the line-of-sight range D_{ls}:

$$D_{int} \leqslant D_{ls} = 4.12(\sqrt{H_r} + \sqrt{H_a}). \qquad (8.7)$$

where H_r, H_a--height of REE antenna and receiver, m;

D_{int}--intercept range, km.

The signals intercept sets and installations, as has been pointed out in foreign sources, provide interception of the characteristics of the means of communications, radar equipment and other devices transmitting radio signals.

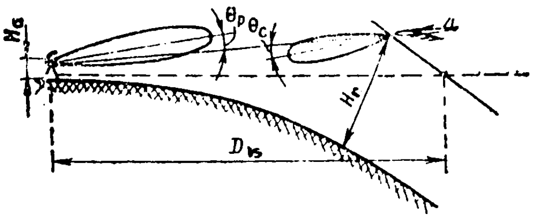


Fig. 8.2. On determining radio intercept range

The radio electronic neutralization or jamming equipment is equipment which creates interference for the REE, false targets and decoys, and equipment which alters the electrical properties for the medium of radio wave propagation.

The equipment for creating jamming for the REE (Fig. 8.3) creates radio signals which, in passing through the receiver of the REE, reduce the effectiveness of its reception. This includes equipment for creating active and passive jamming.

Active jamming is created by special jamming transmitters tuned to the operating frequencies of the REE to be neutralized and sending electromagnetic energy. A distinction is made between two types of active jamming: screening (neutralizing) and simulating (disinforming).

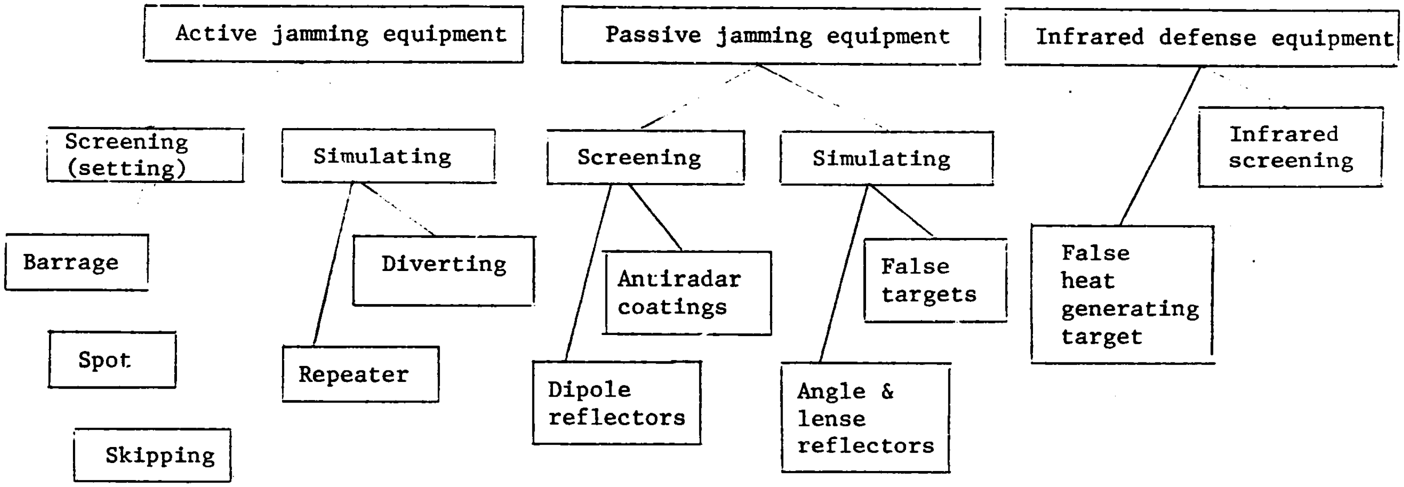
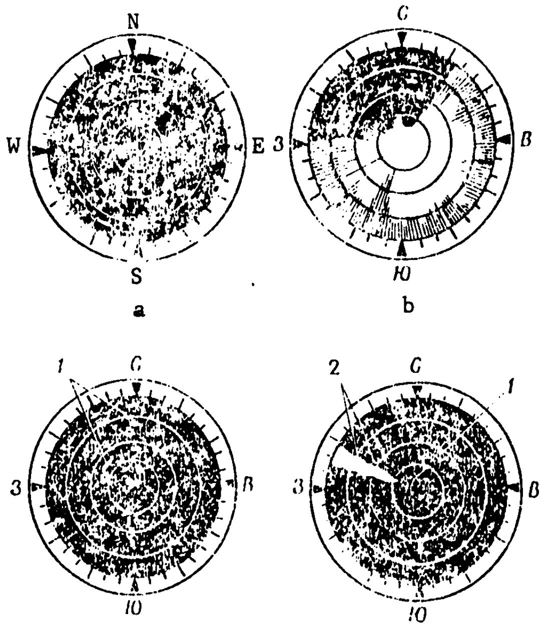


Fig. 8.3. A possible classification of radar clutter

On the screens of the REE to be neutralized, screening jamming creates a background on which it is difficult to distinguish the target blips (Fig. 8.4a, b). For creating this jamming transmitters are used which generate signals which are voltage modulated according to a random law (noise). A distinction is made between barrage and spot frequency jamming.

Barrage jamming is the name given to jamming the spectrum width of which is comparable with the tuning range of one or several REE operating on one or several frequencies. For creating barrage jamming, a precise knowledge of the REE operating frequency is not required. This jamming is employed for neutralizing REE the parameters of which are not sufficiently known.

Spot jamming has a spectrum width close to the passband width of the receiver of the REE being neutralized. This makes it possible to concentrate the jamming power in a narrow range of frequencies and increase the effectiveness of its action. Its creation requires a knowledge of the operating frequency and passband width of the REE.



a b

c d

Fig. 8.4. Appearance of radar indicator screens:

a--in the absence of jamming; b--with active screening jamming; c--with return-pulse jamming (1--signal from real target); d--with passive jamming (1--blip of jamming source; 2--blips from aircraft covered by jamming)

The signals from screening jamming can illuminate certain areas of the REE screens in the direction of the main and side lobes of the antenna directional pattern and worsen the P_s/P_n ratio impeding the isolation of useful information.

The transmitters of the active screening jamming can send continuous high-frequency oscillations which are modulated by the noise voltage or direct-noise jamming. Such jamming is called active noise jamming (ANJ). It possesses a broad spectrum. The energy capability of the transmitter is determined by the power density, watts/megahertz:

$$\rho_j = \frac{P_j G_j}{\Delta f_u}, \qquad (8.8)$$

where P_j, G_j--power and gain of jamming transmitter antenna;
Δf_j--width of jamming spectrum.

Skipping jamming (quasibarrage) is screening jamming which has a comparatively narrow spectrum with a rapid change in the carrier frequency. It is created by a jamming transmitter with a tunable sending frequency. In having a high-powered density, skipping jamming in its effect is close to spot jamming.

Simulating (disinforming) interference is radio signals sent by a jamming transmitter in response to the transmitted signals of a radar.

The simulated signal is created with the operating frequency of the radar and has parameters close to the parameters of the radar signals returned from the targets. The jamming signals received by the radar create false target blips on the indicator screens complicating the radar picture. For each pulse of the radar the jamming transmitter can send several jamming pulses simulating several targets (Fig. 8.4c). Such jamming is called repeater. The jamming transmitters can send jamming pulses the recurrence frequency of which does not equal the frequency F_r of the radar pulses. Such jamming is called pulse unsynchronized. On the radar screens this creates moving signals which impede the determining of the true target positions.

For creating screening jamming transmitters are employed which have elements shown in Fig. 8.5. The intercept receiver picks up the signals of the radar to be neutralized, it determines and remembers the radar's operating frequency and sends a control voltage to the frequency tuning unit of the microwave generator and for this the foreign jammers employ magnetrons, barratrons, traveling wave tubes and backward wave tubes.

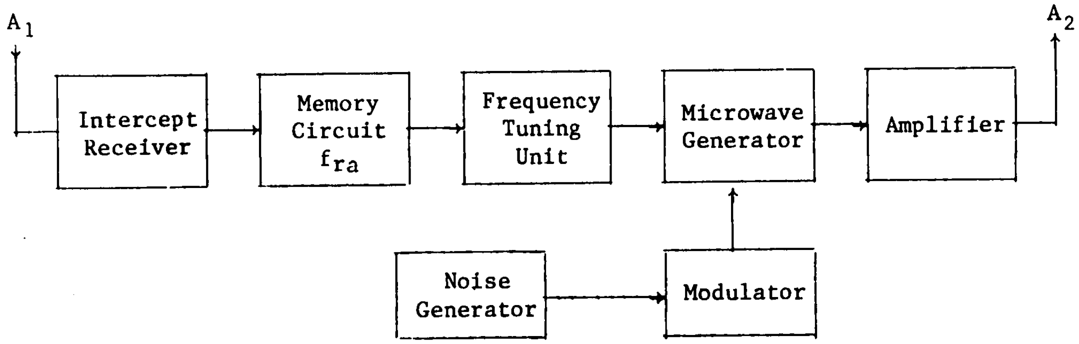


Fig. 8.5. Structural diagram of a jamming transmitter

The microwave generator produces high frequency oscillations that have a frequency equal to the operating frequency of the radar to be neutralized. The input of the high frequency generator receives a modulating voltage produced in the modulator. A noise generator can be employed as the driving source of the modulating voltage. After amplification these oscillations are transmitted by the antenna A_2 in the direction of the radar to be neutralized.

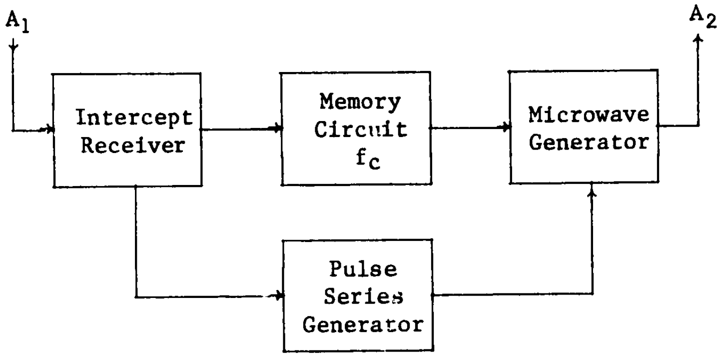


Fig. 8.6. Structural diagram of a transmitter of return pulse [repeater] jamming

Return pulse [repeater] jamming can be created in a transmitter which contains a receiving A_1 and transmitting A_2 antenna, a frequency storage circuit f_c of the REE, a generator of a series of modulating pulses and an amplifier (Fig. 8.6). The signals from the REE picked up by the antenna A_1 go to the frequency storage circuit and to the circuit of the modulating pulse generator which generates a certain number of pulses with preset parameters. These pulses go to the input of the high frequency generator which is frequency controlled. As a result the antenna A_2 sends out return pulse jamming signals.

Passive jamming is hindering signals created by the reflection of radio waves by solid bodies. As such bodies it is possible to use dipole reflectors, angle reflectors and so forth. The radar signals returned from a cloud of dipole interference creates a background on the indicators screening the target blips. The signals returned from angle reflectors can simulate target blips. For this reason passive jamming is divided into screening and simulating (see Fig. 8.3).

Screening jamming can be created by half-wave dipile reflectors which are metal-covered filaments of nylon, fiberglas, metal-coated paper and so forth. A cloud of dipole reflectors has an effective scattering surface of:

$$\sigma_0 = N\sigma_d, \tag{8.9}$$

where N--number of dipoles in cloud;
$\sigma_d = 0.17\lambda^2$--amount of effective scattering surface of one half-wave dipole (λ--radar wave length).

For creating a returned signal close in power to the target signal, it is essential to have a number of dipoles

$$N = \frac{S_{ef}}{\sigma_d}, \tag{8.10}$$

where S_{ef}--target radar cross-section.

The rate of dropping the dipole clusters from the aircraft t_c whereby the interference screens the target blip on the screen of the pulsed radar is:

$$t_c = \frac{c\tau_i}{2} \frac{\sigma_c}{V_c K_n S_{ef}}, \tag{8.11}$$

where τ_i--radar pulse length;
σ_c--effective scattering surface of the dipole cluster;
S_{ef}--target radar cross-section;
V_c--speed of aircraft flying under jamming cover;
K_n--neutralization factor.

Antiradar coatings are a means of camouflaging the targets. These are divided into absorbing and interference. Absorbing materials can be applied to the surface being camouflaged in the form of multilayer coatings and this significantly reduces the reflection of radio waves and creates a great absorption of their energy. Interference coatings attenuate the energy of the reflected wave by several-score-fold, significantly reducing the target radar cross-section.

For simulating targets it is possible to employ angle reflectors dropped from the jamming aircraft on parachutes. These can be reflectors with triangular, rectangular or sector sides. Their maximum reflecting surface is determined from the expressions:

$$\left.\begin{aligned} S_{ef\triangle} &= \frac{4}{3}\pi\frac{a^4}{\lambda^2}; \\ S_{ef\square} &= 12\pi\frac{a^4}{\lambda^2}; \\ S_{ef\triangleright} &= 2\pi\frac{a^4}{\lambda^2}. \end{aligned}\right\} \tag{8.12}$$

where a--length of reflector rib;
λ--wave length.

With comparatively small sizes of the sides (tens of cm), an angular reflector with λ = 3 cm can create a more intensive blip on the radar screen than a bomber.

Another means for creating false blips on radar screens is the Luneberg lens. The radar cross-section of such a lens is:

$$S_{efL} = 4\pi^3 \frac{R^4}{\lambda^2}, \tag{8.13}$$

where R--lens radius.

There is a number of lens modifications which provide intensive reflection of the radio waves and create intensive blips on the indicator screens. A wide-band reflecting antenna array can be used as one of the means possessing the property of strong reflection.

Abroad the possibility is being examined of employing flying bombs as false targets. Such flying bombs can be launched from carrier aircraft. In possessing a significant radar cross-section, the decoy bombs can create blips on the radar screens that complicate the radar picture. It has been pointed out that a B-1 bomber can carry 25-30 false targets.

The decoy flying bombs can also be used as a "lure" for antiaircraft and air-launched missiles. Some of them can carry a nuclear charge.

Equipment for countering infrared devices (onboard passive missile seekers) can be divided into false heat-generating targets and screening devices.

False heat-generating targets (infrared decoys) are pyrotechnic devices which create intense thermal radiation in the infrared wave band.

Jamming for ground radars can be carried out both by specially assigned jammer aircraft as well as by all the groups in a combat group. Here the jammer aircraft can remain in the air patrol zone creating jamming in a certain direction.

With the second method the jamming can be created by individual jamming aircraft which are part of the assault group or by all the group's aircraft equipped with the corresponding devices.

Equipment for the fire neutralization of REE includes the antiradar homing rockets (for example, the U.S. Shrike). Such rockets have a passive radar homing system which guides the rocket from signals transmitted by the radar. As a result of the detonating of the warhead, the rocket can knock out elements of the station.

Radio electronic defense is an aggregate of organizational and technical measures which ensure the continuous operation of the REE under the conditions of the creation of radio jamming by the enemy. This includes passive and active measures to combat signals intelligence and radio electronic neutralization.

Among the equipment for radio electronic defense are the jamming signal compensation devices, the devices for frequency, structural and spatial selection of target signals and devices for time and frequency control of the REE.

For countering enemy intelligence equipment it is possible to employ various angular reflectors and sources which emit misinforming signals or absorb the electromagnetic energy of the medium.

8.2. Ensuring Electromagnetic Compatibility of Radio Electronic Equipment

The development of modern radio electronics has been accompanied by two contradictory factors. On the one hand, the continuous increase in the amount of radio electronic equipment (REE) and on the other the limited opportunities for utilizing the radio-frequency bands which has led to the rise of the problem of electromagnetic compatibility (EMC) in operating various REE.

Electromagnetic compatibility is the aggregate of properties of the REE and their operating conditions whereby no interference arises disrupting the operation of other REE and at the same time ensures normal operation with a limited noise level from various radiating sources (Table 8.1).

Table 8.1

№ диапазона a	Наименование диапазона b	c Границы диапазона	
		d по частоте	e по длине волны
1	Крайние низкие частоты (КНЧ)	3—30 Гц (f	100 000—10 000 км
2	Сверхнизкие частоты (СНЧ)	30—300 Гц	10 000—1000 км
3	Инфранизкие частоты (ИНЧ)	300—3000 Гц	1000—100 км
4	Очень низкие частоты (ОНЧ)	3—30 кГц (g	100—10 км
5	Низкие частоты (НЧ)	30—300 кГц	10—1 км
6	Средние частоты (СЧ)	300—3000 кГц	1000—100 м
7	Высокие частоты (ВЧ)	3—30 МГц (h	100—10 м
8	Очень высокие частоты (ОВЧ)	30—300 МГц	10—1 м
9	Ультравысокие частоты (УВЧ)	300—3000 МГц	100—10 см
10	Сверхвысокие частоты (СВЧ)	3—30 ГГц (i	10—1 см
11	Крайне высокие частоты (КВЧ)	30—300 ГГц	10—1 мм
12	Гипервысокие частоты (ГВЧ)	300—3000 ГГц	1—0,1 мм

Key: a--Band number; b--Name of band; c--Limits of band; d--For frequency; e--For wave length; f--Hertz; g--Kilohertz; h--Megahertz; i--Gigahertz; 1--Extremely low frequencies (ELF); 2--Super-low frequencies (SLF); 3--Infra-low frequencies (ILF); 4--Very low frequencies (VLF); 5--Low frequencies (LF); 7--High frequencies (HF); 8--Very high frequencies (VHF); 9--Ultra-high frequencies (UHF); 10--Super-high frequencies (SHF); 11--Extremely high frequencies (EHF); 12--Hyperhigh frequencies (HHF)

Table 8.2

№ поддиапазона a	Наименование поддиапазона b	c Границы поддиапазона	
		d по частоте	e по длине волны
1	Инфракрасные лучи дальнего поддиапазона	3—30 ТГц (f	10^{-4}—10^{-5} м
2	Инфракрасные лучи ближнего поддиапазона	30—400 ТГц	10^{-5}—$0,76 \cdot 10^{-6}$ м
3	Видимые лучи	400—750 ТГц	$(0,76$—$0,4) \cdot 10^{-6}$ м
4	Ультрафиолетовые лучи ближнего поддиапазона	750—3000 ТГц	$0,4 \cdot 10^{-6}$—10^{-7} м
5	Ультрафиолетовые лучи дальнего поддиапазона	3000—30 000 ТГц	10^{-7}—10^{-8} м

Key: a--Sub-band number; b--Sub-band name; c--Sub-band limits; d--For frequency; e--For wave length; f--Terahertz; 1--Infrared rays of the far sub-band; 2--Infrared rays of the near sub-band; 3--Visible rays; 4--Ultraviolet rays of the near sub-band; 5--Ultraviolet rays of the far sub-band

A classification of radio frequencies. The spectrum of electromagnetic oscillations encompasses frequencies from approximately 10^{-3} to 10^{23} hertz. The portion of electromagnetic oscillations having a frequency below $3 \cdot 10^{12}$ hertz is occupied by the radio frequencies which are in turn divided into 12 bands.

A radio frequency band is an area of radio frequencies including the EM oscillations lying within certain limits.

Each of the bands is within the limits from $0.3 \cdot 10^n$ to $3 \cdot 10^n$ hertz (where $n = 1, 2, 3, \ldots, 12$--the band number. By a frequency band one can also understand frequency areas with large frequency limits if this is caused by organizational or technical considerations. The radio frequency bands used in practice are shown in Table 8.1.

The optical band. With the shortening of the waves the quantum nature of electromagnetic oscillations becomes evermore essential and their wave properties are ever-less apparent.

For this reason the electromagnetic oscillations of the optical band are called rays and they are divided into the sub-bands given in Table 8.2. In accord with the International System of Units there are the following ratios:

1. *For frequencies:*

   1 kHz (kilohertz) = 10^3 hertz;
   1 MHz (megahertz) = 10^6 hertz;
   1 GHz (gigahertz) = 10^9 hertz;
   1 THz (terahertz) = 10^{12} hertz.

2. *For wave lengths:*

   1 μm (micrometer) = 10^{-6} m;
   1 nm (nanometer) = 10^{-9} m;
   1 Å (angstrom) = 10^{-10} m;
   1 pm (picameter) = 10^{-12} m.

The basic ratios for EM oscillations. Electromagnetic oscillations are characterized by the following amounts; wave length λ, m; oscillation frequency f, hertz; oscillation period T, c; phase ϕ; circular frequency ω, hertz; rate of propagation c, m/second.

Between these values there are the following dependences:

$$\lambda = cT;\ f = 1/T;\ \omega = 2\pi f;\ \phi = \omega t (c = 3 \cdot 10^8 \text{ m/sec.}).$$

Parameters which characterize EMC. These include: operating frequency f_0; radiating power P_{rad}; band width of basic transmitter sending Δf_{tr}; modulating oscillations (depth of amplitude modulation, amount of frequency deviation, duration and relative duration of pulses and so forth); receiver sensitivity $P_{re\ min}$ (in the operating frequency and nonbasic frequencies); receiver selectivity (frequency, amplitude and time) for the basic and adjacent channels; the minimum value of the signal/noise ratio q_{min} which ensures normal operation of the REE; frequency stability of the radiolink (transmitter and receiver); antenna directional pattern and gain (considering the side lobes); screening factors for the REE devices.

The necessary frequency band is the minimum band width for the given class of radiation sufficient for transmitting information at the required rate and quality.

The basic radiations are the radiations of the transmitters on frequencies (frequency) within the limits of the band required for transmitting the given type of signals (messages).

Nonbasic radiations are radiations in the frequencies (frequency) located beyond the necessary radiation band. These are divided into stem and extra-band.

Stem radiation is a broad class of nonbasic radiations the frequency and levels of which are determined by random-nature high frequency processes not related to the modulation process.

Extra-band radiations are a class of nonbasic radiations on the frequencies adjacent to the necessary band and arising in the process of modulating the transmitted signal (message).

Harmonic radiations are stem radiations on frequencies which are multiples of the basic radiation frequencies.

The amplitude of the harmonic n is calculated through the pulse amplitude A by the following ratio:

$$A_n = Aa_n,$$

where a_n--coefficient for the expansion of the periodic function (signal) into a Fourier series.

For a periodic sequence of rectangular pulses with a period t and a duration i, the values of the coefficients are determined by:

$$a_n = 2A\frac{\tau_i}{T}\frac{\sin\left(\frac{\pi n\tau_i}{T}\right)}{\frac{\pi n\tau_i}{T}}. \qquad (8.14)$$

Combination radiations are stem radiations arising in the formation of oscillations or the basic radiation by nonlinear conversions of auxiliary oscillations.

Thus, in mixing two oscillations with frequencies f_1 and f_2 there is a combination of totals and differences for the harmonics of these frequencies which can fall into the receiver pass band:

$$|\pm mf_1 \pm nf_2| = f_0 \pm \frac{\Delta f_p}{2},$$

where m and n = 1, 2, 3,...--integers;
f_0--carrier frequency;
f_p--receiver pass band.

Spurious radiations are stem radiations the reason for which is not related to the formation of the basic oscillation (radiations from auxiliary units of the transmitter with the occurrence of self-excitation conditions).

Noise radiations are extraband radiations created by the spurious modulation of the voltage of noise arising in the transmitter elements.

Industrial noise is noise caused by the high-frequency radiations of industrial, scientific and medical equipment as well as the noise created by moving transport, power transmission lines as well as household appliances.

According to the health rules, the maximum permissible electric intensity levels from industrial high frequency units are 20 V [?volts] per meter (in a frequency band of 10^5-$3\cdot10^7$ hertz); 5 B/m (in a frequency band of $3\cdot10^7$-$3\cdot10^9$).

The magnetic field intensity should not be more than 5 angstrom per meter (in a frequency band of 10^5-$3\cdot10^6$ hertz).

The basic receiving channel is a radiofrequency band providing the reception of the basic radiation and matched with the receiver pass band.

The secondary receiving channel is a radio frequency band beyond the limits of the basic receiving channel in which the attenuation of jamming is less than the set for the given device.

The mirror receiving channel is a secondary receiving channel the average frequency of which is distant from the tuning frequency of the receiver by an interval equal to the doubled intermediate frequency and the heterodyne frequency is in the middle of this interval.

Measures ensuring electromagnetic compatibility of the REE. For solving the problem of the EMC of various types of radio electronic equipment, technical (design) and organizational measures are employed. These include: elimination or maximum attenuation of the nonbasic radiations, the design isolating of the transmitters and receivers, the employing of different polarization radiations, optimum signal filtration, spatial and frequency separation of the REE as well as matching the operation of the REE in time and so forth.

Spatial separation of REE is the locating of REE at a distance apart ensuring normal operation due to the attenuating of the EM energy over distance. Here two variations are possible: the first--spatial separation of the REE having the same carrier frequencies; the second--spatial separation of the REE having different carrier frequencies.

For REE having the same carrier frequencies, the excluding of interference is achieved by spatial separation the amount of which is in meters:

$$L \geqslant \sqrt{\frac{P_{tr\,m} G_{tr\,m} G_{re\,p} \lambda^2}{(4\pi)^2 P_{re\,min\,p} q_p K_{re\,p}}}, \qquad (8.15)$$

where P_{trm}--power of transmitter blocking the REE, watts;
G_{trm}--gain (for basic or side lobes) of transmitting antenna in the blocking REE;
G_{rep}--gain (for basic or side lobes) in receiving antenna of operating REE;
$P_{re\ min\ p}$, q_p, K_{rep}--respectively, sensitivity, detection factor and attenuation factor in receiver of operating REE;
λ--wave length of blocking and operating REE.

Consequently, the level of the blocking signal P_{bs} considering the spatial separation is:

$$P_{bs} \geqslant \frac{P_{tr\,m} G_{tr\,m} G_{re\,p} \lambda^2}{(4\pi)^2 K_{re\,p} L^2}. \qquad (8.16)$$

The ratios (8.15) and (8.16) make sense within the limits of the line-of-sight range determined by formula (3.65).

If $P_{bs} \geqslant P_{re\ min}\ q_p$, then the signal of the adjacent REE will have a blocking effect and additional measures will be required to attenuate it.

For the REE having different frequencies, additionally in formula (8.15) one must introduce a frequency separation coefficient K_f the value of which with the complete frequency isolation moves toward infinity and with a coinciding of the frequencies equals 1, that is, $1 \leqslant K_f \leqslant \infty$.

Here the spatial separation should satisfy the following inequality:

$$L \geqslant \sqrt{\frac{P_{tr\,\text{и}} G_{tr\,\text{и}} G_{re\,p} \lambda_p^2}{(4\pi)^2 P_{re\,\min p}\, q_p K_{re\,p} K_f}}. \qquad (8.17)$$

where λ_p--wave length of operating REE;
K_f--frequency separation coefficient.

The frequency separation of REE, in addition to employing different frequencies, presupposes the presence of frequency isolating devices, optimum filters as well as the use of different polarizations. The amount of the frequency isolation is characterized by the frequency separation coefficient K_f. With $K_f \to \infty$, frequency-separated REE can be located directly next to one another [formula (8.17)].

The K_f coefficient is determined experimentally.

Interference of REE as a consequence of tropospheric scattering. For determining the possibility of a blocking influence from a source of interference coming to the receiver input of an operating REE as a result of tropospheric scattering, in formula (8.17) one should substitute the value of the attenuation multiplier K_{ts} as caused by this scattering.

The values of this coefficient for frequencies from 100 to 4,000 megahertz and distances from 100 to 700 km are given in a graph (Fig. 8.7).

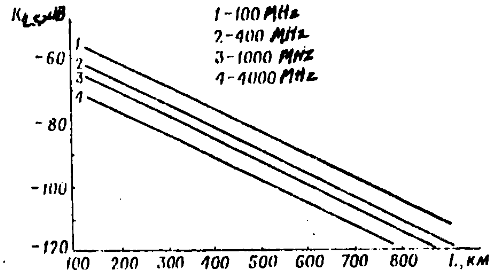


Fig. 8.7. Graph showing changes in tropospheric scattering coefficient

The distance D_{in} of interference of the REE due to tropospheric scattering will be determined as:

$$D_{in} = \sqrt{\frac{P_{tr\,\text{и}} G_{tr\,\text{и}} G_{re\,p} \lambda_p^2}{(4\pi)^2 P_{re\,\min p}\, q_p K_{ts} K_f}}. \qquad (8.18)$$

In turn, this distance will be determined by the values of the height H of tropospheric inhomogeneities from which derives the reflection of the EM oscillations and the elevation for the directional pattern of the blocking REE.

The area covered due to tropospheric scattering by the blocking REE (radar) in the location of the operating REE is:

$$S \approx \frac{\pi H^2 \theta_\varepsilon \theta_\beta}{\sin^2 \varepsilon}. \qquad (8.19)$$

where θ_ε and θ_β--the width of the directional pattern of the blocking REE in the planes of ε and β respectively.

Matching the operation of the REE for time. In those instances when it is impossible to exclude the blocking effect of interference between the REE due to spatial-frequency drift, it is essential to match their operation in time.

This is achieved by: introducing a time schedule for the operation of the different REE excluding the simultaneous operation of the REE in opposite directions, by introducing a ban on the operation of individual REE for certain periods of time, by providing reciprocal synchronizing of the REE comprising a single grouping and so forth.

Problems of EMC. A practical solution to EMC is related to solving a whole series of problematic questions: the elaborating of the EMC criteria, norming the REE parameters, developing instruments with a reduced level of stem and extraband radiations, by seeking out technical ways to reduce interference, by working out special metering methods, by creating a unified EMC theory and so forth.

Providing EMC of radio electronic equipment is achieved by coordinating various measures relating to the target, the tasks, the place and the time.

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