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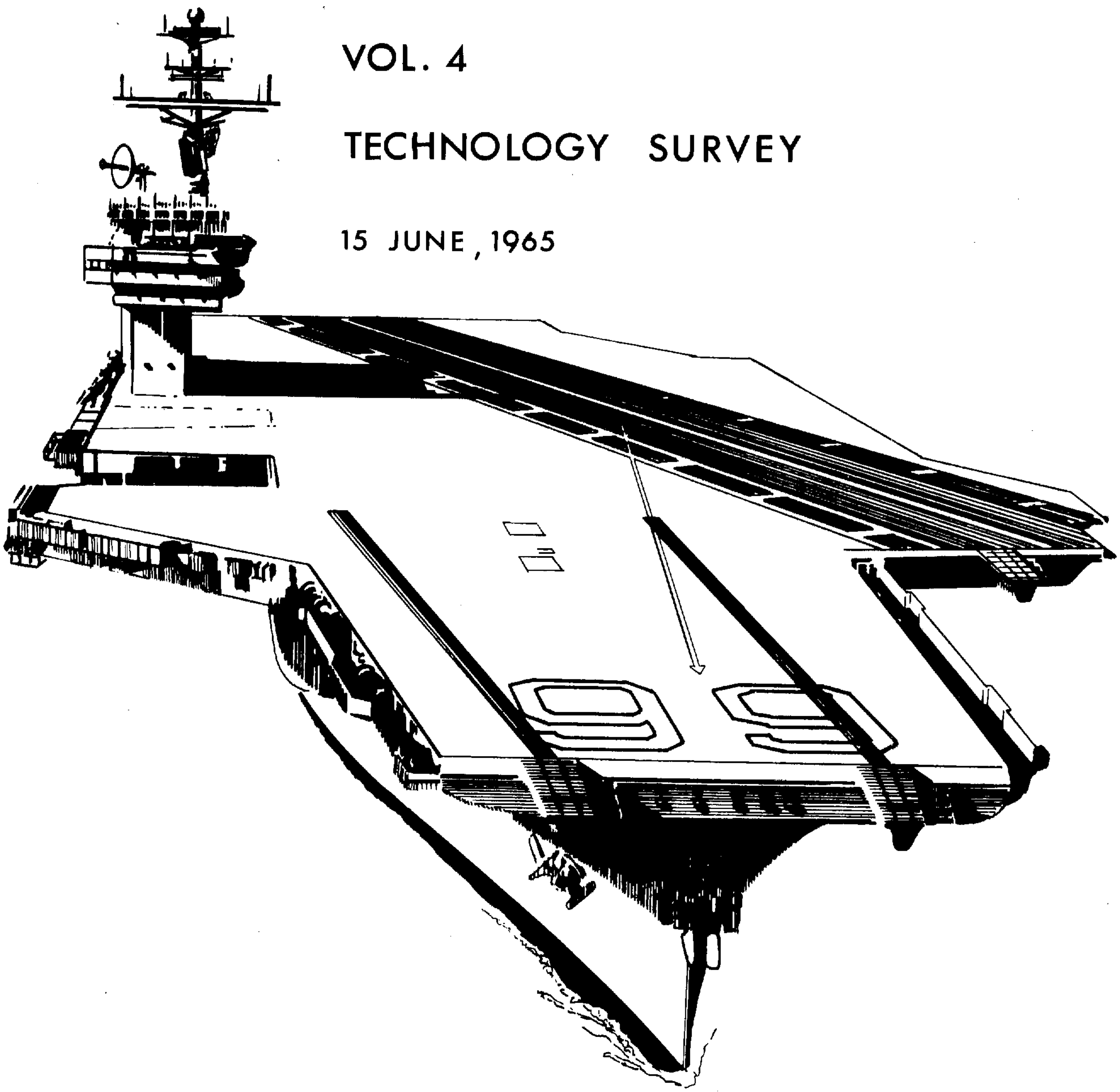
TACTICAL MULTISENSOR RECONNAISSANCE (U)



VOL. 4

TECHNOLOGY SURVEY

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FIGURES

FIGURES (Continued)

1. INTRODUCTION

The technology surrounding multisensor reconnaissance operations requires a breadth of understanding beyond the general knowledge of a specific sensor technology. This survey brings together the basic knowledge of principles and techniques surrounding each of the four basic sensors commonly used for "multisensor" reconnaissance. There sensors encompass photography, infrared, side looking radar, and electronic intelligence. The information from each sensor technology is designed to provide a basic understanding of the building blocks with which each must inherently deal.

The contents of this document are by their nature a combination of basic and transient data. In that light, further modification of the information should be expected from time to time.

This volume is the technology survey for the Tactical Multisensor Reconnaissance document. It contains the detail information which has been purposely abbreviated in the preceding volumes in order that the reader not become mired in detail not pertinent to the text.

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2. PHOTOGRAPHIC SENSORS

Photographic data acquisition in a tactical situation is a continuing process. Prior to initial data acquisition, maps or course charts are usually available, augmented by reports of visual observation and other intelligence data. The commanders involved usually have a reasonable idea of what to look for and where continuing activity should be monitored. However, data acquisition requirements change depending upon the operation that is involved.

Ground forces need various types of information. Artillery commanders want low distortion in their photography so that range and azimuth to potential targets can readily be determined. Infantry commanders want maximum detail, but over relatively small areas. Armored units want stereo coverage to enable them to scale heights of terrain and obstacles and measure grades.

Air forces want confirmation of strike effectiveness; they are generally more interested in the overall picture: road and rail networks, towns and villages, location of airfields and possible emergency landing sites.

Operations and Intelligence want to see repeated coverage to detect changes since their last "look". Higher Headquarters want large area coverage and general surveillance type of information.

Whatever the requirement, all information is wanted quickly, plus being easily legible, tilted, annotated and, if possible, fully interpreted. In addition, operations cannot be limited to daytime only, and provision must be made for night-time coverage which requires artificial illumination.

Unfortunately, different requirements call for contradictory solutions. Thus, the long focal length, high-altitude spotting camera, ideal for bomb assessment work, is unsuitable for obtaining close detailed information for infantry support. Therefore, in response to many different needs, many different types of cameras have become available over the years. Some of these were designed for specific applications, while others represent compromises to make them more versatile and generally acceptable. We will now consider some of the characteristics which determine the use of a camera. Initial discussion will be primarily concerned with the frame camera; the strip and the panoramic camera will be covered further along in the text.

2.1 GENERAL CAMERA CHARACTERISTICS

There is a basic division between a high-altitude application in which a relatively large area can be covered with a reasonable amount of group detail, and a low-altitude application aimed at obtaining the finest possible ground detail over a relatively restricted area. This leads directly to considerations of:

1. Focal Length
2. Ground Resolution
3. Angular Coverage
4. Camera Size

2.1.1 Focal Length Versus Ground Resolution

Since the scale of the resultant photography is equal to the ratio of focal length over altitude, the focal length primarily determines how small an object can be resolved from a given altitude. Of course, this is an over-simplification, since many other factors will affect the final ground resolution. (It is in accord, however, with the "first law of aerial reconnaissance" formulated by General George Goddard: "There is no substitute for Focal Length.") The choice of focal length therefore depends on how fine an object the user needs to resolve on the ground and from what altitude.

Typically, in the arbitrary altitude ranges of 300 to 1,500 feet for a low altitude range and above 30,000 feet for a high altitude range, the following resolutions would be expected:

Low Altitude: 4 inches to 1-foot resolution
High Altitude: 1 to 5-foot resolution

With the lens-film resolutions currently available, focal length selections for the different altitudes can be made. Using presently available equipment, and

Using presently available equipment, and varying with the film type and format, the obtainable lower and upper resolution boundaries can be arbitrarily set as follows:

15 to 20 lines per millimeter can readily be obtained in nearly all cases

100 lines per millimeter or more is difficult to obtain operationally and require rather sophisticated equipment.

Itek and other companies have produced equipment that exceeds the 100 lines per millimeter upper boundary consistently; some systems do not always meet the 15 to 20 lines per millimeter taken as the lower boundary. These represent, however, generally valid limitations.

A table can now be constructed which shows the resolution (in lines per millimter) for various focal lengths required to meet the desired ground resolutions from representative altitudes. Table 2-1 shows these values for focal lengths from 1.5 to 24 inches.

A number of conclusions can be drawn from this table.

1. 1.5 to 2-inch focal lengths will comfortably accommodate requirements to 1,000 feet altitude.

2. 2 to 3-inch focal lengths will handle requirements to altitudes of 2000 feet.

3. 12-inch focal lengths will be adequate at the lower end of the high-altitude range, and will be satisfactory at the upper end of this range for ground resolutions beyond two feet.

4. If a single focal length had to be chosen to cover both high and low altitudes, a 6-inch focal length would be most satisfactory - at least for the low and medium speed aircraft.

2.1.2 Angular Coverage

The angular coverage obtained with lenses of a given focal length varies with the chosen film format. The cross-track angular coverage determines how wide a swath of terrain can be recorded from a given altitude, while the

Table 2-1 - Lens-Film Resolution Required for Desired Ground Resolution

Ground Resolution	Focal Length	Lens-Film Resolution (1/m) at 1000 ft	2000 ft	30,000 ft	50,000 ft
4 in	1.5 in	80	160		
1 ft		27	53		
4 in	2 in	60	120		
1 ft		20	40		
4 in	3 in	40	80		
1 ft		13	26		
4 in	6 in	20	40		
1 ft		7	13	197	330
3 ft				67	110
4 in	12 in			197	
1 ft				98	165
3 ft				33	55
4 in	24 in			150	250
1 ft				50	82
3 ft				17	27

fore-and-aft, or along-track, angular coverage determines, for a given aircraft velocity and altitude, the rate at which photographs must be taken to obtain continuous coverage of the terrain. Using conventional frame cameras, and for a particular film format, a shorter focal length provides an increase in the width of the swath of terrain that can be covered and a decrease in the cycling time (i.e., frame rate).

The trade-offs in this case are that the shorter the lens focal length, the smaller will be the scale of the resultant photography from any given altitude, and, in general, the coarser will be the ground resolution. Moreover, it is more difficult to achieve high resolution in lenses of wide angular coverage than in lenses with a relatively narrow field of view. This also applies to making lenses of wide relative aperture, which results in fast exposure times. It is very difficult to make "fast" wide-angle lenses of reasonable quality.

Table 2-2 shows the angular coverage in degrees of different focal length lenses on the three most commonly used formats - 70 mm, 5-inch and 9 1/2-inch film.

Table 2-3 has been calculated for a number of representative altitudes to give the reader a feeling for the equivalent ground distance covered by a vertical camera with the angular coverages calculated in Table 2-1.

Table 2-3 illustrates one of the problems of present day tactical reconnaissance. As aircraft fly lower and lower, each photograph covers an even smaller area. As an example, an angular coverage of 41.1 degrees - typically, what a 6-inch focal length camera can record on 5-inch film - will cover only about 225 feet on the ground when flying at 300 feet altitude. To extend the cross-track coverage, a "fan" of cameras must be used, or panoramic cameras must be employed. Panoramic cameras using existing lenses can give side-to-side coverage from horizon to horizon.

Another factor directly affected by the angular coverage is the cycling rate of the camera equipment. The tendency has been to make tactical aircraft fly both faster and lower to make them less vulnerable to enemy defenses, which then requires, for any given angular coverage, higher frame rates. Frame rates in modern reconnaissance cameras range from one frame every 1 to 3 seconds for the larger formats to 3 to 8 frames per second for the smaller formats. These

Table 2-2 - Angular Coverage of Different Focal-Length Lenses on Standard Film Formats

Focal Length (inches)	Film Size 70-mm	5-inch	9 1/2-inch
1.5	73.7°	–	–
2	58.8	96.8°	–
3	41.1	73.7°	–
6	21.2	41.1°	73.7°
12	10.8°	21.2	41.1°
24	5.4°	10.8°	21.2°

Table 2-3 - Equivalent Ground Distance Covered (in feet) by a Vertical Camera of Given Angular Coverage from Several Representative Altitudes

Angular Coverage	Altitude (ft) 300	1000	2000	30,000	50,000
73.7°	450	1500	3000	45,000	75,000
58.8°	340	1120	2240	33,700	56,000
41.1°	225	750	1500	22,500	37,400
21.2°	110	375	750	11,300	18,700
10.8°	–	–	375	5,600	9,300
5.4°	–	–	–	2,800	4,700

rates are barely adequate for current low-altitude missions, and may fall short of projected requirements.

Table 2-4 is a compilation of cycle times required in order to obtain 55 percent overlap (for stereo coverage) in cameras of varying angular coverage operating at representative altitudes, typical of both the low and high-altitude missions. For each case, three values have been computed, corresponding respectively to 700 feet per second (415 knots), 1000 feet per second (590 knots), and 1500 feet per second (890 knots). Even using a relatively wide-angle lens covering 73.7 degrees-typically, a 3-inch lens on a 5-inch format - operation must be at five frames per second when operating from 300 feet at a ground speed of 1000 feet per second. At smaller angular coverages, required cycle times become shorter; a 41.1 degree coverage from an altitude of 300 feet and at a relatively moderate velocity of 700 feet per second results in a cycle time of only 0.14 seconds, which is equivalent to a frame rate of 7 exposures per second.

Thus, the frame rate (i.e., the inverse of the cycle time) increases directly with the ground speed (V), and decreases with altitude (h). It is common usage to say that the frame rate is proportional to the ratio of V/h. V/h ratios can be expressed either as feet-per-second/feet-of-altitude, in which case the resultant dimension is sec^{-1} or radians-per-second; or it may be expressed as knots/feet-of-altitude or knots/foot. As an example, the values shown in Table 2-4 range from 700 feet per second/50,000 feet of altitude to 1500 feet per second/300 feet of altitude, which is equivalent to 0.014 to 5.0 radians/second. Alternatively, it can be said that the V/h ratios range from 0.0083 to 2.96 knots/foot.

2.1.3 Camera Size

Camera size is influenced primarily by the focal length of the lens and by the film size employed. A 12-inch focal length camera recording on 9 1/2-inch film is the equivalent in coverage and frame rates to a 3-inch focal length camera recording on 70 mm film; furthermore, if the larger camera averages around 15 lines per millimeter while the smaller one yields 60 lines per millimeter, the two will be equivalent to one another in the amount of information obtained. Yet, the first camera will easily occupy 12 to 20 times as much

Table 2-4 - Cycle Times Required at 55% Overlap for Various Angular Coverages, at Representative Altitudes and Ground Speeds

		Ground Speed		
Angular Coverage	Altitude	700 ft/sec	1000 ft/sec	1500 ft/sec
73.7°	300 ft	0.29 sec	0.20 sec	0.14 sec
	1000	0.97	0.68	0.45
	2000	1.9	1.4	0.90
	30,000	29.	20.	14.
	50,000	48.	34.	22.
58.8°	300	0.22 sec	0.15 sec	0.10 sec
	1000	0.73	0.51	0.34
	2000	1.4	1.0	0.68
	30,000	22.	15.	10.
	50,000	36.	25.	17.
41.1°	300	0.14 sec	0.10 sec	0.07 sec
	1000	0.48	0.34	0.23
	2000	0.96	0.68	0.46
	30,000	14.	10.	6.8
	50,000	24.	17.	12.
21.2°	300	0.07 sec	0.05 sec	0.03 sec
	1000	0.24	0.17	0.11
	2000	0.48	0.34	0.23
	30,000	7	5.1	3.4
	50,000	12	8.5	5.6
10.8°	300	–	–	–
	1000	–	–	–
	2000	0.24 sec	0.17 sec	0.11 sec
	30,000	3.6	2.5	1.7
	50,000	6	4.2	2.8

space, and will weigh over 10 times as much as the second one. The obvious questions are why aren't we using only small cameras, and what are the advantages of the larger cameras over the smaller ones?

The first question can be answered by saying that initially space was available to accommodate the larger cameras. However, the trend throughout the tactical reconnaissance field has been away from the 9 1/2-inch format and toward the 5-inch and even 70-mm sizes, the reason being that there just is not enough room in the modern high-performance tactical aircraft to accommodate the larger cameras. This is even more true of unmanned reconnaissance drones which nowadays tend to be smaller and less vulnerable. Here 70-mm equipment has come into much use.

As for the second question, the main advantage of 9 1/2-inch photography over the smaller sizes is that it can be viewed directly without the need for making enlargements or using magnifying viewers. However, where hard-copy prints must be distributed, modern techniques make it almost as easy to print enlargements as it is to make contact prints. In the final copy, it is often very difficult to say whether the print is a 4X enlargement from a 70-mm frame or a contact print from a 9 1/2-inch film.

As a whole, low-altitude cameras are relatively small while high-altitude cameras tend to be larger.

One of the most important factors in determining the size of a camera system is the total area one must cover in a single mission and, in turn, the quantity of film that must be carried. It can readily be seen that flying low and fast requires the exposure of a great deal of film in a very few minutes. Fortunately, the fine detail obtainable from this type of low-altitude mission is not usually required over more than a relatively small area.

Typically, a 3-inch focal length camera using 5-inch film and flying at 1000 feet will use as much film (approximately 140 feet with 55 percent overlap) in covering a 40-mile long strip, as will a 12-inch focal length camera also using 5-inch film, but flying at 30,000 feet and covering a strip 300 Nautical Miles long. Also, the high-altitude camera will cover this strip with a swath over seven times wider than the single low-altitude camera.

2.2 FRAME CAMERAS VERSUS OTHER TYPES OF CAMERAS

So far, the discussion has been based primarily on the use of frame cameras. They are the most widely used type of camera, and until quite recently were practically the only ones available. However, as pointed out in the discussion, modern trends in tactical reconnaissance has promulgated two basic problems:

1. The need for ever faster cycling rates when using frame cameras at continuously lower altitudes and faster speeds, and
2. The need for wider cross-track coverage than can be obtained with conventional lenses.

These problems have led to the development of the Strip Camera and the Panoramic Camera.

2.3 STRIP CAMERAS

The strip camera developed from the concept of image motion compensation (IMC). The basic idea of IMC is that photography of a moving object with the maximum amount of sharpness requires that the object's motion be followed during the time of exposure. Press photographers have done this for years when taking pictures of automobile races and similar events; they track the object to be photographed, and operate the shutter some time during this tracking operation.

In reconnaissance photography, where the ground appears to move under the aircraft, often at a rather fast rate, IMC becomes important particularly when ambient light conditions do not permit operation at fast shutter speeds. Most high-performance aerial cameras have some means of image motion compensation. Although a number of ways exist to "track the ground" during film exposure, one of the better methods is to move the film inside the camera in proportion to the apparent ground motion. Done properly, this means that although the image of the ground moves inside the camera, the film on which the scene is recorded will move at precisely the same rate, resulting in a sharp, unblurred photograph. The ratio required for perfect IMC between the apparent ground motion and the film motion is focal length over the flying altitude above terrain.

The next step in IMC development was caused by the following reasoning. Since film is transported between frames, the transport mechanism could be made to be double duty. If the camera is oriented such that the take-up reel is in the direction of flight, then a relatively small amount of film can be transported during exposure (and at the proper speed) for IMC. After completion of the exposure, the balance of the exposed frame could be taken up.

After this, it only remained to combine the idea of IMC with that of a focal plane shutter, in which the total format is exposed by a slit traveling from one edge to the other. The width of the slit divided by the rate at which it moved across the format determined the exposure time. This became then the strip camera as shown schematically in Fig. 2-1.

Using Fig. 2-1, a lens of focal length f is shown being flown over terrain at an altitude, h. The ground appears to recede at a velocity Vg, and therefore the image in the camera moves forward at a velocity Vg x f/h or f x Vg/h, which is the V/h ratio that we had encountered earlier. To compensate for this image motion, the film must be moved at this same rate in the forward direction. If a slit is inserted between the lens and the film and its position is fixed with respect to the lens, we will have a continuously operating focal plane shutter, with the difference that now the slit is stationary and that the film moves. Again, the exposure time will be determined by the width of the slit divided by the rate of film motion.

The advantage of such a system for high V/h rates, i.e., combinations of high velocities and low altitudes, is that it voids the need for increased cycling rates; the entire film supply is exposed in one continuous IMC motion, and no intermittent shutter or film transport action is required. Itek and other companies have built such cameras capable of operating at V/h ratios of six radians per second or more. This is equivalent to operating at Mach 1 from 200 feet. The problem with this camera lies more in the opposite direction. In order to provide reasonably short exposure times at very low V/h ratios, one must reduce the slit width to only a few one-thousandths of an inch. Also, the strip camera does not solve the problem of cross-track coverage, which still is limited to what a normal lens can cover.

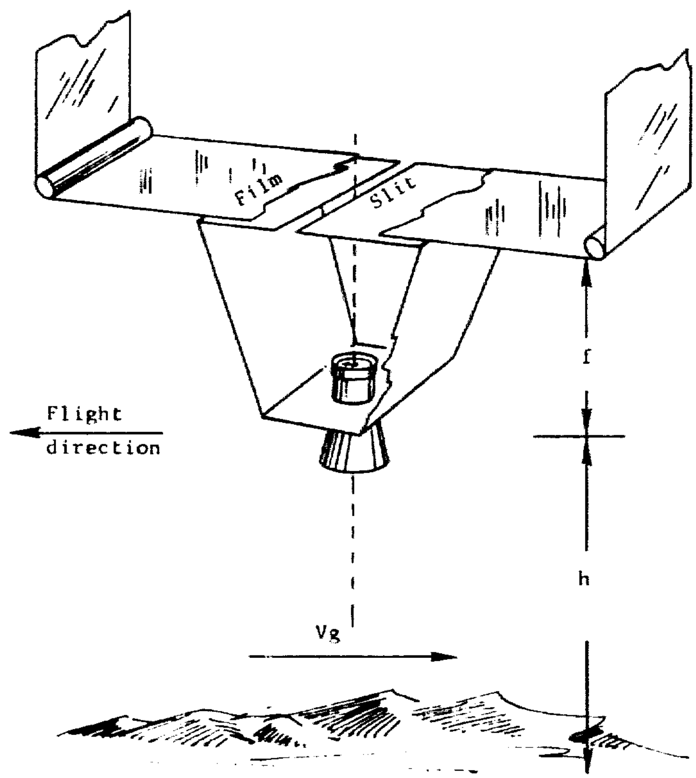

Fig. 2-1 — Strip camera schematic.

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2.4 PANORAMIC CAMERAS

The panoramic camera, like the strip camera, is a scanning type camera, i.e., it only looks through a slit at a small strip of terrain at one time. Unlike the strip camera however, which sweeps the terrain in the direction of flight, the panoramic camera sweeps the terrain from side to side across the line of flight.

A typical example of a panoramic camera is the Hyac type. As shown in Fig. 2-2, the design involves rotating the lens about its rear nodal point and accurately positioning the film in the proper focal plane location by means of two small rollers mounted on the end of a scan arm which rotates with the lens. The scan arm also carries the scanning slit. With the lens sweeping at a given rate, the width of this slit (in the direction of scan) determines the amount of exposure given each picture element; the wider the slit, the longer the exposure. In a typical application, this width may be varied from 0.07 to 0.40 inch. The length of the slit across the scan direction must cover the width of the image strip to be obtained. The maximum scan which can be obtained from a camera of the type shown is necessarily somewhat less than 180 degrees, since at that angle the lens would be looking back onto the film platen. (The example illustrated here was designed for 140 degrees of angular coverage.) However, as can be seen in Fig. 2-3, a full 360-degree coverage can be obtained with a direct-scanning camera if the optical system is offset by means of two mirrors.

Note that in the direction of scan, only the lens and scan arm move, while the film remains stationary. Furthermore, since the center of the lens rotates as a unit with the scanning slit, the sharpest possible image is always projected onto the film, even if irregularities should develop in the scan rate. At the very worst, there could be some variation in the exposure because of these irregularities (resulting in corresponding variations in the film density), but the resolution would remain essentially unaffected.

Fig. 2-4 illustrates the coverage that can be obtained with the three types of cameras discussed. It can be seen, that although the panoramic camera solves the problem of cross-track coverage, the cycling rate problem remains; continuous cover in the direction of flight is obtained by sequential scanning at properly selected intervals.

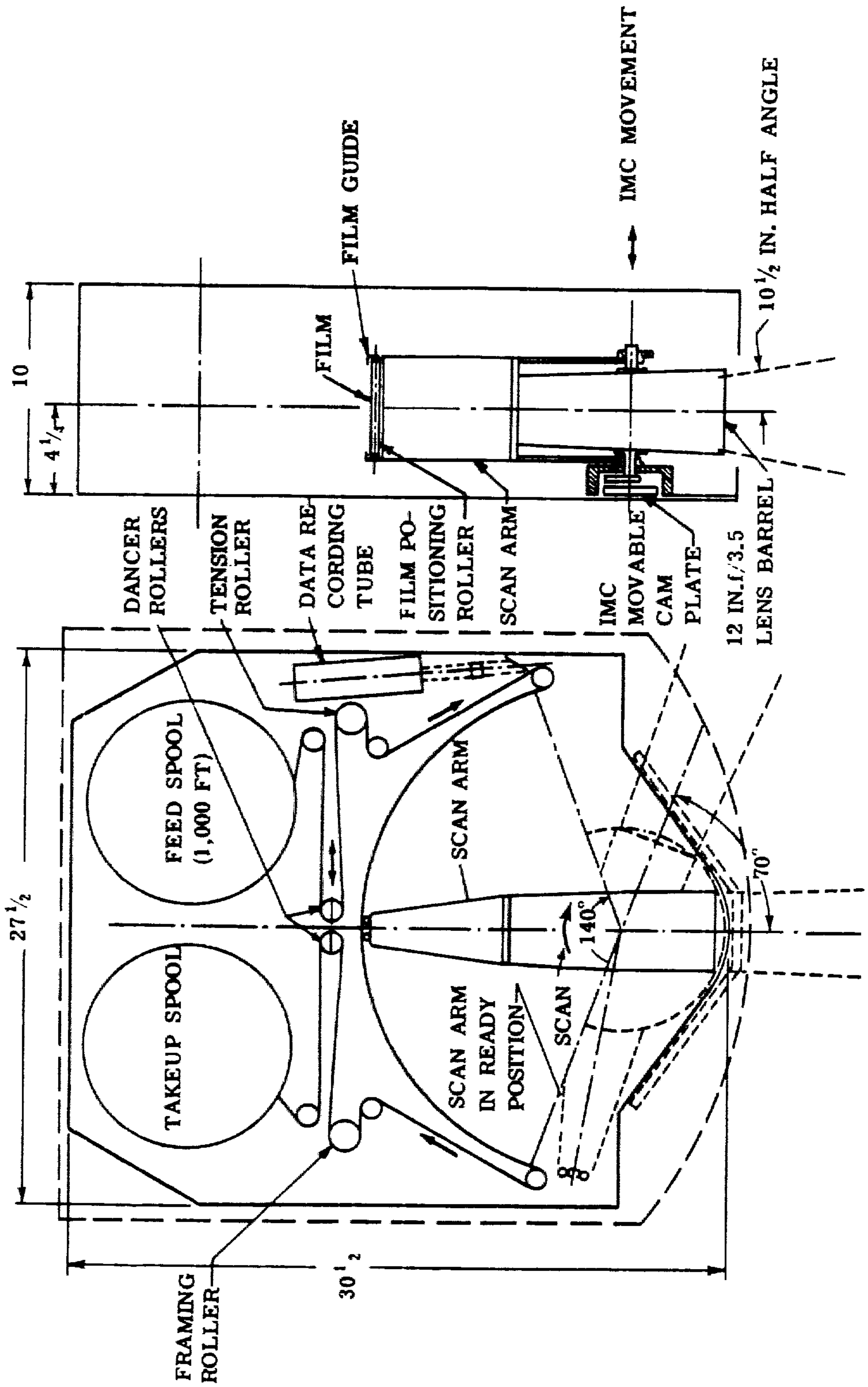

Fig. 2-2 — HYAC-type panoramic camera.

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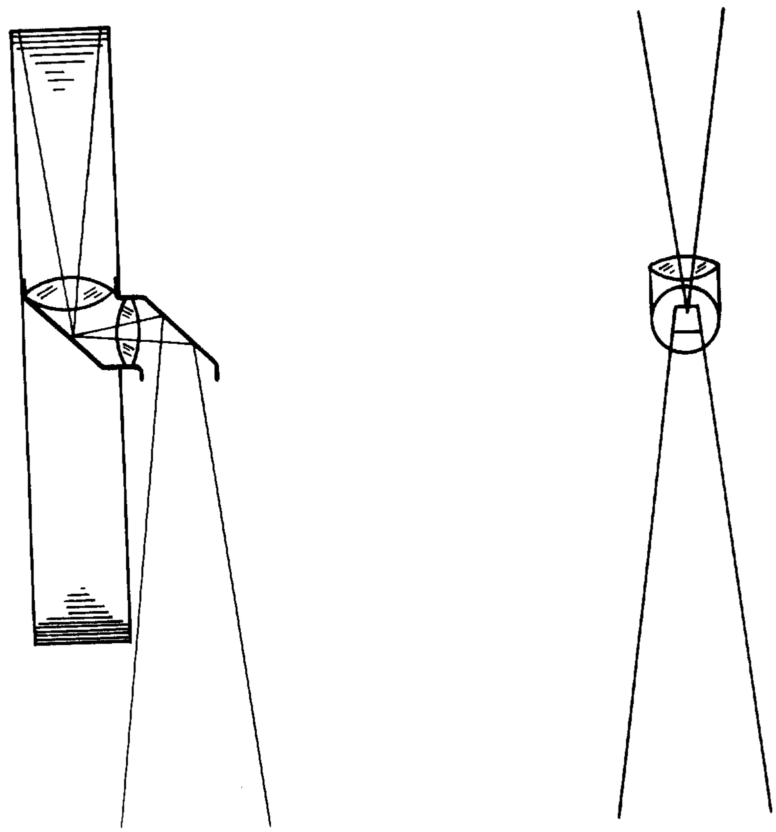

Fig. 2-3 — Direct scanning camera with 360° coverage.

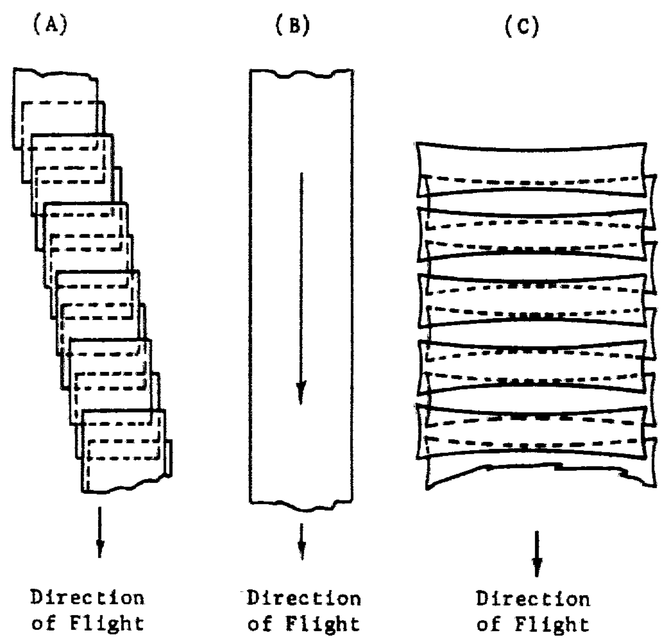

Fig. 2-4 — Ground coverage obtained with (A) frame, (B) strip, and (C) panoramic cameras.

2.5 REPRESENTATIVE CAMERAS

Having discussed some of the characteristics of aerial reconnaissance cameras, Table 2-5 presents a listing of some representative types of aerial reconnaissance cameras. No attempt will be made to show a complete listing of these cameras, but rather the intention is to show the more recent models, and primarily those that are currently in use.

The listing is arranged by camera types and the film width used, and includes 27 cameras. For a more complete compendium of existing cameras, refer to the catalog published last year (1964) for Recon Central, Reconnaissance Applications Branch, Air Force Avionics Laboratory, Wright Patterson Air Force Base, Ohio, under Contract AF 33(615)-2020. The Contractor was Data Corporation, 7500 Old Xenia Pike, Dayton 32, Ohio.

2.6 STABILIZED MOUNTS

The problem of IMC which compensates for predictable image motion has been discussed briefly. Random image motion, primarily caused by aircraft perturbations, may also cause considerable image degradation. In general, these degradations are of less concern for the low altitude case. At low altitudes, resolutions are sought on the order of one foot at altitudes of 1000 feet, or in terms of angular resolution, about one milliradian. Thus, even with a relatively high roll or pitch rate of 4 degrees per second (70 milliradians per second), the use of a slow exposure time such as 1/250 of a second is certain to keep the image blur at less than 0.3 milliradians. Slower exposures will reduce this still further.

For the high-altitude missions, where typically a 2 to 3 foot-resolution is sought from 30,000 feet or more, the aim is for an angular resolution of 0.1 to 0.05 milliradians and smaller. Using the same numbers as in the example above, the image blur (0.3 milliradian) caused by such roll or pitch rates would amount to several times the desired resolution. Under these circumstances, a stabilized mount would have to be used.

In its simplest form, a stabilized mount suspends a camera in a gimbal arrangement which has such low friction that any torque applied to the system will act on the gimbals, leaving the camera undisturbed in the center. The

Table 2-5. Representative Listing of Frame, Strip, and Panoramic Cameras

Designation	Manufacturer	Focal Lengths	Film Gap (feet)	Frame Rates (per sec)	Remarks
		70 mm FRAME CAMERAS			
KA-26	Fairchild	3 in.	250	7	
KA-61	Itek	2 in.	50	3.3	Day/Night Inflight Processing
KB-8	Maurer	1.5, 3, 6 in.	50	6	
TA-7m	Old Delft	1.5, 3, 6 in.	160	15	
		5-inch FRAME CAMERAS			
KA-30A	Chicago Aerial	3, 6, 12, 18 in.	100, 250	6	Day/Night
KA-45A	Chicago Aerial	1.5, 3, 6, 12, 18 in.	100, 250	6	Day/Night
KA-51A	Chicago Aerial	1.75, 6, 12 in.	100, 250	6	Day/Night
KS-72A	Hycon	3, 6, 12, 18 in.	500	6	Day/Night Inflight Processing
		9½-inch FRAME CAMERAS			
HR-230	Hycon	6 in.	390	3	
HR-233A	Hycon	24 in.	1250	0.7	Programmed positioning at 0°, 19° and 36° oblique
KA-25	Fairchild	6 in.	500	4	
KA-27	Fairchild	36 in.	390	0.8	9 x 18 in. format
KC-1B	Fairchild	6 in.	390	1/3 cps	Mapping Camera
KC-3	Aeroflet	88 mm	390	1/2.5 cps	110° Coverage Mapping
KC-4	Fairchild	6 in.	390	1/3	Mapping
KC-6A	Fairchild	6 in.	390	1/2	Mapping, incl. verticality recorder
		STRIP CAMERAS			
KA-18	Chicago Aerial	3, 6 in.	250,500	continuous	Provides 2 strips 5 in. or single 9 in. strip
IS-51	Itek	1.75 in.	250	continuous	Wide angle experimental
—	Chicago Aerial	1.75 in.	250	continuous	Wide angle, ditto

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Table 2-5 (Cont.)

70 mm PANORAMIC CAMERAS

Designation	Manufacturer	Focal Length	Sweep Angle	Film Gap (feet)	Frame Rate (per sec)	Remarks
Hyac I	Itek	12 in.	140°	500	1/2	
KA-54	Fairchild	3 in.	140°	500	1.5	
KA-57	Perkin Elmer	3 in.	180°	3000	3	
KA-60	Fairchild	80 mm	180°	250	6	

5-inch PANORAMIC CAMERAS

Designation	Manufacturer	Focal Length	Sweep Angle	Film Gap (feet)	Frame Rate (per sec)	Remarks
F-415	Fairchild	3 in.	180°	1000	1/2	
KA-55A	Hycon	12 in.	90°	500	1	Inflight Processing
KA-56A	Fairchild	3 in.	180°	250, 500, 1000	6	Inflight Processing
KA-58A	Perkin Elmer	18 in.	180°	2500		
KA-59A	Fairchild	12 in.	180°	4000	1	

higher the moment of inertia of the camera and the lower the gimbal friction, the more stable will be the camera in its mount. Ideally, with zero friction, no torque can be coupled through to the camera, and the camera would be completely motionless regardless of any rotational disturbances to the gimbals.

However, in actual practice idealized conditions can only be approached. Since the primary function of a stabilized mount is to hold the camera steady during exposure, the criterion for the quality of this type of mount is the degree to which it can hold a position while an aircraft is going through typical roll, pitch and yaw motions. Typically, these aircraft perturbations may occur at rates of several degrees per second. A good mount can reduce this motion to 7 seconds of arc per 1/100 second of time, and mounts that are steady to 20 seconds of arc per second of time are possible.

In terms of ground resolution, the image blur resulting from a camera motion of 7 seconds of arc per 1/100 second of time when photographing at an exposure of 1/300 second from an altitude of 45,000 feet corresponds to only about 6 inches. The image blur of an unstabilized camera under similar flight conditions and assuming a 4 degree per second aircraft motion would correspond to over 10 feet. The main disadvantage of a stabilized mount is its size and weight. Such a mount will weigh from about half to over twice as much as the camera it carries.

2.7 NIGHT PHOTOGRAPHY

Although it has been recognized that modern warfare, and especially guerilla type warfare, will rely increasingly on night operations, the development of night photographic systems has lagged. The primary reason is the difficulty in providing illumination, even over a restricted area, that compares with the light that the sun provides during daylight hours. The efforts have therefore included not only the search for bigger and more powerful light sources, but also the search for ever more sensitive materials and sensor systems which can take advantage of what moon or starlight is available.

In the area of artificial illumination, the primary emphasis has been to provide brief, high-intensity flashes corresponding to the flash bulbs used by press photographers. Two such types of artificial illuminants are:

1. The pyrotechnic cartridge and,
2. The electronic flash

2.7.1 Pyrotechnic Cartridge

The pyrotechnic cartridge is usually ejected from the aircraft carrying the camera equipment, and is fused to ignite from 0.6 seconds to several seconds after ejection. Depending on their size, these cartridges furnish enough light to properly expose a fast film in existing cameras at altitudes from 1200 feet to around 4000 feet. (A number of flash-bombs exist for single shot operation; these weigh as much as 165 lbs and are capable of illuminating the terrain below from up to 45,000 foot altitude.) This is one of its advantages over the electronic flash systems which generally can furnish sufficient illumination only for altitudes of 1200 feet or less. Other advantages that pyrotechnic cartridges have over electronic flash systems are smaller size, lighter weight, and negligible power consumption.

For practical purposes, three types of cartridges are presently in use: the M-112, the M-123 and the XM-161 (Daisy) cartridge. Their characteristics are compared in Table 2-6. The table shows that for low-altitude night missions, several dozen of the small cartridges can be carried with an added weight comparable to that of the camera itself. The M-112 cartridges, weighing 1 pound each, will not add excessively to the weight or space requirements of the sensor package. Power required is only that necessary to ignite the ejection charge. However, pyrotechnic cartridges have serious drawbacks which are as follows:

1. The flash duration is approximately 15 milliseconds for the smallest and as long as 40 milliseconds for the largest of the cartridges. This corresponds to exposure times between 1/65 to 1/25 second which are very long in terms of use for aerial photography. So unless the camera is stabilized, and equipped with excellent IMC provisions, considerable image blurring may result.

2. Most aircraft have a limit on the number of cartridges they can carry which limits the number of photographs they can take at night.

3. Cartridges are expendable ammunition that must be replenished after every mission. The explosive character of these devices make them very undesirable to operate in training, in peacetime, or over friendly areas.

Table 2-6. Characteristics of M-112, M-123 and XM-161(Daisy) Cartridges

	M-112	M-123	XM-161
Weight (total)	16.4 oz	4.3 lbs	3.8 oz (incl link)
Flash power weight	7.0 oz	1.7 lbs	1.0 oz
Length	7.73 in	8.45 in	1.87 in
Diameter	1.57 in	2.89 in	1.25 in
Muzzle velocity	130 fps	70 fps	400 fps
Peak candlepower	110 million	265 million	30 million
Time to peak	0.003 sec	0.004 sec	0.0015 sec
Duration of flash	0.030 sec	0.040 sec	0.015 sec
Integral light	1,400,000 candle-sec	5,600,000 candle-sec	200,000 to 300,000 candle-sec
Fuze delay	1, 2 and 4 sec	2, 4 and 6 sec	0.6 sec (experimental model)
Ejector	A-6 9A	B-4	LA-183( )
No rounds	52 26	20	Variable, depending on vehicle
Ejector weight (empty)	50 lb 25 lb	60 lb	10 lb
Ejector weight (full)	100 lb 50 lb	140 lb	10 lb

2.7.2 Electronic Flash

Electronic flash equipment has the problems of being cumbersome, heavy and requiring considerable power (up to several kilowatts). The main problem arises from the need for storing up to several thousand joules (or watt-seconds) of electrical energy in banks of capacitors so that it can be dissipated, almost instantaneously, in the flash tube. Power supplies, capacitors, reflectors, and associated cabling weigh about 200 pounds. The result, however, is a very short burst of light - typically of the order of 1/10,000 of a second. This short exposure time is the primary advantage of the electronic flash light over any other night-time sensor system. This very short exposure effectively stops all aircraft or ground motion. Such a system needs neither IMC nor camera stabilization.

The principal drawback of the electronic system is its limited light output. A demonstration was given in the spring of 1964 of one of the most powerful flash units developed to date. It was flown at a 1200-foot altitude, and covered an area less than 1000 feet square. Examination of the resultant photography showed that only about 25 to 30 percent of that area was adequately illuminated (2,000 joules, 6-inch f/2.8 lens, Royal-X-Pan film).

A number of developments are underway which, by means of "light intensifiers", generate an image on a phosphorescent screen from the very low light levels existing under moonlight or even starlight conditions. By cascading two, or even three of these stages, an image of sufficient brightness eventually results which can be recorded photographically. At this time, none of these programs have resulted in operational hardware, but they should be watched to see if they could offer any solutions to the problems of nighttime photography.

The illuminance parameters for typical electronic flash systems are illustrated in Fig. 2-5, which indicates the terrain clearance possible with various film-lens combinations. It should be noted that an electronic system requires a finite recharge time, thus limiting the power versus the cycle time parameter. This is reflected in a reduced flash intensity and terrain clearance. The typical parameters of this relationship are shown in Fig. 2-6. It can be seen that low light levels, which require low altitude operation, result from high frame or cycle rates, thus reducing focal length and ground resolution in order to have sufficient light for exposure.

2.8 CAMERA CONTROL SYSTEMS

This section on Photographic Sensors is concluded with a brief discussion of camera control systems. It was shown throughout the description of the various camera types and auxilliary components that a complete camera system performs many functions. A few of these are as follows:

Camera system placed on standby
Camera system turned on
Sensing of light level
Calculation of proper exposure and diaphragm settings
Sensing of height
Measurement of velocity
Derivation of the combined V/h ratio
Determination of the frame rate
Setting of IMC rate
Distribution of signal pulses
Monitoring of proper operation
Display of warning lights in case of failures
Computation of data to be recorded
Distribution of information to cameras

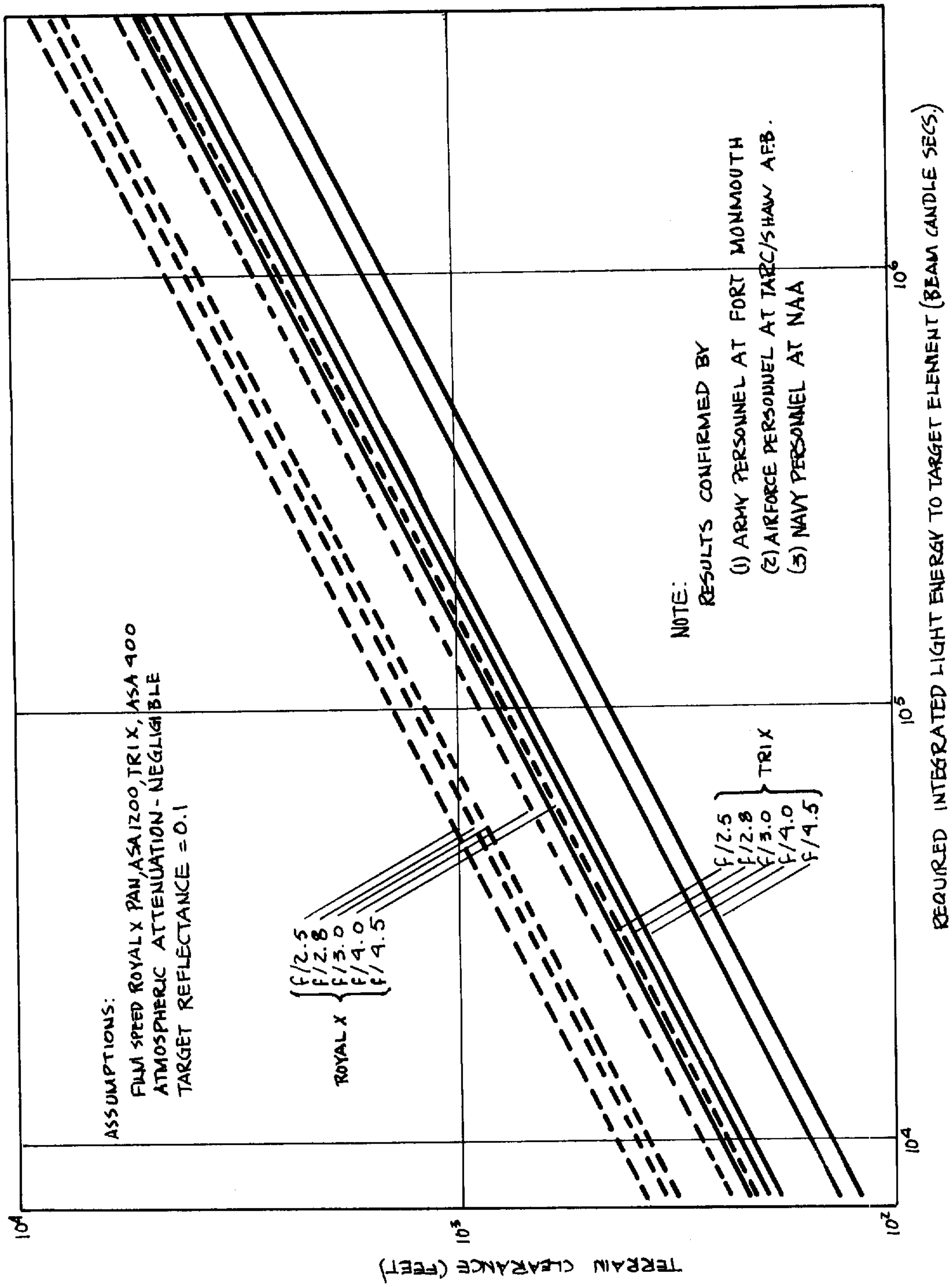
In the case of night operation, additional functions are added:

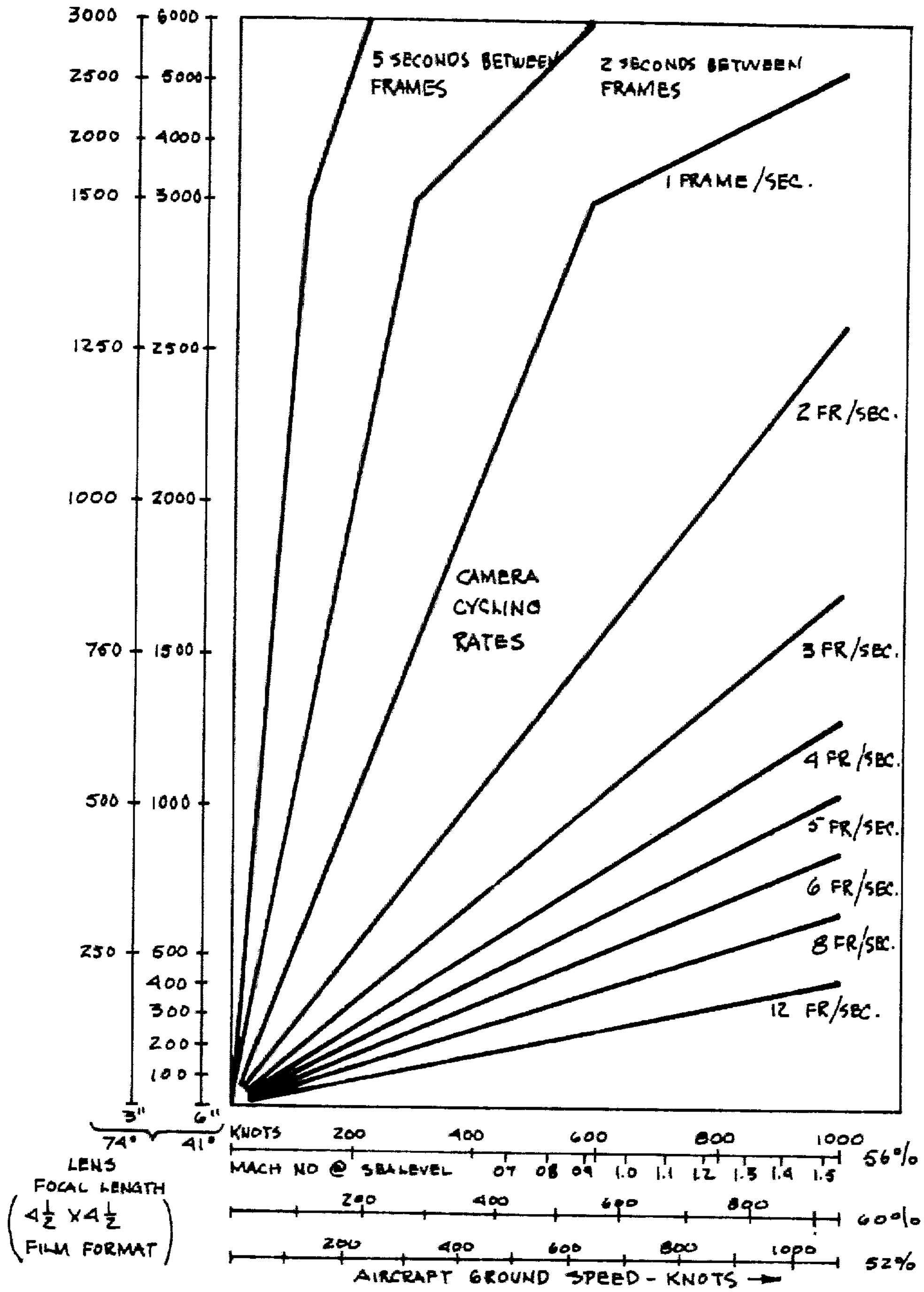
Ejection of pyrotechnic cartridge
Triggering of cameras after a suitable delay
Sensing the flash
Camera shutters are closed, recycling initiated
Selection of next cartridge

Some mechanism must be provided to perform all of these functions in proper order and, where more than one photosensor is involved, provisions must be made for the distribution power, control signals and recording data to other cameras or other reconnaissance sensors. This mechanism which performs these functions is the camera control system.

Two basic systems are now in general use. The Universal Camera Control System (UCCS) and the Simplified Camera Control System (SCCS). These systems consist of a number of mutually compatible modules that can be assembled to fit a large number of different camera systems configurations.

Some of these modules or building blocks are input devices. They permit the pilot or operator to set desired frame rates and basic exposure parameters, such as the filters desired for the mission and percentage of overlap between successive photographs. For night operation, such input modules permit presetting the number of flash cartridges to be released during one photographic sequence, and the rate at which they are to be ejected.


ASSUMPTIONS:
FILM SPEED ROYAL X PAN, ASA 1200, TRIX, ASA 400
ATMOSPHERIC ATTENUATION - NEGLIGIBLE
TARGET REFLECTANCE = 0.1
ROYAL X
F/2.5
F/2.8
F/3.0
F/4.0
F/4.5
TRIX
F/2.5
F/2.8
F/3.0
F/4.0
F/4.5
NOTE:
RESULTS CONFIRMED BY
(1) ARMY PERSONNEL AT FORT MONMOUTH
(2) AIRFORCE PERSONNEL AT TARC/SHAW AFB.
(3) NAVY PERSONNEL AT NAA
10^4
10^5
10^6
REQUIRED INTEGRATED LIGHT ENERGY TO TARGET ELEMENT (BEAM CANDLE SECS.)
10^4
10^3
10^2
TERRAIN CLEARANCE (FEET)



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Other modules are actuators for camera position doors, power amplifiers for servo motors for camera and film magazine drives, pulse shapers for proper signal distribution, and junction boxes to tie several camera stations together.

Still other modules are automatic intervalometers, which compute the proper interval between camera exposures to provide ground coverage at a predetermined overlap for stereo coverage. Others furnish the voltage required to transport film at the proper IMC rate during exposure. All of these modules are mounted on one of several standard base plates, which are equipped with mounting provisions, power and signal connectors, vibration isolators, etc.

Some additional control components have been under development for some time, such as direct image motion sensors to provide accurate IMC signals by direct measurement of the apparent ground motion rather than to derive these from navigation data. Other devices provide accurate vertical indication which is important in mapping and charting. Also, improvement is being made on data recording instrumentation to provide aircraft altitude, and other flight data as well as time and even geographic longitude and latitude information for direct recording on each photograph.

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3. PHOTOGRAPHIC DATA PROCESSING

Upon completion of the photographic mission, its value then lies in the delivery of the photographic material to the user. However, before the user can extract any information the material contains, it must be processed with regard to time so as to maximize the validity of the information, and with regard to quality so as to maximize the content of the information.

Processing can be accomplished during flight or at a ground processing station. Inflight processing approaches real-time availability; however, it does not present the best quality. Ground processing provides high quality, but requires additional time over inflight processing. Rapid processing techniques are being improved to narrow this time margin. In addition, duplication processes can be used to enhance the information content.

This section deals with all of the above facets to familiarize the reader with the technology available in photographic data processing.

3.1 INFLIGHT PROCESSING

A number of techniques have been evolved in recent years to provide inflight photographic processing including those utilizing free liquids and absorbed liquids.

These devices and techniques have, for the most part, satisfied the particular requirements of the system for which they were designed. How well each technique might satisfy the general parameters of airborne rapid processing will now be discussed, including the major advantages and disadvantages inherent to each approach.

3.1.1 Atomized Spray

Very rapid processing has been accomplished by subjecting the photographic emulsion to a heated spray of developer, fixer and rinse bath in sequence. Variations of this technique include single and multiple spray nozzles, and continuous or step and repeat processing.

In the Kelvin-Hughes RP series, a Venturi-type jet operated by compressed air is used to bring the atomized chemicals in contact with the emulsion, with processing being accomplished at rates up to 40 feet per minute in some models. Solutions are used only once, and then discarded. Processing temperatures are usually in the order of 100°F, providing for very rapid development and short access time. Densities of 2.0 and gammas of 1.3 have been achieved by this process with Ilford BY film in approximately 10 seconds total processing time.

While this system can provide rapid processing and relatively consistent quality, there are serious problems inherent in the handling of the liquids and the subsequent spray condensate. The situation is further compounded by the fact that the size of the spray droplets effect the uniformity of the processed image.

Such a system, being potentially subject to leakage about the film seals, solution container, and other points, greatly reduces its application for airborne usage.

3.1.2 Viscous Processing

Several techniques of utilizing viscous processing solutions have been incorporated in airborne processors in recent years. Common to such systems is some type of mechanical dispenser which applies the viscous chemistry directly to the film emulsion. The chemistry emitter may be a monobath for single stage operation, or a dual system applying developer and fixer sequentially.

In the Fairchild PTS system, a plastic overlay is provided encapsulating the processing chemistry and permitting immediate film handling and evaluation. Other models, like the Fairchild KS-64, provide for the removal of the viscous processing chemistry along with the plastic cover, leaving a damp emulsion suitable for readout or high energy drying. The use of the highly thickened solutions (up to 60,000 centipoise) greatly reduces the possibilities of equipment damage due to leakage of the chemistry, but restricts the mobility of solution and retards chemical activity. Although access times can be obtained as low as 10 seconds with certain combinations of film and monobath, approximately 1 minute total processing time is required for two-stage systems with films such as EK type Tri-X aerial at raised temperatures.

Such viscous processing systems are advantageous for airborne processing principly because they are relatively attitude and altitude insensitive, and access times are minimal. Solutions being used only once assures uniform quality, and the sensitometric characteristics approach those of conventional processing, although with some loss of speed.

The use of a mechanical applicator, in which close tolerances are required, and elevated temperatures necessary for rapid readout capability, result in the possibility of film abrasions and scratches as well as jamming or breakage of the film at the applicator station. Maintaining the proper orientation of the plastic overlay on the film during subsequent readout or handling requires special care, and drying upon removal of surface chemistry by preferential separation is very difficult due to residual chemistry in the emulsion.

3.1.3 Web Processing

The use of various types of chemically saturated webs have been employed in airborne processing systems with varying degrees of success. Plastics, paper, foil laminates and film base have been utilized as the carrier.

These systems offer simplicity of operation, compactness, and attitude insensitivity. The mechanics of the operation require only the contact of the previously saturated web material with the exposed film. This is usually accomplished by mating the two materials through a pressure roller system, the web being drawn off its supply spool as required.

The Eastman Kodak Bimat system produces a positive image of the negative in process on the carrier web which, in this case, is a gelatin coated polyester, using monobath chemistry and diffusion transfer. Both the negative and positive are usable after processing although neither film is dry.

Limitations of the system are the relatively short life of the imbibed solution, and the detrimental effects caused by premature drying of the solution, which results in voids or unprocessed spots where contact was imperfect or solution was not fully absorbed.

Some speed loss is incurred and density range is lowered, but maximum resolving power is retained. The requirement of a 15 to 20 minute, 80°F processing time of the negative does not rank this system with the fastest, but the positive image can be obtained in approximately one minute.

The Itek web system utilizes a porous plastic web saturated with a high energy monobath. This web produces a high quality negative and is capable of being modified to produce a positive print on the web.

Utilizing a very versatile monobath, the web processes EK type 4404 film in less than 5 minutes, Ilford Aerial-N in 10 minutes, and EK type Royal-X Pan recording in 15 minutes, all at 70°F. Maximum densities of greater than 3.0 have been obtained on some films.

Saturated web processing techniques have in common the advantages of simplified solution containment, relatively failproof mechanics, and independence from attitude. The disadvantages are primarily storage life of imbibed solution, evaporation of chemistry during operation, and limited mobility of solution.

3.1.4 Liquid Cell Processors

Optomechanisms Inc. has developed an airborne processing device which utilizes a "liquid cell" directly in contact with the emulsion of the exposed film. The entire exposed frame is in a seal as the appropriate processing solution is pumped into the chamber and drawn off by vacuum. Developer, fix and rinse solutions are programmed into the chamber independently. The film is required to maintain its position during a three second bath period in the cycle, and is therefore not suitable to continuously moving film. The problems of liquid handling and transport are further compounded by the reliance on the film as a perfect liquid seal during the entire cycle.

Another type of liquid cell device is found in a CRT recording processor developed by the Army Signal Corps. The film is indexed into a separate developer chamber where it is simultaneously exposed through a "window" and lens system, and developed. The cell is constantly maintained full of developer solution during operation by a positive pressure pump. Indexed to a similar fixing cell immediately after developing, the image is projected for interpretation while clearing. The total time, using Ansco Telerecord film, is less than one second at approximately 200°F. Leakage of solution during processing is controlled by negative pressure pumps.

The very short processing cycle is partially due to the high temperature processing, thus limiting the selection of emulsions to those capable of withstanding such temperatures. Further, the orientation of components (lens, film, chamber) requires that the film be exposed through the base. This, besides adding distortion, and theoretically reducing speed, would further limit the selection of films to those having a suitable transparent base.

As with other free liquid systems, the problems of solution leakage limit this technique to very specific applications.

3.1.5 Viscous Diffusion Transfer

The viscous diffusion transfer system most notably utilized is the Polaroid Land technique. This offers a relatively "dry" process which is a distinct asset to airborne photographic processing. Basically, the system consists of the application of a developer that contains a silver halide solvent to an exposed photographic emulsion, while in contact with a second film or paper support that is not light-sensitive. While a negative image is being formed in the light sensitive film, some unexposed silver halides are transferred to the nonsensitive support forming the positive image. This process can be completed in as little as 10 seconds at 70°F with specially prepared emulsions.

While the technique is not limited to the use of viscous chemicals, processors have been fabricated specifically for airborne operation using both rupturable pods of highly viscous processing chemicals for intermittent processing, and piston actuated supply containers for continuous processing.

The system is limited to the use of special emulsions and therefore cannot be directly compared with other rapid processing systems compatible with a number of standard emulsions.

Quality, reliability, and environmental requirements are similar to those of other viscous single stage processes discussed under "Viscous Processing".

3.1.6 Meniscus Processing

A rapid film processor utilizing a porous teflon felt roller with a sintered metal core has been developed by Eastman Kodak to record airborne side looking radar line scan displays. The device utilizes a liquid monobath at temperatures in excess of 100°F, supplied through the periphery of a driven porous roller in close proximity to the exposed film. A meniscus is formed at the tangent point allowing transfer of chemicals to the film without physical contact of the roller and film. Complete processing has been accomplished in 18 seconds at 130°F using EK type SO-1188. The porous roller, being driven independently, offers good agitation to the process and the roller-film separation eliminates the possibility of scratching or binding at the applicator.

The primary objection to airborne usage is the containment of the solution during the processing cycle. Maintenance of the proper meniscus would be difficult with a change in the vehicle attitude and with the shock and vibration characteristics inherent in an airborne environment.

A variation of the meniscus type of processing is found in a unit designed by Photomechanisms, Inc. The exposed film is positioned against a backup plate, and a meniscus of the low-viscosity processing solution is formed between the film and a sintered or porous plate. The processing solution is fed through the porous plate from a heated solution chamber. Excess solution is collected in a surrounding trough and routed to a solution waste container. At a processing rate of 10 inches per minute, access time is in the order of 20 seconds.

The system, utilizing low-viscosity solutions within an overflow circuit, encounters the difficulties found in other free liquid systems, and is thus not particularly suited to an airborne application.

3.1.7 Systems Under Development

Research is currently underway by various agencies to simplify and improve the rapid airborne production of photographic records.

These include the use of dry chemicals in the production of aqueous solutions only when required at the processing station. This would impart almost indefinite life to the stored processing materials and minimize solution handling problems. Another approach is a multicell canister of dry ingredients and liquid, which are automatically mixed and applied to the film as needed. This system also offers a maximum shelf life.

Other systems involving specially prepared emulsions, including a number of non-silver halide materials are being studied in view of airborne processing applications. Detailed information regarding the success of these techniques is not currently available.

3.1.8 General Comments

Color - Airborne processing of color materials usually requires a much greater complexity of mechanics and a subsequent increase in size and weight as compared to black and white processing. For this reason, only relatively little work has been done in this field.

The recent introduction of "Polacolor" offers the potential of color by diffusion transfer for those systems that can utilize a reflection print for information analysis. This method is likely to see expansion into color transparency production. The system would be subject to the same limitations of black and white diffusion transfer processing.

A color system utilizing low-viscosity liquids was developed by Kelvin-Hughes in a modified RP3 unit specifically for the processing of a two color Ilford radar color recording film. The cycle consists of developing, bleaching, washing and drying applied through a plurality of jets. Twenty second processing has been accomplished at 104°F. This, however, is a "false" color system utilizing a specially formulated emulsion made specifically for recording CRT traces.

Almost all of the previously described black and white processing systems could be adapted to color processing by duplicating the basic processing station to handle all the solutions required for color processing. This would result in a substantially larger and heavier device, and would multiply the areas of potential malfunction as well as greatly increasing required access time.

Positive versus Negative - Photographic information is generally available more rapidly in a negative form and photointerpretation personnel have been able to successfully utilize this type of image. Reversal to a positive image is possible but always involves an additional operation although this may be accomplished simultaneously with the negative production (Bimat, diffusion transfer). All of the processes previously mentioned produce a negative image unless otherwise noted.

Base Coatings - Most emulsions currently available are manufactured with some type of film base coating. In some cases, as with EK type 4404 film, a colored dye backing is normally removed during wet processing. However, rapid processing systems are generally arranged such that only the emulsion side of the film is treated in order to conserve chemicals and to facilitate drying. These systems are therefore limited to use with those emulsions whose base coatings do not restrict printing or visual observation.

3.1.9 Summary

The ideal airborne photoprocessing system would have the following features:

1. absolute reliability
2. real-time readout
3. minimal weight and size
4. no safety hazards
5. freedom from attitude and altitude
6. low power requirements
7. dry to dry film handling
8. acceptance of wide variety of emulsions
9. acceptance of color and black and white film
10. maintenance of high sensitometric, optical and physical characteristics
11. simplicity of operation and maintenance
12. indefinite storage life of processing agents
13. archival life of processed film

All these factors are important only as they affect the successful completion of the objectives of the particular program. In many cases only a few of these items are of importance to a particular system, and one factor may far outweigh all the others. The type of airborne processing selected for a system, therefore, depends upon the specific requirements and parameters of the program.

Where access time requirements are of more importance than quality, high temperature spray monobath may be the optimum technique, but certain safety hazards are involved here as previously noted.

Optimum safety considerations would make a high-viscosity process more acceptable than some other methods. Demands of simplicity, light weight and relative freedom from malfunctions would merit the study of a web processing system, particularly if a colored dye backing is involved. For the immediate production of positive imagery, diffusion transfer or a double web system would be most satisfactory.

There is currently no one system that offers a complete solution to all the problems and answers all the requirements of airborne photoreconnaissance.

3.2 GROUND PROCESSING

Although inflight processing yields close to real-time data and information, ground processing remains the best way of handling reconnaissance photography to produce maximum image quality and optimum tone reproduction. The intelligence yielded by high acuity reconnaissance photography depends greatly upon the quality of the processing procedures. Today's photographic reconnaissance systems are able to record vast amounts of information. Modern films and lens systems have been optimized to a point where they can be deleteriously affected by the ground processing and printing operations.

To be able to preserve this information for later critical analysis, the processing of the original reconnaissance film must be carefully done. Localized processing nonuniformities, machinery breakdown, abrasions, dirt, uneven drying and water marks can cause a serious reduction, or even complete loss of reconnaissance information.

Since a photographic record consists of an infinite number of density changes, any alteration of the true density record through non-uniform processing may cause either loss or alteration of the recorded information. Much reconnaissance is done under adverse weather conditions and at extreme altitudes. Constant controllable sensitometry from day to day is essential to accommodate for these variables.

Information is wanted not only of high quality, but also as rapidly as possible, especially when concerned with tactical operations. In many cases, photographic processing must be handled in the field far from ready supplies and under environmental conditions adverse to the photographic process.

Basically, the time to develop a film is constant. The volume of film to be processed in a given time is the determining factor as to the time required and the type of processing installation required. For example, a 100-foot roll of film may be handled easily by a simple reel processing kit, and yield the same quality as a high cost continuous processor which can process film at 40 feet per minute, and turn out 20,000 feet of film in 8.5 hours.

3.2.1 Basic Techniques

Ground processing equipment varies widely in complexity and purpose. Equipment range from the wind-rewind reel type to complex continuous processors which have automatic development control using IR scanning, spray, automatic tension control and automatic replenishment. Although a complete list of processors will not be given in this report, the general classes will be discussed.

Portable Reel Units - Portable reel units (such as the Morse Type 5A) generally are designed to handle 70 mm to 9 1/2-inch film in lengths up to 250 feet. These units are self-contained and portable, with agitation provided by the winding and rewinding action of the film in a static developer. These units have the obvious advantages of ease of use and portability. Film can be processed in the field by handcranking if necessary. For precision however, they are hardly satisfactory as agitation, and hence uniformity and repeatability is poor. The low film capacity is a disadvantage if larger quantities of film must be processed rapidly. Generally speaking, the portable reel processors are only useful for extreme field locations.

Immersion Processors - In common use throughout the military establishment are continuous type immersion processors which handle up to 9 1/2-inch roll film on paper. A continuous processing capability is accomplished by splicing one roll of film onto the end of another without interrupting the movement of the film through the solutions. There are two basic types of immersion processors - static tank and immersion turbulation.

In the static tank processors, agitation is provided by the forward direction of the film through the solution, and recirculation. Processors of this type (such as the EH-6) are semiportable, relatively simple to operate and reasonably compact. On the other hand, they give poor agitation which means that uniformity and repeatability and sensitometric control are relatively poor. Because of the lack of agitation, the attainable transport speeds are low, having a maximum speed of approximately 25 feet per minute.

With the immersion turbulation processors, agitation is provided by submerged jets which agitate the solution at the emulsion surface by directing streams of solution at the film. Such processors (as the HTA-3CM) allow moderate transport speeds up to 40 feet per minute, and good sensitometric control. Uniformity is good if the turbulation system is carefully designed. For practical purposes however, a slight streaking often results with this type of processor. This type of processor can be a good machine with moderate uniformity.

A common advantage with both types of immersion processors is the relative simplicity of temperature control. The processing system is self-contained, and the temperature sensing and control can be done in the tank. This type of machine is somewhat limited from the standpoint of flexibility. Since large quantities of solution are usually required (40 to 90 gallons), it is difficult and time consuming to change chemistry to do other films. This is a serious disadvantage if the laboratory is expected to process many different emulsions requiring different developers.

Spray Processors - For high speed, high acuity processing, spray processing has proven successful. High pressure spray nozzles are placed adjacent to the film's path of travel, and the impinging spray removes the reacted solution from the films surface, replacing it with fresh chemicals.

Film developed under conditions of poor agitation results in the accumulation of a layer of reacted chemicals on the emulsion surface, which must be removed to effect optimum processing. It can be seen in Fig. 3-1 that the intensity of agitation can be increased to a point where no additional photographic difference can be detected. After this point, the surface layer is so effectively displaced that the chemical reaction is insensitive to moderate changes

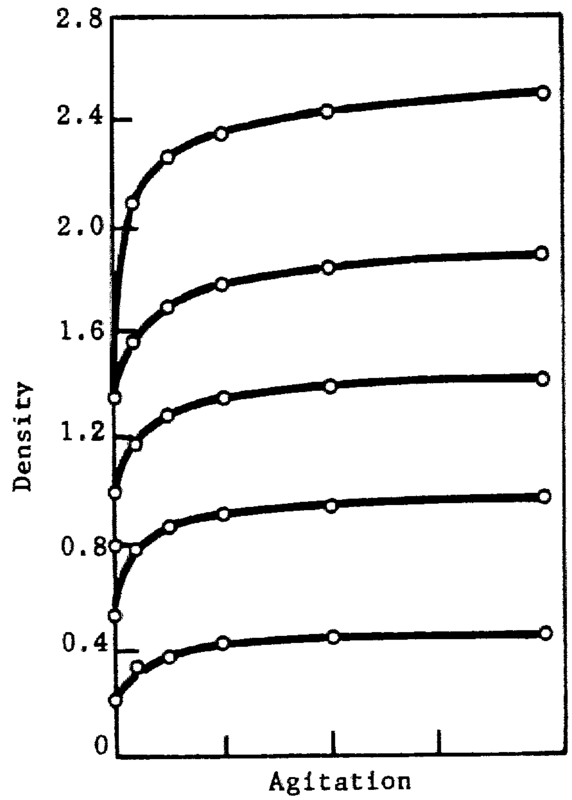


Fig. 3-1 — Change in density for five constant exposure values with changes in agitation.

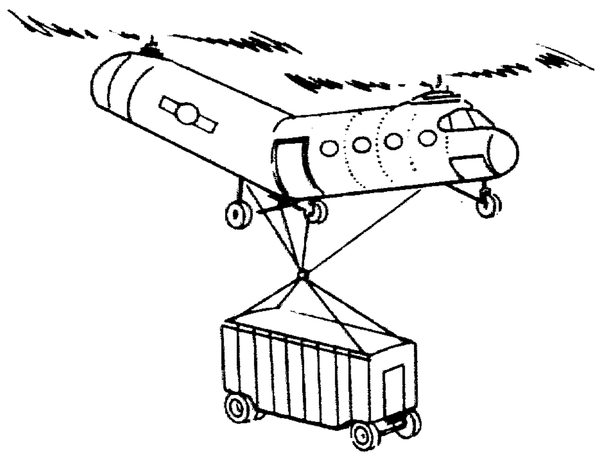
in agitation. (See Turner, J. R. and Jensen, E. W.; Some Principles of Spray Processing, SMPTE, Vol. 65, February 1956, page 92.)

The spray nozzles, which generally are in open tanks, can reduce processing time by a factor of two or three over immersion techniques. At the same time, lower fog and higher maximum density can result. Processing rates in excess of 100 feet per minute can be obtained with some of these machines. Generally fresh chemicals are used, thus requiring a continuous chemical mixing capability. The logistic support required for one of these processors restricts its use to large permanent facilities.

The advantages of a spray processor are that good uniformity and sensitometry can be obtained, although extreme care in spray distance and alignment is necessary. It also produces a high speed and development rate, and the chemicals can be easily changed to readily accommodate different films. Some of the disadvantages are high chemical consumption and complex machines which are prone to failure. Uniformity has been a problem with the wide 9 1/2-inch films, but the spray jets have worked very successfully for 70 mm film widths.

Self-Threading Roller Transport Systems - Considerable interest has been given to the new type self-threading roller transport system such as the Versamat. These units are generally compact and portable, and provide a ready machine for small job processing. They are versatile in that they handle sheet film as well as aerial film with no modifications. The machines are limited in the volume of film that can be handled. Agitation is only fair, and emulsion damage from the 212 rollers required to transport the film is possible. They also require special chemistry which cannot be used with all films.

Semitrailer Laboratories - Advanced field operations may require the use of a mobile photolaboratory. Self-contained units have been built being a complete processing facility built into a trailer. These trailers can either be towed to the desired location or loaded into a C-119 aircraft and moved by air (see Fig. 3-2). Since these trailers are used in fairly remote areas, problems sometimes arise in providing the necessary support functions such as water and power. To compensate for lack of these utilities, ion exchange units and electric generators can be used.



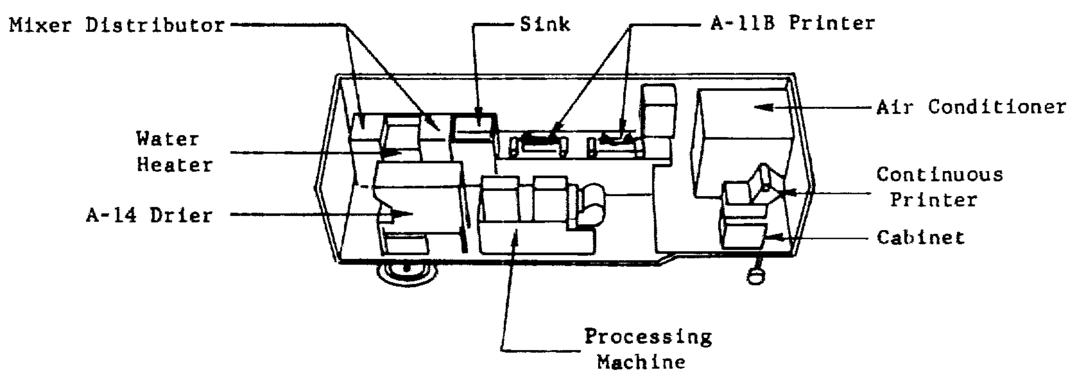


Fig. 3-2 — Photographic Laboratory ES-14 or FM-25.

Clean Rooms - Clean rooms provide the ultimate in precision processing. Contamination and dust are controlled to the submicron region. The entire laboratory is sealed off and filtered air is pumped into the facility. Personnel must observe the utmost precautions in cleanliness and suited to prevent any body contaminations such as dandruff and skin flaking. By using carefully designed processors and high acuity printing equipment, optimum information can be preserved in the photographic image. These facilities require the support of a permanent base operation.

3.2.2 Precision Processing

The trend in recent years has been for extremely high photographic quality despite the considerable costs involved. The cost of a sortie, the risks involved, and the intelligence information gained considerably offset the cost of high precision processing. Unfortunately, the setting up of high precision laboratories in the field for support of local photointerpretation units is not practical, although considerable work has been done in providing the mobile vans which are fairly complete with processing and photointerpretation capabilities.

Some field operations are provided with high quality continuous processing units and the necessary accessory equipment that must go with it such as ion exchange, humidity and temperature regulating equipment. Limitations are still encountered as to the volume of material that can be handled and the general physical restrictions of limited manpower and supplies.

To the other extreme, clean room processing provides the ultimate in film processing conserving the film's informational imagery down to the micron region. Clean room environments require the support of permanent base facilities thus putting a delay in the acquisition time of the photographs.

Possibly of the greatest importance is the ability to handle great volumes of high quality photographic reconnaissance. A sortie may produce photographs of which copies must be disseminated to many photointerpretation elements and tactical units. The aspect of time is important. Preliminary photoanalysis may induce return action within minutes. Continued analysis may be radioed to dispatched units who are traveling with the prints. Complete versatility is needed with a high volume of quality photographs.

Logistic support of a photographic facility requires considerable planning. Large amounts of chemicals and utilities are needed. Provisions must be made for emergency loss of electricity or water. Temperature and humidity of the facilities must be regulated. Control must be held over the storage and shipping environment of the photographic supplies.

Mission accomplishments bear greatly on the physical design of a processing facility. High precision processing equipment costs in the tens of thousands of dollars. Rapid high pressure spray equipment can process film at up to 100 feet per minute. These machines require a continuous supply of fresh chemicals and water and maintenance.

3.3 RAPID PROCESSING

The numerous approaches to rapid processing are the natural outgrowth of the ever increasing need to obtain a visual record of an event with a minimum of delay. To meet this need, emulsions with improved physical characteristics and great facility for processing, chemical processes and techniques of increased efficiency, and specialized processing equipment have been developed.

Airborne rapid processing, a specialization of conventional rapid processing, has evolved as essentially a military reconnaissance requirement. It is the result of a relatively abrupt combination of electronics, photographic data recording, camera optics, emulsion technology and process chemistry. The result has often been achieved at some sacrifice in the potential quality of the record, but in the majority of cases, the end has been achieved.

In actual use, the term "rapid processing" can be misleading; it may denote total processing times of as much as 10 minutes, and may even refer to the rate of travel of a film through a processor, rather than the treatment times involved. A more precise term, particularly for airborne use, is "rapid access processing", i.e., the length of time required to expose, process and view the material. This survey considers a process "rapid" if the access time does not exceed 30 seconds, and ultrarapid if it does not exceed 10 seconds.

This survey presents a summary of airborne rapid processing equipment known to be available in late 1961, and readily acknowledges that tremendous improvements have been made in this field since that time. Reference is made to an article published by Hersch and Smith in Photographic Science and Engineering, Vol. 5, No. 1, January-February 1961, and titled "Rapid Processing: Present State of the Art".

In reading over the information presented, the following observations should be considered:

1. The most successful rapid processing systems are the results of carefully matching the film, the chemistry, the process, the application technique and the equipment. The specifications required limit the films suitable to a relatively few types. The chemistry tends toward high energy, high pH, and high concentrations of chemicals.

2. While the majority of the processors shown have exhibited airborne processing capability, only a few have been proven practical and are accepted by the military in service tests.

3. The units that are commercially available are relatively high in cost, reflecting low production volume and custom construction.

In the need for immediate access, some systems sacrifice the original negative for a positive. Others require a post-process to retain the original negative and to achieve permanency of the positive.

Inflight processing systems are limited usually in size, as to the type film that can be used, and many suffer losses in emulsion speed, loss in gamma (contrast), and present a higher fog.

Very few rapid access systems are capable of archival quality, although granted it is not always required. Most inflight processors add to already loaded vehicles. The extra load of cameras, electrical systems, etc., must be carefully considered. Also, it is necessary to consider whether simple viewing of a positive is adequate, plus scan and transmission via CRT.

Classification of Equipment

A. Directly Applied Processing Solutions:
   1. Low Viscosity Fluids
      a. Immersion
         (1) Maurer Monobath Processor

(2) Fairchild Minirapid Processor
(3) Maurer Cine-Instant Processor

b. Jet Spray
(1) Kelvin-Hughes SAGE Processor
(2) Ansco (Berley) Spray Chamber Processor

c. Cell or Chamber Applicator
(1) Ansco KD-11,-12,-13,-14, and 9 by 9 Industrial Camera-Processor Printer
(2) Ansco Inflight F st Processing Magazine
(3) Optomechanisms KD-5
(4) Specialties Rapromatic 4000
(5) Aeronutronics Capillary Chamber
(6) Signal Corps Stepwise Processor
(7) C.E.C. "Datarite"
(8) Hycon 9 1/2-inch Rapid Processor

B. Indirectly Applied Solutions
1. Low Viscosity Fluids
a. Saturated Web
(1) Rapromatic, Inc., Raproroll Processor
(2) Chicago Aerial Industries Inflight Processing Magazine for KA-30 Aerial Camera
(3) Eastman Kodak Bimat Process
(4) Rapid Processing Monobath Cassette, (H.R.B. Singer)
b. Porous Roller or Plate Applicator
(1) Photomechanisms Rapidata Processors - 35 mm and 9 1/2-inch
(2) EK 5-inch Inflight Processor
c. Nonporous Roller Applicator
(1) USAS-RDL Wheel Processor
2. High Viscosity Fluids

C. Diffusion Transfer Reversal
1. High Viscosity Fluids
a. Polaroid Continuous Strip Processors for Aerial Film - 70 mm, 5-inch, and 9 1/2-inch films
b. Polaroid 35 mm KD-5 type Camera-Processor-Projector
2. Low Viscosity Fluids

D. Unconventional, Non-Silver or Dry Processes
1. Electrostatic Systems
a. Continuous-Tone Xerographic Recorder
b. Haloid Xerox PROX1 Processor-Projector

Table 3-1 lists current processors, and gives their major features.

3.4 PRINTING

Originally, Aerial Photography was accomplished through the use of rather large negative formats, centering about a 9 by 9-inch negative which is still in

TABLE 3-1. PROCESSING EQUIPMENT

TYPE	NOMENCLATURE	COST	WATER REQUIREMENTS	POWER REQUIREMENTS	GROSS WEIGHT AND SIZE	NET WEIGHT AND SIZE	REMARKS
Maurer Monobath	Processor	$1,075	N/A	7 amps, at 110 vac 60 cycle	N/A	30 lbs 30" x 11.5" x 6"	Daylight loading, very limited airborne use because of excessive altitude sensitivity.
Model F316A (Fairchild)	Processor	$1,375	N/A	1335 watts at 110 vac - 60 cycle	N/A	65 lbs 16" x 13" x 27"	Monobath or partial reversal, long film path (74-inches) delays viewing, limited airborne use because of altitude sensitivity.
Maurer Ciné	Processor	Unstated, commercially available	N/A	15 amps, 115 vac - 60 cycle	15 lbs 21" x 18" x 1.5"	N/A	Extremely compact, but unsatisfactory demonstration, somewhat sensitive to altitude.
Sage (Kelvin Hughes)	Processor	$45,000	N/A	N/A	450 lbs 24" x 36" x 72"	N/A	Excellent for airborne use if modified to use sealed, self-feeding bottles. As such, would be 24" x 12" x 24" and 40 lbs. Film is crimped to prevent fogging. Used for 6 years by SAGE, FAA and WADD installations.
Berley (Ansco)	Processor	N/A	N/A	N/A	N/A	N/A	Breadboarded and patented, similar to SAGE processor (above), should be acceptable for airborne use.
KD-11, 12, 13, 14 (Ansco)	Camera-Processor-Viewer	$83,000 (development price)	N/A	4 amps at 28 vdc, 2 amps at 110 vac, 400 cycle	N/A	156 lbs 15" x 15" x 28" (largest model)	Successfully flown and service tested in B-47's, used on Project Michigan. Altitude sensitivity has been minimized by enclosing.
Bimat (Kodak)	Processing Film	N/A	N/A	N/A	N/A	N/A	When brought into contact with exposed negative, completely develops and fixes negative and produces a positive image in the Bimat. Films must then be dried before winding, and rinsed before storage.
(Singer)	Processing Cassette	N/A	N/A	N/A	N/A	N/A	Needs no water or power, film is dry and completely processed. May be handled immediately but must be rinsed prior to permanent storage. Can be fitted to any camera, as it replaces takeup spool.

TABLE 3-1. PROCESSING EQUIPMENT (Continued)

TYPE	NOMENCLATURE	COST	WATER REQUIREMENTS	POWER REQUIREMENTS	GROSS WEIGHT AND SIZE	NET WEIGHT AND SIZE	REMARKS
(Ansco)	Camera-Processor-Printer	$5,969 (Processor) $7,616 (w/camera)	N/A	10 amps at 115 vac - 60 cycle	N/A	45 lbs N/A	If an aerial camera magazine can be modified to accept the processor subassembly, the processor may be suitable for airborne use.
(Ansco)	Processing Magazine	Unknown	N/A	1000 watts, 110 vac - 400 cycle	N/A	50 lbs 15" x 15" x 25"	Satisfactory for type 2241 Ansco Pan Aerial only. Undetermined altitude sensitivity, otherwise acceptable for airborne use.
(Opto-Mechanisms)	Camera-Processor-Viewer	$20,000 - $40,000 (development cost)	N/A	115 vac, 60 cycle	4 ft^3	N/A	Airborne capability very acceptable to 70,000 feet.
Rapromatic 4000	Camera-Processor-Projector	$4,000	N/A	5 amps at 110 vac, 60 cycle	N/A	60 lbs 13" x 16" x 27"	Not approved by AFSC-ASD. Early models suffered various breakdowns.
Aeronutronics Fomoco	Capilliary Chamber	N/A	N/A	N/A	N/A	N/A	Not altitude sensitive, but presently processes 35 mm film chips only.
USAS Stepwise	Processor	N/A	N/A	N/A	N/A	N/A	Development model only. Capable of airborne operation in principle.
"Datarite"	Magazine Processor	Not Known	N/A	15 amps at 115 vac	24 lbs 14" x 14" x 14"	N/A	Line-copy material only. Material is light and humidity sensitive altitude sensitivity slight.
(Hycon)	Camera-Processor-Viewer For Line Scan Recorder	N/A	N/A	N/A	N/A	N/A	9 1/2-inch strip film only. One development model made for AFSC-ASD in 1952 and flown.
(Fairchild)	Camera-Processor-Viewer	N/A	N/A	N/A	70 lbs 15" x 15" x 24"	N/A	Design never considered practical.

TABLE 3-1. PROCESSING EQUIPMENT (Continued)

TYPE	NOMENCLATURE	COST	WATER REQUIREMENTS	POWER REQUIREMENTS	GROSS WEIGHT AND SIZE	NET WEIGHT AND SIZE	REMARKS
EH-33A	Processor	N/A	N/A	N/A	N/A	N/A	Development model built for Navy. Should exhibit little altitude sensitivity and be suitable for airborne use.
Model 470	Processor	N/A	N/A	5 amps at 115 vac - 60 cycle	30 lbs 24" x 24" x 6"	———	Web-type. Various models accept 16 mm to 9 1/2-inch film. Adaptable to standard cine cameras. With improved web material, airborne capability should be quite satisfactory.
KA-30	Processor	N/A	N/A	Supplied by camera	50 lbs (estimated)	40 lbs (estimated)	Web-type. At least one model flight tested with marginally acceptable results. Excellent for low altitude use, but may not be acceptable for high altitude.
Rapidata Model 414	Camera-Processor-Viewer	$2,000 (prototypes)	N/A	50 watts, 110 vac at 60 cycles	N/A	13.25 lbs 10 7/8" x 6 1/2" x 5"	35-and 70-mm film only. May have limited airborne capability due to altitude and gravity sensitivity. (See PS E, Vol. 5, 1961)
Rapidata 9 1/2"	Camera-Processor-Viewer	N/A	N/A	N/A	N/A	50 lbs 12" x 12" x 16"	Very limited airborne use as is very sensitive to altitude and gravity.
5" Eastman Kodak	Camera-Processor-Viewer	N/A	N/A	250 w. probably 110 vac, 400 cycle	N/A	70 lbs	Flyable breadboard made for W.A.D.D. in 1957. Restricted airborne use due to altitude sensitivity.
RDL (USAS)	Processor	N/A	N/A	N/A	N/A	N/A	Apparently only development concept. Limited airborne use because of altitude sensitivity.
(Polaroid)	Processors 70 mm to 9 1/2"	N/A	N/A	N/A	N/A	N/A	Experimental models built for W.A.D.D. from 1953 to 1958 and service tested. Use of present 10-second Polaroid-land processing modification would boost efficiency and reduce time lag to viewing.
KD-5	Camera-Processor-Projector	N/A	N/A	N/A	N/A	N/A	One frame per 15 seconds of 35-mm only. Several units built for W.A.D.D. for ground and airborne use. Successfully tested. 10-second Polaroid-land process would reduce time.
(Xerox)	Camera-Processor-Viewer 3"-strip format	N/A	None	N/A	N/A	N/A	Image quality degraded by projection on curved drum. Change in format involves major redesign. Considerable air and vacuum equipment needed. Need cleaning after 25 minutes of operation.
Proxi (xerox)	Processor-Projector	N/A	None	N/A	N/A	18" x 36" x 36"	Only line contrast images. Dust from powder presents serious operational problems.
Transflo 1205	Processor	N/A	1/2" Tempered water and 1/2" cold water, 1/2" drain	Two 115 volt, 60 cycle, 15-amp sources	N/A	500 lbs 60" x 46" x 26"	Development time is 15 to 25 seconds. Accepts all films up to 12" wide.

TABLE 3-1. PROCESSING EQUIPMENT (Continued)

TYPE	NOMENCLATURE	COST	WATER REQUIREMENTS	POWER REQUIREMENTS	GROSS WEIGHT AND SIZE	NET WEIGHT AND SIZE	REMARKS
A-9	Processing Machine	$5,021		500 watts, 60 cycle 110 volts	1525 lbs 40" x 26" x 70"	1000 lbs 78" x 19" x 60"	9 1/2" Roll film and paper.
A-14	Film Drier	$995.00	N/A	6700 watts, 110-220 volt 1-phase on 115-208 volt, 3-phase	400 lbs 42" x 24" x 40"	360 lbs 54" x 24" x 10"	5" to 9 1/2" film, 5 to 400 ft lengths, black and white or color
C-1B	Continuous Contact Printer	$1,440.00	N/A	150 watts, 115 volt, 50-60 cycles	65 lbs	40 lbs 22" x 48" x 14"	Manual Focus.
A-2	Printing Kit	$597.00	N/A	180 watts, 110 volt, 50-60 cycles	190 lbs	190 lbs 24" x 30" x 24"	Consists of A-14A Printer, C-1B Timer, and accessories.
D-1	Contact Printer Unit	$14,329	N/A	2200 watts, 115 volts 60 cycles		600 lbs 72" x 60" x 24"	9" x 18" Format, air-drive step and repeat.
B-15A							
FN-8	Photographic Roll Printing Easel	$508.00	N/A	N/A	185 lbs 43" x 21" x 17"	125 lbs 59" x 23" x 16"	Print size 6" x 8" and 9" x 9". Applicable to B-15A and B-16 printers.
FN-7	Light Assembly Projection Printer	$440.00	N/A	300 watts, 115 volt, 50-60 cycles	50 lbs 20" x 14" x 14"	35 lbs Hd: 10" x 9" x 15" TR: 5" x 6" x 7"	Permits dodging of negatives with B-15A.
EN-54	Automatic Projection Printer	$11,017.00	N/A	1,000 watts, 115 volt, 60 cycles	900 lbs 2-boxes: 68" x 34" x 50" 68" x 34" x 35"	778 lbs 26" x 53" x 77"	Prints 35, 70-mm and 5" film, step and repeat.
FM-6	Semi-Automatic Print Chopper	$812.00	N/A	250 watts, 115 volts 50-60 cycles	130 lbs 20" x 16" x 20"	130 lbs 48" x 20" x 30"	Cuts prints 5" to 18" in length, 0-50 ft/min.

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use today, and frequently including the 9 by 18-inch negative, as well as other specialized systems encompassing several feet in their maximum dimensions. Although enlargers have been built to handle large format negatives, the bulk of printing has been by contact. For normal applications the significant detail will be acceptable.

Modern trends have been toward much smaller negative formats which have resulted in the development of more precise projection equipment to achieve optimum results from these smaller negatives. The enlarger is used to secure a print of given size whether enlarged or reduced. The contact print is by no means obsolete, but the enlarger, or projection printer, is the primary means for conveniently producing prints.

Improvements in the ability of modern aerial reconnaissance systems to resolve greater detail have necessitated comparative improvements in enlarging equipment. These trends have been toward instruments which can, at a rapid rate, project images onto film or paper, control the contrast of the finished print, and rectify any distortions apparent in the original photography. For slower or more conventional print production rates, the step-and-repeat printer (a single exposure at a time) is usually used, while for higher production output the continuous printers are employed.

The high speed continuous printer is basically a unit which will accept long lengths of negative input, as well as an equal length of unexposed film or paper. The two are sandwiched under tension across a drum in which a slit, above a light source, provides the actual exposure. These units do provide a degree of exposure control through such means as varying slit widths and lamp intensities. At least one continuous printer is in use which provides an electronic contrast control.

3.5 AUTOMATIC CONTRAST CONTROL (Dodging)

Pictorial photographers have for a long time tried to compensate for the restricted brightness range of a paper print. The loss in tone quality, as well as information, has led to various printing tricks, from simple shading and local overprinting during the enlarging, to more advanced methods of deliberate distortion.

What in a pictorial photograph is merely a lack of aesthetic quality becomes a serious matter of information content in specialized applications such as aerial photography. Trial and error methods of contrast control in such cases are inefficient, expensive, and unpredictable.

This section provides a brief description of the various approaches to contrast control. It is assumed that the reader is aware of the general use of various contrast grades of photographic paper. The difference between contrast control through the use of varying contrast grades, as compared to the various other employable techniques, which not only reduce contrast but actually gain in detail, is most important.

The use of various printing paper grades for contrast control can somewhat compress a negative tone range to that of a printing paper, but only at the expense of detail contrast, and usually with a notable loss of detail near the ends of the tone range. The masking processes, widely used in the graphic arts field, get over some of these difficulties.

The obvious difference between the use of varying paper grades, and the introduction of masking of any sort, is basically that through the use of the mask modulation of the printing light has occurred. All efficient contrast control systems depend upon control of this modulation in one form or another. The following variations will be discussed:

1. Variable contrast papers
2. Hand dodging
3. Manual dodging printers
4. Unsharp mask techniques
5. The electronic methods
    a. Velocity modulation
    b. Intensity modulation
6. Quenchable phosphors
7. Photochromic or phototropic masking films

Included with No. 6 is a brief description as to its ability to produce effective edge enhancement with no additional laboratory equipment.

3.5.1 Variable Contrast Papers

For all practical purposes, the contrast or printing capacity of a paper may be defined in terms of its useful exposure scale, or inherent gradation.

Photographic papers in which this image contrast may be varied over a wide range by changes in the color of the exposing light have been introduced in recent years. With these papers it is possible, by use of filters, to duplicate on one paper, the range of contrast obtained on the different contrast grades of other papers.

There are several distinct methods of achieving this, all of which are incorporated into the manufacture of the various emulsions.

1. Multigrade is a blend of two emulsions, one of low contrast sensitive only to blue and violet light; the other of high contrast sensitive to green as well as to blue and violet light.

2. Varigam is a single emulsion to which a green sensitizer has been added. It is believed that the sensitizer is absorbed to the larger grains in greater amounts than to the smaller, with the result that the larger grains are made more sensitive to green. Thus, with an emulsion in which the contrast varies with the average size of the silver halide grains utilized in the exposure, the use of a yellow filter will confine the exposure to the larger grains, producing a soft print, while a blue filter will cause only the smaller grains to be affected, producing a print of higher contrast. If a single exposure is made through a filter transmitting both blue and green, an intermediate degree of contrast is obtained, depending upon the proportion of each transmitted.

3. "Unicontrast" type is not true variable contrast paper, but simply emulsions with a characteristic curve of such shape that the contrast of the print may be adjusted to the requirements of the negative by exposing so as to use the proper part of the paper curve.

When printing with variable contrast papers, it is possible, and often desirable, to vary the contrast in separate areas of the photograph. By using different filters to expose separate areas of the print, a harshly-lighted area can be softened, or a thin flat area snapped up, without changing the contrast of the rest of the print. This gives the effect of several grades of contrast in a single sheet of paper.

It is important to realize that the major difference between the use of varying paper grades to achieve contrast control, as compared to the more exotic methods such as the electronic or quenchable phosphor, is that paper grade variation subdues gross detail and reduces the gross contrast, while the electronic and quenchable phosphor systems maintain the detail contrast. To state it more simply, the electronic or quenchable phosphor control compresses the overall tone range but keeps the detail contrast at any chosen value. In practice both these principles are capable of compression ratios far in excess of any known paper grade.

3.5.2 Hand Dodging

Exposure is varied between relatively large areas by a hand-held mask placed between the printing light and the sensitized material being exposed. Although judgment is permitted, this is a laborious and time-consuming task. Small area contrast control is not obtained.

3.5.3 Manual Dodging Printers

Many printers presently in use make provision for manual dodging during exposure by using as the exposure light source a large number of low-power, mercury-vapor type lamps which can individually be extinguished by manually throwing switches associated with the lamps. The operator can, therefore, view the negatives and adjust the light intensities of the individual lamps comprising the light source in accordance with variations in the density of the negative to compensate within limits for the varying undesirable densities in the negative. Such manual manipulation to satisfactorily dodge the negatives, however, requires long experience and good judgment, and can be effectively practiced by only a few highly skilled operators. Also, because of the very careful inspection of the minute increments making up the total areas of each negative which is required to effect proper adjustment of the bank of lamps forming the exposure source, this practice is both time-consuming and laborious. Printers of this description commonly accept negatives of formats up to 10 by 10 inches, while larger printers accepting formats up to 10 by 20 inches are also in everyday use, and are essentially a one-man bench-top operation. Because of the setup time involved, they are not normally considered high-production printing equipment.

3.5.4 Unsharp Mask Techniques

Light modulation is accomplished by placing a previously-prepared unsharp positive of the negative being printed between the printing light and the negative. In this process, light modulation is applied to somewhat smaller areas than in hand dodging. The system is time consuming because of the need for careful registry between the unsharp positive and the negative.

The overall tone compression is still not selective; it affects the whole image. To preserve both shadow and highlight contrast requires multiple mask systems, leading to various laborious tone separation processes based on extensive densitometric evaluation of the original negative.

3.5.5 Electronic Control

This method has been successfully employed in both contact and projection printing systems, and until quite recently was the most widely used contrast control method employed by the military and large civilian laboratories. The electronic dodging printers are manufactured by only two companies at this date, namely, LogEtronic of Alexandria, Virginia, and Rank-Cintel of England. Each is similar in that both employ a scanning light beam from a cathode-ray tube as the printing light source. Two methods by which this light may be modulated are: (1) intensity modulation, and (2) velocity modulation.

In intensity modulation, the scanning beam passes over the different parts of the negative beneath which a photo-multiplier tube monitors the light coming through. When scanning a dense negative area, the light reaching the photomultiplier tube is reduced; when the beam passes over thin areas, more light gets through. An inverse feedback amplifier receives the output from the photomultiplier and, in turn, controls the intensity of the scanning spot in the cathode-ray tube. The reduced light from dense negative areas thus makes the scanning spot more intense to compensate; when the beam passes over a thin portion of the negative image, the feedback circuit reduces its intensity.

Velocity modulation differs somewhat in that the photosensor provides a feedback signal to the cathode-ray tube, which causes a simultaneous and controlled variation in the speed of the moving spot on the face of the tube. The scanning speed at any given instant is inversely proportional to the density of the negative in the area of the spot. Automatic contrast control is thus provided in areas as small as the moving spot. With either of these methods, the net effect is that the negative is printed with a light source that corresponds to a luminous positive image. The printing light is thus modulated to suit the negative instead of being continuous. This "light mask" is formed automatically during the printing process and so requires no laborious preparations or processing. It is automatically related to the negative, and is in register with it, and the mask density and contrast are controllable by adjusting the feedback of the amplifier. However, this type of printer cannot compensate for brightness variations over areas smaller than the scanning spot.

In practice, a negative of high contrast, but with comparatively little fine detail, would be printed with a fairly large (3/8 inch approximately) spot size and appreciable feedback. A negative of lower overall contrast, but containing a great deal of fine detail (aerial photography) would need a small spot size with moderate dodging.

An objection frequently voiced against the electronic dodging system is its inherent ability to produce "fringed" edges. As the flying spot scans a boundary of the image from light to dark, the light incident on the photomultiplier changes gradually. When the spot straddles such a boundary, the shadow area begins to relieve more exposure than the shadow region just scanned by the spot. The edge of the highlight gets less exposure. The result is a dark fringe within the border of the shadow area, and a light fringe in the border of the highlight. With a fixed scanning speed, this "fringing" effect is greatest with a large spot and least with a small one.

The electronic means resorted to for effecting automatic dodging of aerial photographs are highly complex and have, therefore, produce maintenance problems of an extensive nature. However, when operated by skilled technicians, the results are outstanding.

To illustrate the flexibility of electronic printing, the LogEtronic Enlarger is claimed to handle a negative density range up to 2.2. This can be compressed to a range of 0.3 on the print; in terms of actual contrast, this is a compression factor of about 80 to 1. The claim for the Cintel equipment specifies a maximum density range of 3.0 and a print limit of 0.1.

The electronic units are large, console type averaging approximately 25 by 40 by 68 inches high. These require factory installation, with special instruction by factory representative and are quite expensive. Operation is much more involved than convention printing, but basically it is still a one-man operation with the possible addition of another man for maintenance assistance.

3.5.6 Quenchable Phosphors

A printing method in which a phosphor plate is made to glow brightly when energized by ultraviolet light, but becomes quenched upon the application of sufficient infrared light. Since normal printing emulsions are not sensitive to infrared, it is possible to pass this quenching energy right through the support and the emulsion of the unexposed material, through the original negative (where the infrared is modulated by the imagery), and on to quench the phosphor plate, almost entirely under very thin areas of the original, and little or none under the most dense areas. The differentially quenched phosphor plate thus becomes the "unsharp positive" which is automatically in perfect register with the original. This unsharp positive is also the light source which exposes the sensitive emulsions of the film or paper to produce positive "dodged" copy. In an enlarging system utilizing this principle, the phosphor and the negative are in quite close contact. The infrared source is directed toward the negative but outside the field of the lens. The exposure is similar to that made in contact; the infrared modulating, through the negative, the blue activated phosphor. A great deal of contrast control is available through variations in voltage on both the ultraviolet and infrared power sources. The quenchable phosphor method of contrast control presents many advantages over others in that its actual dodging increment is infinitely smaller. This area can well be defined as the size of the actual grains that make up the phosphor, proportional to their separation from the negative. This, in effect, means an infinite number of light sources for incremental dodging, with automatic control of the intensity of each minute source by the ability to use the negative as the modulating medium.

The quenchable phosphor printers also offer, through use of a special screen, a very effective method of edge (or image) enhancement. This is accomplished by taking advantage of the slight halation effect produced on image boundaries by the glowing phosphor. In effect, this actually enhances the difference between boundaries and can actually be carried to the point where only the edges are imaged. This capability is useful for emphasizing man-made objects for the photointerpreter, making hasty "maps" from aerial photographs, or eliminating the need for halftone resolution losses in preparing plates for reproduction.

The simplicity of operation and low maintenance costs of these printers are most important considerations. At this date both contact and projection printers are available from the Watson Electronic & Engineering Co., Alexandria, Virginia; and from the Kelsh Instrument Co., Baltimore, Maryland. The Kelsh Instrument is a projection unit utilizing optics for essentially a 1:1 output.

The density compression through use of quenchable phosphors is (at this writing) not as high as that which can be obtained electronically. Neither printer will print through densities much in excess of 2.0. The Watson Printers will compress a negative density range of 0.25 - 1.80 to 0.60 - 0.80. The Kelsh will compress a negative density range of 0.3 - 1.5 to 0.6 - 0.9.

All these printers operate on conventional 115 volt, 60 cycle alternating current; they are compact, bench-top operations, require no special skills or maintenance, and can be operated by one man.

The Watson (Fluoro-Dodge) printers average approximately 17 by 22 by 35 inches including reels. Its weight is approximately 85 pounds.

3.5.7 Photochromic or Phototropic Masking

This approach to dodging, or contrast control, is quite similar to the method of unsharp masking described at the start of this survey. The main difference is that the mask material is not a silver halide emulsion, but rather an ultraviolet sensitive dye in a clear film base. This material is exposed to ultraviolet light while in contact with the original negative. No processing is required. The two are then printed as a sandwich. The photochromic densities are proportionate to the densities in the negative; hence the brightness range is compressed and considerably more detail is picked up in areas which would otherwise yield none. Following the printing operation, the photochromic material can be erased by means of heat and used with another negative.

At this date the photochromic mask, though workable, is not truly neutral but displays rather a magenta hue which somewhat limits its applications with certain films or papers; however, it is being steadily improved. The use of photochromics as a dodging medium would necessitate the addition of ultraviolet light systems as well as a heater for erasure to conventional enlargers. This system has merit in that it would be by far the cheapest and easiest to adapt to existing printing equipment.

The production rates on any of the three systems described are completely compatible with any others in use today with the possible exception of high-speed xenon flash projection printers. If specialized controls are to be applied, or a high degree of resolution is to be attained, an awareness of some of the limitations must be forthcoming.

3.6 DUPLICATION PROCESS

One of the most important aspects of the data handling problem is the duplication process. In this section, the photographic aspects of the duplication process that can affect the quality of the final product are discussed, and not the specific equipment (i.e., printers, processors, enlargers, etc.). There are two main aspects of the photographic image than can be altered by the duplication process; namely, tone reproduction and image quality.

3.6.1 Tone Reproduction

Tone reproduction is that aspect of photographic science which evaluates the relationship between the duplication process and the original object. The correct utilization of tone reproduction theory can greatly aid in the evaluation of the proper process gammas to determine the optimum reproduction technique. In fact, for precision photographic processing and the derivation of the maximum amount of information from the photo-optical camera system, the use of tone reproduction is mandatory. The following discussion will serve to illustrate the need and use of tone reproduction in aerial photography.

Classical tone reproduction theory states that if the log object luminance range of the scene is recorded on the straight line portion of the D-log-E curve, a linear reproduction will be achieved. For typical ground photography, this is true. However, for aerial photography, this is generally not true. For example, the greatest tonal degrading factor in aerial photography is the intervening atmosphere since the atmosphere adds a non-linear degradation to the ground scene object contrast. This non-linear degradation of the ground scene contrasts is not corrected for by recording on the straight line portion of either the D-log-E curve of the duplicating or original taking film.

In aerial photography, several factors can act to alter the tone reproduction of the final product. Aside from the atmosphere, there is camera flare, the characteristic curves of the duplicating stock, printer flare, the viewer flare, etc. However to illustrate the point, the discussion will continue with the atmospheric effect and the application of tone reproduction theory. As stated, the atmosphere complicates the photorecording process, and it does so in two ways: (1) it reduces the object luminance through scatter and absorption and (2) it increases object luminance through the addition of its own energy. This phenomenon can be expressed mathematically as:

$$B_o = I_s R_g T_a + B_a, \tag{3.1}$$

where B_o = luminance of the object above the atmosphere,

I_s = solar illumination,

R_g = object reflectance,

T_a = atmospheric transmission, and

B_a = atmospheric luminance.

If there were no atmosphere, and no camera flare, there would be a linear relationship between camera exposure and ground object luminance. Because of the atmosphere, the relationship is non-linear. (Camera flare will be discussed later.) A simple relationship can be established to calculate the effect of atmospheric luminance on a given camera system.

On-axis light losses through a lens can be expressed as:

$$I_f = \frac{B_o T_1}{4(f/no.)^2 F}, \tag{3.2}$$

where I_f = illumination in focal plane,

T_1 = lens transmission,

$f/no.$ = relative aperture,

F = filter factor, and

B_o = object luminance.

Substituting Eq. (3.1) in Eq. (3.2), and taking camera exposure time into account, Eq. (3.3) is obtained.

$$E = \frac{t(I_s R_g T_a + B_a)T_1}{4(f/no.)^2 F}, \tag{3.3}$$

where E = exposure in foot-candle seconds,

t = exposure time,

F = filter factor,

$f/no.$ = relative aperture,

I_s = solar illumination,

R_g = object reflectance,

T_a = atmospheric transmission,

B_a = atmospheric luminance, and

T_1 = lens transmission.

Eq. (3.3) can be made to yield exposure in meter-candle-seconds, a term more commonly employed in film evaluation by the multiplication of the numerator by 10.76 (1 foot-candle = 10.76 meter-candles). Thus, Eq. (3.3) becomes:

$$E = \frac{2.7t(I_s R_g T_a + B_a)T_1}{(f/no.)^2 F} \tag{3.4}$$

Eq. (3.4) can now be used to calculate the effect of a given atmosphere on the ground scene. Fig. 3-3 shows how this effect alters the camera exposure. For a given range of ground luminance, the effect of a constant atmosphere was calculated. The assumed lens and atmospheric conditions are noted in the figure. From this figure, the exposure resulting after atmospheric attenuation is clearly demonstrated. The contrast loss accrued by the atmosphere is illustrated by object b and its background b', which are presented to the film as a and a' with a definite loss in contrast.

The figure further emphasizes an important point that the atmospheric attenuation, being uniform, produces a non-linear alteration of object luminances. This non-linear degradation of the original scene complicates the recording process in that a simple increase in gamma, to increase the recorded object contrast, does not truly compensate for the alteration in original object contrast. The purpose of the reconnaissance mission is to record information about the ground scene and, ultimately, the greatest information will be recorded when the ground scene is perfectly reproduced. Obtaining a perfect reproduction is, however, difficult unless one considers not only the taking material, but the duplicating material as well. For optimum reproduction of ground scene detail (from the tone reproduction standpoint), it is necessary to select both the proper negative and positive duplicating films.

To aid in the selection of the appropriate films (both taking and duplicating) for a given mission, tone reproduction theory can gainfully be employed. Fig. 3-4 shows a typical tone reproduction cycle in aerial photography. The original luminance is altered by the atmosphere and, as shown in the figure, presents the film with an altered camera exposure. This camera exposure becomes the exposure for the negative material. When processed, the density of the camera negative images become the log exposure for the positive stage. If the first generation positive is the last stage in the reproduction process, then the reproduction can be characterized by a plot of density versus log luminance of the original ground objects.

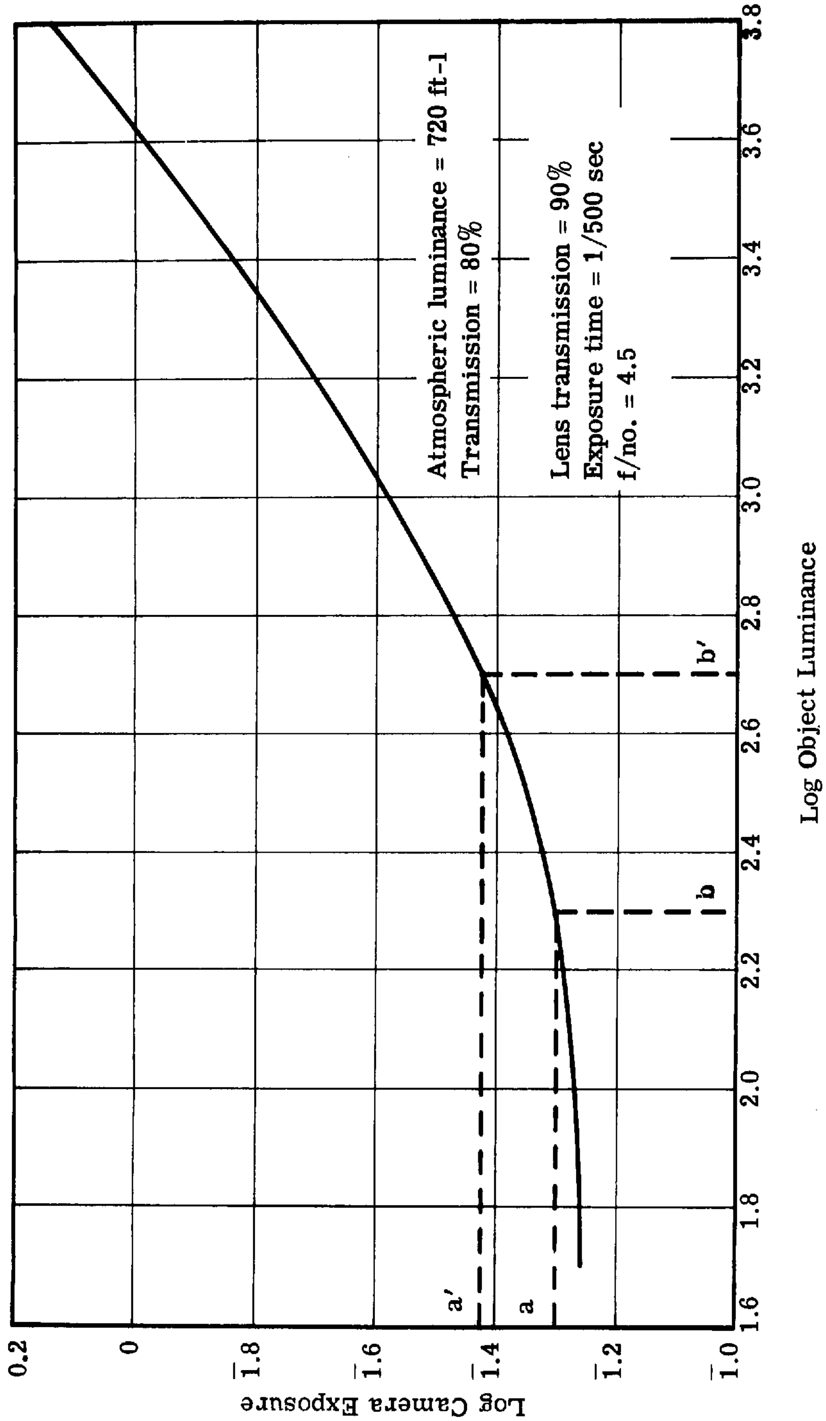
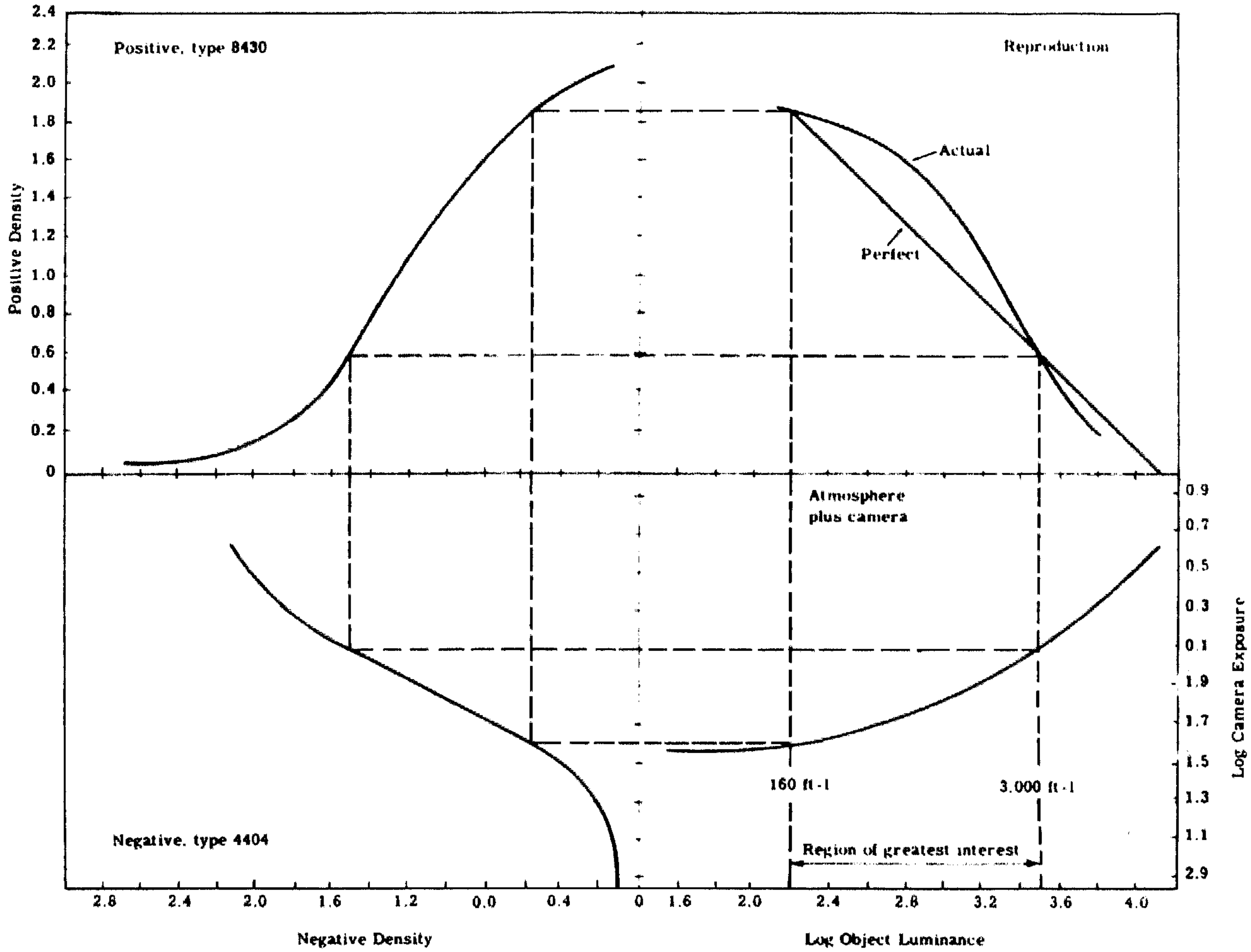


Fig. 3-3 — Effect of sample atmospheric luminance on log camera exposure



Conditions

1. Atmosphere
   Luminance - 720 ft-lamberts
   Transmission = 60%
2. Camera
   Flare = none
   f/no. = 4.5
   Transmission = 90%
   Exposure time = 1/250 sec
3. Negative
   Film type = 4404
   Processing = 6 min, D-19 at 68°F
   Gamma = 1.95
4. Positive
   Film type = 8430
   Processing = 6 min, D-19 at 68°F
   Gamma = 1.5

Fig. 3-4 — Typical tone reproduction cycle in high altitude aerial photography (moderate haze condition), showing perfect and actual reproduction of original scene.

Fig. 3-4 illustrates photography on EK type 4404 film, and duplicated on 8430. The examination of the figure demonstrates the imperfection of the final reproduction. Although the shadow detail has been somewhat enhanced, it is still recorded at a contrast lower than the original contrast, while the highlights have been degraded due to the limitations in the photographic materials.

Consider the case of extremely clear weather. Fig. 3-5 illustrates a case of photography taken on SO-190, and duplicated on 8430. In this case the reproduction is far worse than that illustrated for the moderate haze condition. The high contrast of the SO-190 has recorded the scene contrast at a density range greater than the duplicating film can accommodate. As a result, the highlight information and some medium tone information has been seriously degraded and distorted during the reproduction process. This example could have been significantly improved by processing the original photography at a low gamma instead of the typical high gamma. Fig. 3-6 illustrates the same clear weather condition, but the substitution of a low gamma processed negative instead of the high gamma SO-190. The figure shows that the final reproduction has been considerably improved over the high gamma case.

Fig. 3-6 also illustrates the other use of tone reproduction theory, that is, the determination of the proper film processing parameters. If the characteristic curve of the taking film and the desired final reproduction is known, it is possible to determine the optimum duplicating characteristic curve. Such an example is given in Fig. 3-6 where it was assumed that a perfect reproduction was desired. The desired positive characteristic curve to obtain a perfect reproduction with the given negative curve and haze conditions is shown. For these conditions, the desired characteristic positive curves to light, moderate, and heavy haze are shown in Fig. 3-7. Such curves are difficult to obtain with standard films and processing conditions. The point is, however, that using tone reproduction theory, one can obtain the best compromise between the original negative characteristics and the duplicating film sensitometry to obtain the best reproduction possible with existing materials. Without the use of such theory, it is possible to lose a considerable amount of information simply through the use of the wrong characteristic curves in the taking and duplication process.

For a variety of haze conditions then, the desired duplicating film characteristic curve could be determined. The above discussion illustrates two points.

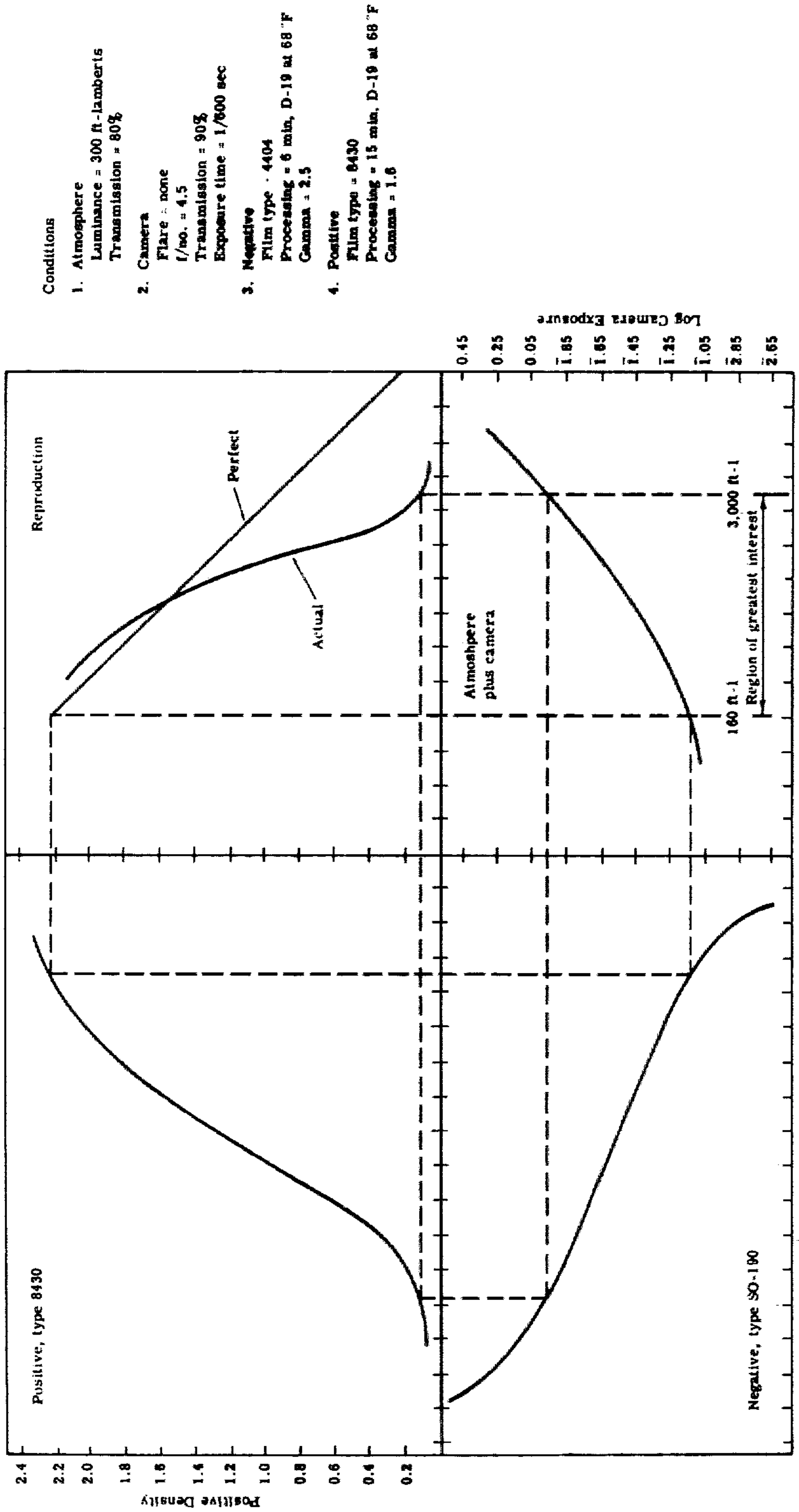
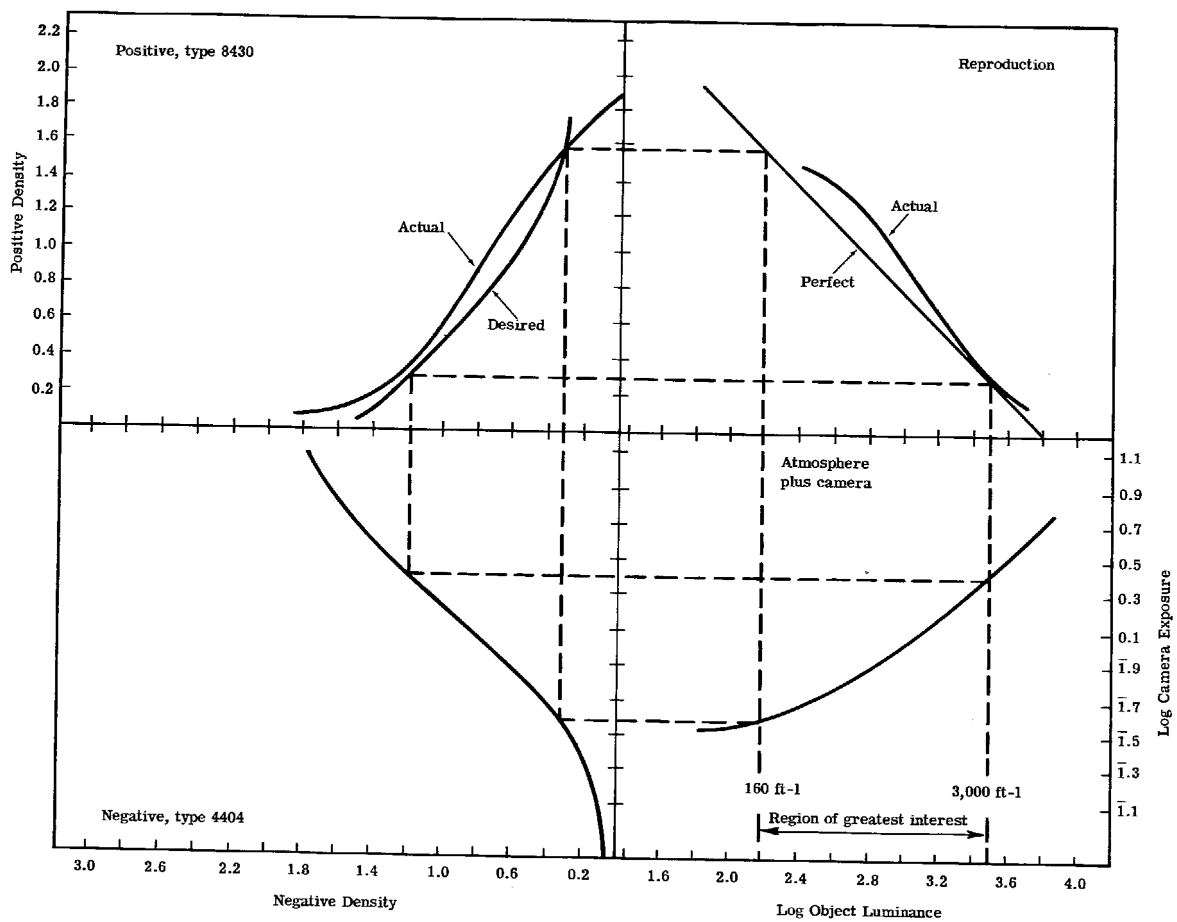


Fig. 3-5 — Typical tone reproduction cycle in high altitude aerial photography (extremely clear weather), showing perfect and actual reproduction of original scene.



Conditions

1. Atmosphere
   - Luminance = 300 ft-lamberts
   - Transmission = 80%
2. Camera
   - Flare = none
   - f/no. = 4.5
   - Transmission = 90%
   - Exposure time = 1/225 sec
3. Negative
   - Film type = 4404
   - Processing = 3 min, Cramer HD at 68 °F
   - Gamma = 1.2
4. Positive-Actual
   - Film type = 8430
   - Processing = 6 min, D-19 at 68 °F
   - Gamma = 1.5

Fig. 3-6 — Typical reproduction cycle for high altitude aerial photography showing aerial reproduction of sample case, and desired characteristics of positive duping film for perfect reproduction.

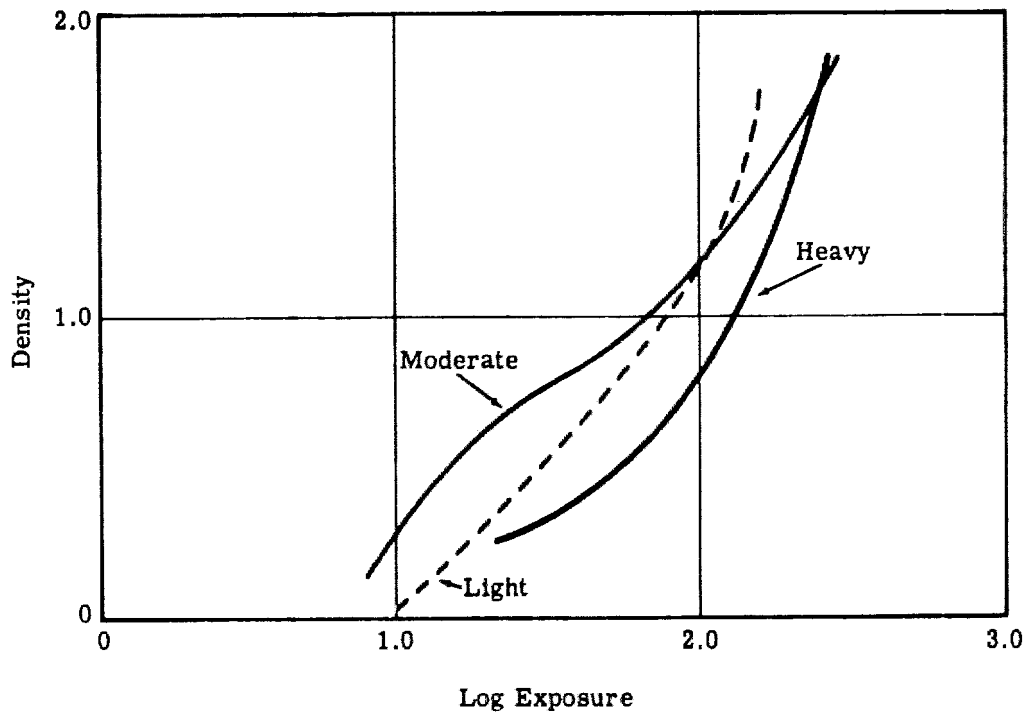


Fig. 3-7 — Desired characteristic curves of positive duping film for perfect reproduction of ground scene tonal relationships for three haze conditions and 4404 negative material as shown in Fig. 6-7

First, simple contrast enhancement through increased gamma does not of itself correct for the distortions introduced in the photorecording process by haze or flare. Second, for maximum information transfer and optimum tone reproduction, the selection of a camera negative film cannot be made independently of the duplication process, and vice versa.

3.6.2 Image Quality in Duplication

Of equal importance with tone reproduction in the duplication process, is image quality. Image quality can be affected at two stages - processing and printing.

Processing - In the processing station, there is very little that can be done to drastically alter the quality of the recorded image, short of gross over or under processing. Most of the serious effects on image quality in the processing station relates to physical damage. The most common damage is scratching, breakage, physical damage to the emulsion due to too high a temperature in either the wet or dry stages, reticulation due to temperature or chemical pH, etc. There are less severe, but nonetheless important physical changes that can occur during processing. The importance of these depends on the film usage. Dimensional changes during processing can be a problem if the film is to be used in taking accurate measurements. There are two types of processing size changes - general and local. The general processing size changes are primarily related to the physical processing problem. There are several reasons why processing dimensional changes take place and the reasons differ for cellulose, triacitate and polyester base films. In the cellulose triacitate films, a shrinkage occurs due to the loss of solvent from the base or to mechanical strain release of the gelatin. Typical values for processing dimensional change in the cellulose triacitate base films is generally -0.06 to -0.10 percent under reasonable processing conditions. Processing dimensional changes with the polyester base films are solely the results of mechanical effects of the gelatin layers. Because of this fact, the moisture history before and after processing will largely determine the observed processing size change. Typical size changes for polyester are still lower than for the triacetate being in the order of 0.01 to 0.03 percent over a reasonable processing range. These effects are general and change the entire format uniformally.

There are other effects which are random. These relate to the drying stage and are caused primarily by drying film with water drops on the emulsion surface. When water drops are present on the surface of the emulsion, the film will dry at a different rate. This means that one will be dry before another. The result of this is a random distribution of image positioning within the format. The amount of such a distortion is impossible to measure or know. However, it can be significant enough to warrant the use of a good air knife or squeeze roller before the film enters the dry cabinet.

Although processing chemistry generally does not drastically alter the image quality of the processed film, there are some effects which do occur. Changes in processing chemistry can have a small effect on image quality. Fig. 3-8 demonstrates the difference in the transfer function of Plus-X Aerographic (5401) in two different developers, D-76 and D-19; the D-76 curve being higher than the D-19 curve. It also can be demonstrated that D-76 developer also produces a finer granularity than does D-19. Table 3-2 illustrates the granularity comparison for several films.

A similar comparison can be demonstrated in terms of resolving power. Table 3-3 shows the results of resolving power determination on EK type 4404 emulsion for different chemical formulations.

Although there are some improvements in going to a "fine grain" developer such as D-76, the magnitude of the improvements is usually small in comparison to other factors which hamper the image quality of a photographic system. In fact, there are many situations when going to a fine grain developer can hurt image quality more than help it and that is through a deleterious effect on film speed.

In many systems, it is desirable to use a fast shutter time to minimize the effects of image motion and/or vibrations. The selection of processing chemistry now becomes extremely important to system image quality if maximum emulsion speed must be obtained. Although fine grain developers aid film image quality, they also retard emulsion speed. The use of such developers, when maximum speed is desired, could well impair image quality if it was necessary to use a longer exposure time. Hence, film speed is an important parameter in the effect of processing on image quality.

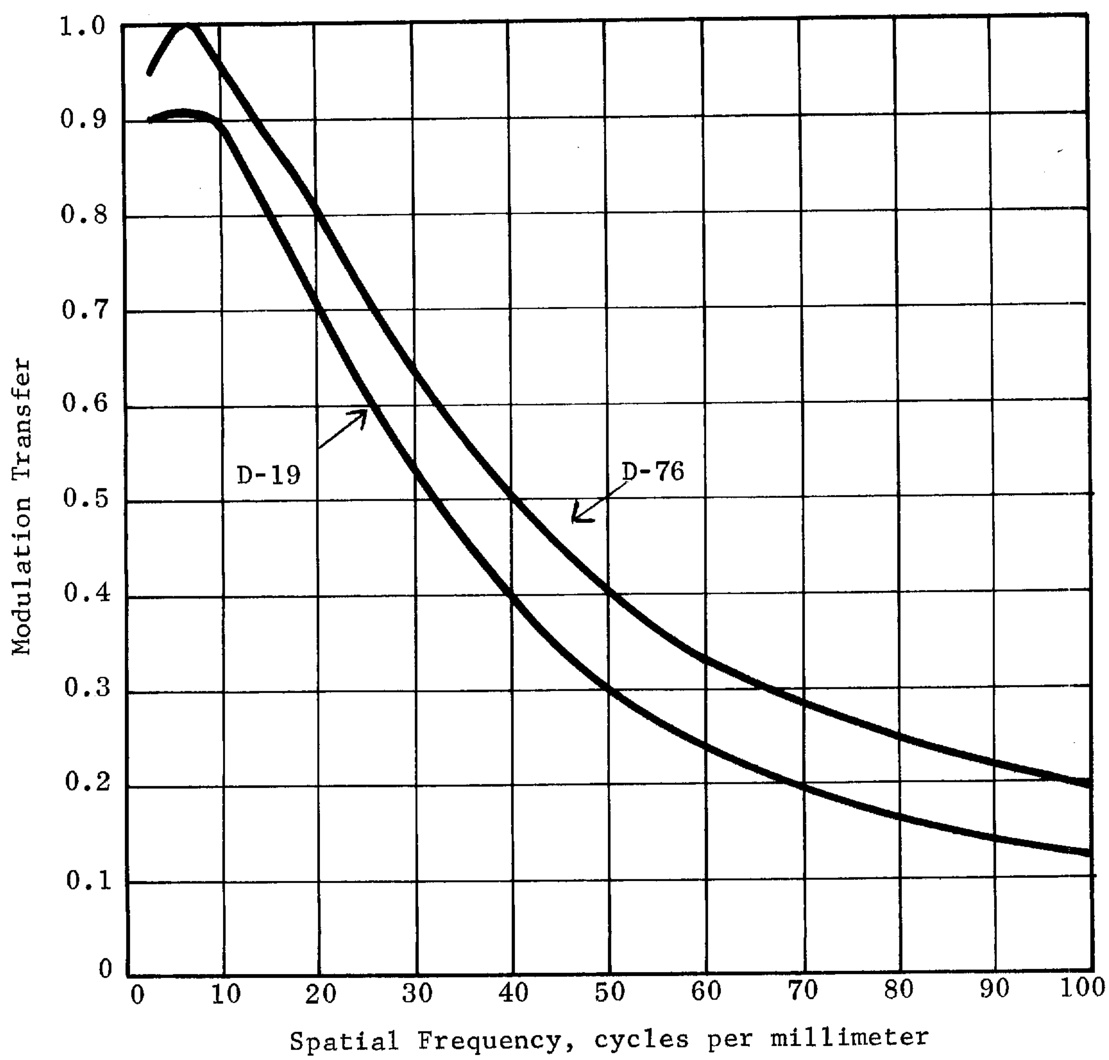


Fig. 3-8 — Modulation transfer function of Plus-X Aerographic (5401) in developers D-19 and D-76 (EK data).

Table 3-2. Granularity Comparison for Several Films

Film	Granularity $(JD)^x$ D-19	Granularity $(JD)^x$ D-76
Plus-X Aerocon (8401)	0.085	0.058
Plus-X Aerographic (5401)	0.088	0.074
SO-243	0.016	0.013
Aerographic Duplicating (5422)	0.043	0.037
Fine Grain Aerial Duplicating (8430)	0.021	0.020

Table 3-3. Resolving Power Determination on EK Type 4404 Film for Different Chemical Formulations

	Resolving Power in l/mm			
	TOC = 1000:1		TOC = 2:1	
Developer	l/mm	% Diff. from D-19	l/mm	% Diff. from D-19
D-19	839	0	278	0
D-19 + D-76 (1:1)	832	-1	295	+6
HC-110	714	-14	269	-3
12-DX-90	684	-17	270	-3

The speed of the aerial emulsion is, within reasonable limits, a variable parameter that can be partially controlled through processing. For example, the speed of all aerial films can generally be varied over a range of 6:1 or better. Fig. 3-9 illustrates the speed increase over normal D-19 processing through the use of a special high energy developer (MX-577). As shown, the speed has been increased by a factor of approximately 3.3. Under processing, in relation to the D-19 curve, could reduce the speed by the same factor.

For significant emulsion speed increases, using aerial emulsions, a higher than normal fog level must be accepted. The amount of fog buildup that is tolerable depends upon the system and its intended use. As a general rule, a gross fog level of 0.4 is usually acceptable for most reconnaissance applications. This value is selected since with most of the aerial emulsions the beginning and range of the linear portion of the D-log-E curve is not significantly altered at 0.4 or lower fog levels. For cases where maximum speed and efficiency are desired from an aerial emulsion, exhaustive testing is required. Both the speed and the developer efficiency (i.e., the speed produced in relation to the resultant fog level) are directly a function of the developer formulation, temperature, agitation, and development time. The same speed and fog relationship is not possible with different developer formulations, and some are considerably more efficient than others. For example, the comparison shown in Fig. 3-9 shows the MX-577 developer producing an increase by a factor of 3.3 in speed, with a fog level of 0.3. Such a speed is not obtainable with D-19 with the same fog level. In fact, such a speed is not obtainable with D-19 under any processing condition.

The important aspect of this problem is that for any film-developer combination there is an optimum set of processing conditions, and for the utmost speed performance from an aerial emulsion these conditions should be determined.

Fig. 3-10 illustrates the speed and fog relationship of SO-243 in D-19 for several process temperatures. From this plot, it is obvious that 100°F would produce the optimum efficiency for developing SO-243 in D-19. Maximum speed in conjunction with lower fog levels are produced at this temperature. For most practical processing conditions, then, the emulsion speed produced by a given processor, chemistry, time and temperature, has a more important effect on image

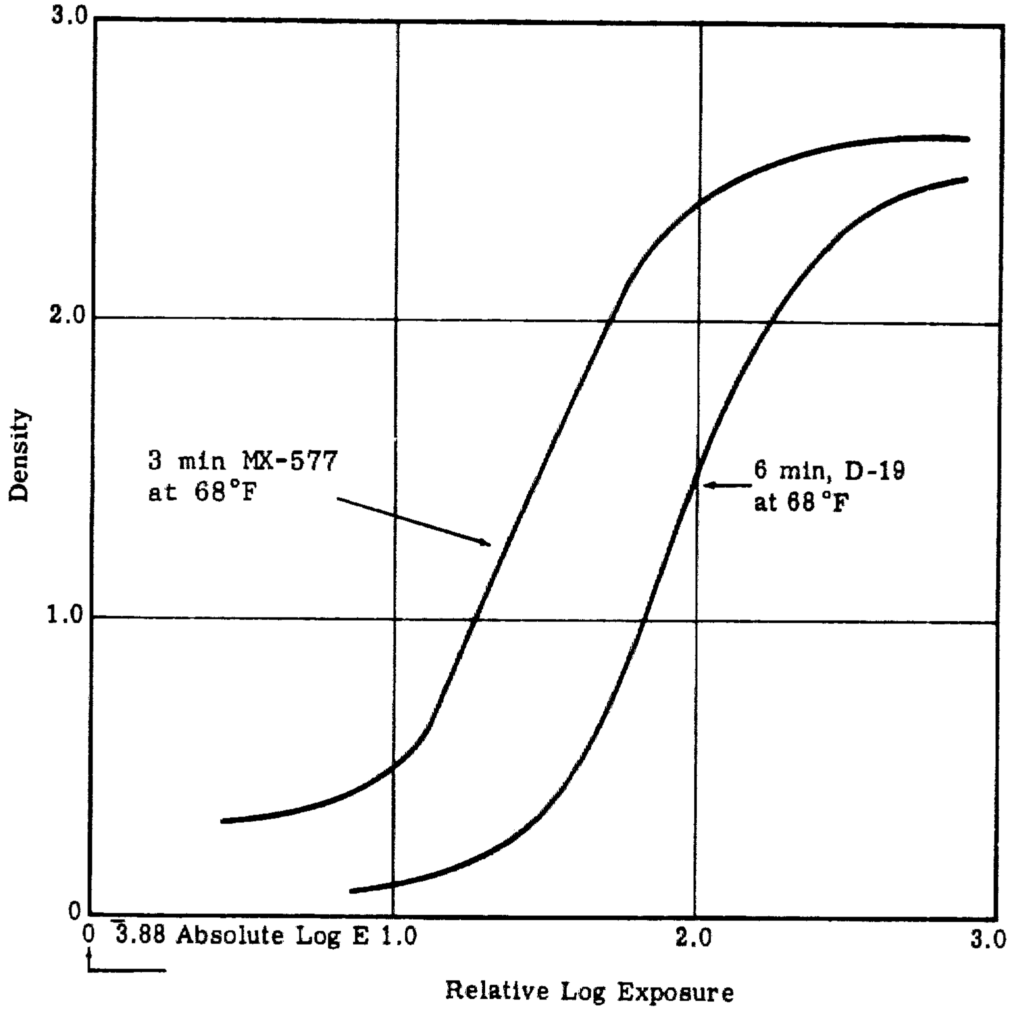


Fig. 3-9 — Characteristic curves for EK type 4404 emulsion, showing increase in film speed possible with high energy developer MX-577 (special EK developer) as compared with normal D-19 processing.

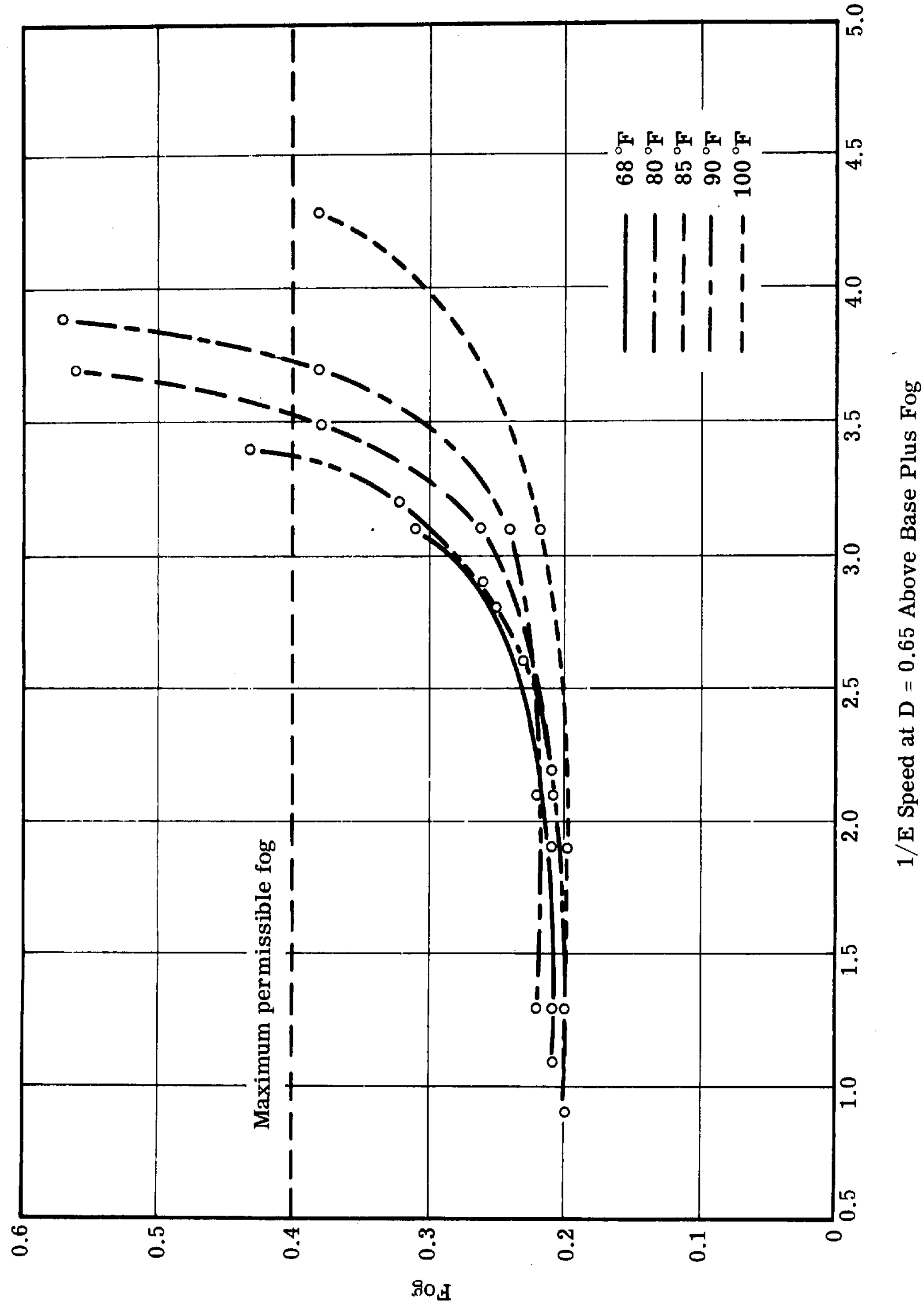


Fig.3-10 — 1/E speed vs fog, SO-243

quality than does the simple effect of developer formulation on the physical film quality parameters.

Printing - The printing operation can have several effects on photographic image quality, some of these relate directly to the printer and its characteristics, others are independent of printer characteristics.

Contact printing of high definition images for maximum image quality requires consideration of a number of factors, all of which influence the formation of the printed image. When the negative image has low contrast and the printed image must likewise have low contrast, additional contributing criteria must be carefully weighed.

Implicit in obtaining maximum image quality with contact printing in generally a parallel light source, elimination or reduction of stray scattered light in both the negative and the raw stock, the elimination or reduction of halation in the printing stock, and the elimination or reduction of interference fringes.

If perfectly parallel illumination could be ensured between the negative and printing stock, the two materials could be separated indefinitely. However, in practice this is not possible, so that optimum results are achieved by having the emulsions of the two materials in direct contact. Any deviation of the light rays is minimized, since they have the shortest possible distance to travel.

Absolute contact between the two emulsions is made particularly difficult because the negative image has associated with it a relief image, and because in reality two surfaces can never be placed directly in contact. However, several techniques have been used to successfully print resolving power test patterns up to 300 lines per millimeter.

One technique employs a vacuum to provide differential pressure sufficient to force the two emulsion surfaces close together over a 10-inch square area. Unlike conventional vacuum printing frames in which the two materials are sandwiched between a flexible membrane and a glass plate, this system compresses the two materials between a glass plate and a resilient rubber pad. This technique is useful primarily for step-and-repeat operations, but adaptations may prove useful for continuous printing.

A second, and more conventional approach, is to press the two surfaces together by placing one on a resilient pad, placing the other material over it, and then forcing them into contact by the application of weighted glass. Inverting the system has been successfully used on continuous printers.

Resilient or flexible backing for at least one material is necessary to permit the printing emulsion to accommodate to the uneven surface of the negative. For low contrast negatives, the relief image is not so pronounced, and a more rigid backing material can be used to advantage.

Conventionally processed negative images have a relief image associated with the silver image. The height of this relief can be varied to some extent by the choice of the proper developer. However, even when processed to produce the least pronounced relief, all parts of the nonuniform surface cannot be placed in direct contact with the recording material. For this reason, liquid printing is especially useful in effecting optical contact for eliminating interference patterns and for transferring maximum information from the negative to the raw film.

All the light which strikes the negative image does not proceed directly through the negative; some is scattered by the negative image, some is scattered by scratches and striations in the base, some is reflected back from the emulsion-base interface, and some is reflected back from the emulsion and air interface. That portion which is reflected does not produce a latent image in the recording material until it has again been reflected back from another interface or by a clump of silver grains. Unfortunately, these light rays do not produce a well-defined image, and some degradation is produced because of their effect. Even the rays which are not reflected from interfaces but are scattered by the silver image and base-side scratches also produce a loss in image quality.

Shadowgraphs of interference patterns are also a frequent cause of image tone distortion. Since this phenomenon is caused by a nonuniform spacing between two surfaces in physical contact, an obvious solution is to have the surfaces in optical contact or to separate them entirely. The latter solution, however, is inconsistent with the conditions required for optimum image definition. A more obvious solution is to establish optical contact between the two emulsion layers. Even with high vacuum in a step-and-repeat operation, this technique has not proven satisfactory nor is it expected to be perfectly achieved with dry materials. However, the use of a liquid between the two emulsions overcomes this difficulty. The liquid must have approximately the same index of refraction as the emulsion layers, must not cause physical distortion of the emulsion layers, must be readily removable, and must be nonviscous to permit the two emulsions to come into close contact. A variety of such liquids have been examined and a number have been used successfully in such printers. Liquid gate printing, as this technique is called, is being used in a number of commercial laboratories and appears to be the most logical way to overcome this difficulty. Finally, some light which penetrates the recording emulsion is reflected back into the emulsion layer from the emulsion and base or base and air interfaces. For this reason, the raw film emulsion is frequently dyed to limit light penetration, and/or the base contains an antihalation dye.

The technique of liquid printing is helpful in restricting the scattering and reflecting of light between the two emulsion layers, from base-side scratches, or at the emulsion and air interfaces. However, this technique must be carefully handled; the liquid must be maintained in a high degree of cleanliness. To be most effective, the liquid must not be allowed to introduce bubbles, and turbulence must be avoided.

It should be pointed out that parallel illumination does not always produce the "best" image quality. An example is when EK type 4404 film has imbeded in the Polloid backing extremely small quartz particles which give the back a roughness to prevent ferro-typing while spooled on the roll. When printing onto a high resolution SO-105 duplicating film with parallel light, these particles print out. The images of these particles is deleterious to the image quality. In this case, the use of a diffuse source materially improved the image quality of the final duplicate.

Even assuming that the printer is very good, with a minimum of image quality loss, there still will be losses in image quality due to the physics of the process. For example, one can see that the simple process of making several generations of duplicates will increase the noise of a duplicate. Film granularity is a statistical parameter. Thus, since the total variance of a system is the sum of the individual variances, the sum granularity (σ_D) will be equal to the square root of the sum of the individual $(\sigma_D)^2$. That is:

$$\sigma D^2_{total} = \sigma D_i^{\ 2} + . . . \ \sigma D_N^{\ 2}$$

Table 3-4 illustrates the two cases. In case 1, the original photography was gathered on Pan-X Aerial (EK type 4400 film) and duplicated on 8430. The granularity of 1, 2, and 3 generations of 8430 duplicates was calculated. It is seen that the granularity increases as the number of the generation increases, even though the same film is being used for the duplication. The second example is for taking on High Resolution Aerial (EK type 4404 film) and printing on 8430. The same point holds here, as the number of generations increases, the granularity increases. In this case the granularity of the third generation 8430 duplicate is nearly twice the original granularity of EK type 4404 film (0.023), and almost exactly twice the inherent granularity of 8430 (0.021).

3.6.3 Reversal Processes

Historically, in aerial photography, the positive prints (or transparencies) used for photointerpretation have been made from a duplicate negative. This negative is presented from a positive transparency that, in turn, has been printed from the original negative. Thus, the valuable original negative is used only once in the duplicating process, and is not subjected to wear and tear through successive handling. As discussed, however, each stage of the duplication process is accompanied by a certain loss in image quality and degradation in tone. The use of a direct reversal process would seem to offer advantages, therefore, from the standpoint of reducing the number of generations necessary.

Although abbreviated reversal processes have been reported (see H. K. Howell, Photo Engineer 5:182, 1952), the most common direct reversal processing technique is bleach reversal. A bleach reversal process is so named because, after the initial negative is developed, a chemical bleach is used to remove the negative silver image. This action leaves a positive image of underdeveloped silver salts which are then exposed to light and developed. When carried out in its most complete form, this process involves the following steps: imagewise exposure, first development (produces negative image), rinse, bleach, clear, rinse, uniform re-exposure, second development (produces positive image), fix, wash and dry. Even though the bleach reversal technique eliminates a printing stage, it possesses

Table 3-4. Granularity Comparison

(All values based on net D = 1.0.)

Film Combination	4400	+	8430	4400	+	8430
No. of 8430 Duplicates	1	2	3	1	2	3
Resulting σ_D (calc.)	0.057	0.061	0.065	0.031	0.031	0.043

Film Type	σ_D
4400	0.052
4404	0.023
8430	0.021

Table 3-5. Resolving Power Comparison (c/mm)

Test	Target Contrast		
	100:1	6.3:1	2:1
LIBR Dupe-Positive	360	310	150
1st gen. Dupe (Conv.)	360	360	180
2nd gen. Dupe (Conv.)	220	190	120

several disadvantages which makes it undesirable for many applications. In order to obtain clear highlights, a combination of heavier than normal exposure and high silver halide solvent developers are employed. The increase in exposure generally produces a spreading of the image which degrades image quality. The addition of the silver halide solvent reduces the density range. Such reversal processes also reduce the control which can be exercised over the sensitometric characteristics of the duplicate. The requirement for development to completion in the first developer reduces the ability to significantly change the sensitometric characteristics in the second developer. For aerial photography, this is a serious disadvantage since changes in atmospheric attenuation can drastically alter the contrast range recorded on the original negative.

Utilization of the Itek LIBR (Latent Image Bleach Reversal) processes would appear to eliminate many of the disadvantages associated with the above mentioned techniques. Reversals obtained with LIBR have the following basic steps: imagewise exposure, bleach, clear, uniform re-exposure, develop, fix, wash, and dry. It is important to emphasize that with LIBR the first developer is eliminated, and the first chemical step is the bleach. Since there is only a single development, which produces the positive image, LIBR reversals have the ability to provide sensitometric control comparable to that obtainable with a normal negative-positive processing technique (i.e., develop, fix, wash, and dry). From a sensitometric standpoint, then, the LIBR process combines the best of both approaches to photographic duplication. The sensitometric control of a single development process, and the single printing stage of a direct reversal process.

From the standpoint of image quality, LIBR also appears to offer considerable advantages. A summary of the image quality tests to date is given below.

Resolving power tests were conducted on 8430, LIBR, and the conventional duplicating process (negative-positive). For all tests, identical precision printing and exposing conditions were used. The results reported in Table 3-5 are the average of 18 replicate tests at the optimum exposure conditions.

From the tests in Table 3-5, it is obvious that the LIBR duplicate maintains significantly better resolving power than the second generation duplicate. At high contrast 8430-LIBR maintains 140 c/mm greater resolution, at 6.3:1 - 120 c/mm and at 2:1 - 20 c/mm.

The resolving power results require some explanation. The 360 c/mm reported for both the 100:1 and 6.3:1 contrast tests for the first generation duplicate most likely indicates that the limit of the printing system was 360 c/mm. It is expected that with a better printing technique, the high contrast values for both the LIBR and first generation duplicates would be higher. Secondly, it is realized that the second generation conventional values are probably lower than what could be obtained with a better printing technique. However, the important comparison is between LIBR and first generation duplicate, and LIBR maintains nearly as good a resolving power as the first generation duplicate.

A RMS granularity comparison was made between LIBR and the conventional process. Three conditions were tested with 8430, which are as follows:

1. The standard LIBR process.
2. The first generation conventional duplicate processed 6 minutes in D-19.
3. The second generation conventional duplicate processed 6 minutes in D-19. These samples were prepared by printing the first generation uniformity samples onto 8430.

All uniformity samples were carefully prepared to insure that no random uniformities, dust, or dirt were present. The results are shown in Fig. 3-11. This figure shows that the LIBR processed sample produced the lowest granularity of all the conditions. Particularly significant is the comparison between LIBR and the second generation conventional duplicate, where LIBR shows a 75 percent lower granularity. The increase in the granularity of the second generation duplicate is to be expected on the basis of the statistical nature of granularity. As previously discussed, when combining two standard deviations, even when equal, the resultant standard deviation will always be higher.

The MTF test was conducted, as with the other parameters, as a comparison between LIBR and the conventional two-stage duplicating process with type 8430 film. The test was conducted by printing a photographic knife-edge, and evaluating the resultant edge by graphical techniques (see Scott, Scott, Shack, P.S. and E. 7:345-249, 1963).

Fig. 3-12 is a plot of the MTF data for the several tests. The results show that the MTF of the LIBR process is slightly lower than that of the conventional

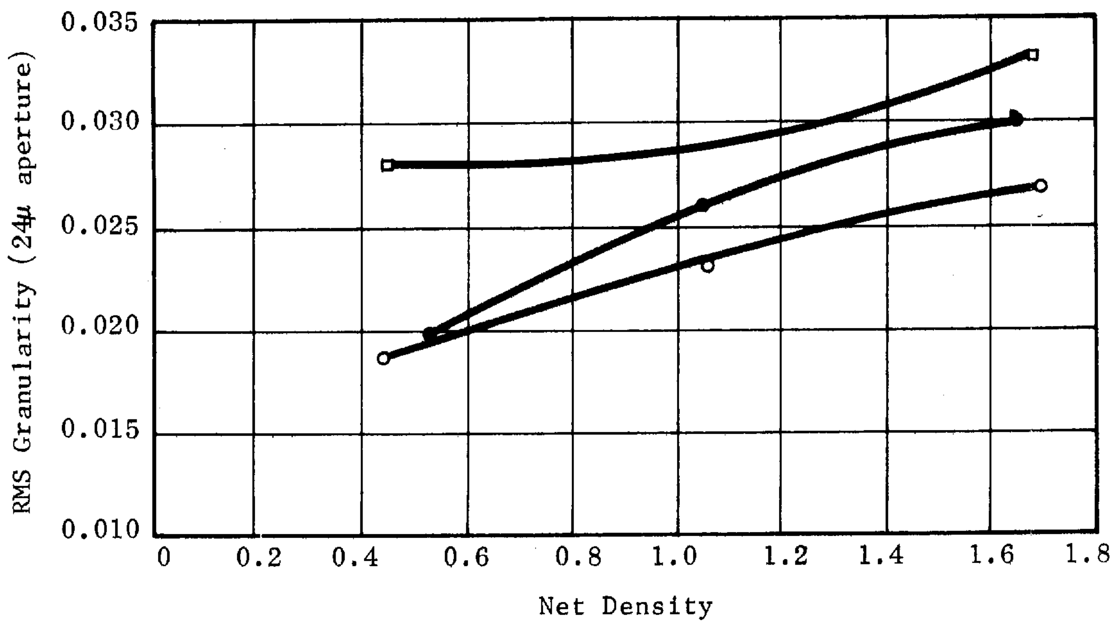


Fig. 3-11 — RMS granularity comparison of LIBR versus conventional processing of 8430 film.

- □ Second generation conventional printed with the granularity samples from the first generation (8 min D-19)
- ● First generation conventional (8 min D-19)
- o LIBR process

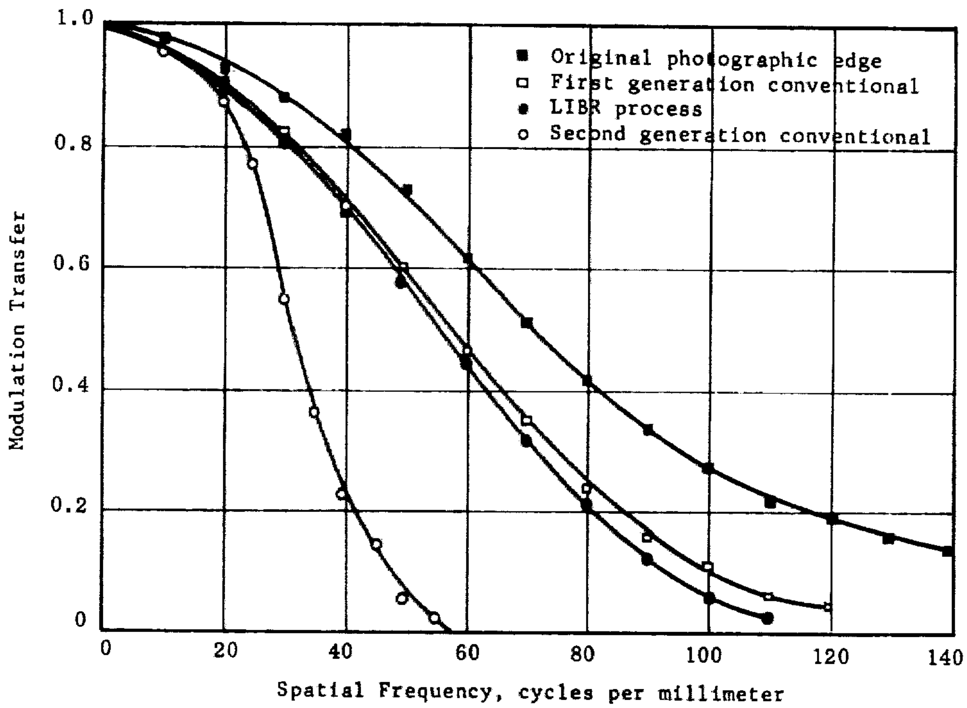


Fig. 3-12 — Modulation transfer function comparison of LIBR versus conventional processing (developed for 6 minutes at 68°F in D-19) of 8430 film; MTF curves have had the transfer function of the microdensitometer removed.

first generation duplicate. The results presented here are purely relative since we could do no better than the quality of the original photographic edge. The first generation and the LIBR duplicate are indicative of the relative loss in modulation due to both the printing technique and the scattering in the emulsion. The second generation duplicate is indicative of the loss accrued by the second printing operation, plus the scattering of light in the first generation print during the printing operation. The loss from the first generation to the second generation is greater than would be intuitively expected. This loss can be explained by several reasons.

1. The loss is, in fact, this great, and the multiple scattering that takes place during printing is a significant factor. During the first printing operation, the emulsion is being exposed by essentially parallel light. However, during the second printing stage the emulsion is exposed by partially incoherent light, due to the additional scattering that takes place in the degraded edge used to make this second dupe.

2. The sample size used here may be too limited, and the second generation curve presented may not be representative of the average loss that would occur over several samples.

3. The theory of transfer function is not adequate to handle such a second stage duplicating process. These tests were made by exposing edges, and not in the more conventional manner of exposing sine waves. The theory of edge transformation to obtain the MTF is not as well developed as is the sine wave technique. This could mean that there is inherent error in the results that is not well understood at this time.

Regardless of the difficulties involved in obtaining the MTF from an edge trace, it is felt that the data is, on a relative basis, correct. The important conclusion is that the LIBR duplicate produces nearly the same MTF as the first generation conventional. This is, of course, as would be expected since all test conditions, except chemical processing, were identical for these two samples. Even assuming that the results for the second generation duplicates are too low, they could only approach the MTF of the LIBR process by being printed in a system with no transfer function loss (i.e., straight line at 1.0 modulation). Such a printing system is impossible to obtain. Therefore, it is concluded that the LIBR - MTF is sufficiently good to always be better than a second generation duplicate.

4. PHOTOGRAPHIC DATA REDUCTION

In extracting data from photography, the most important instrumentation to be considered is a viewing configuration. Viewers can generally be classified by their function as screening viewers, detail viewers and special viewers; these three functions can be accomplished either by an optical or by an electro-optical means. Table 4-1 presents the basic characteristics of these three types of viewers.

4.1 VIEWERS

4.1.1 Screening Viewers

Screening viewers can rapidly view photography to make gross determinations of the usefulness of the imagery, that is, to separate out imagery affected by clouds, water, or any of the many possible cases of abortive photography.

A basic screening viewer is the common light table. The most refined screening viewer is a continuously variable magnifying rear-projection viewer; most of the commercial available viewers in this class are generally too complicated with respect to film loading, and too large to be of any practical operational use.

The screening viewer should be easy to operate, that is, it should be simple to load, have human factored viewing (image position and illumination), have a large range of transportation speeds, and not damage the image in any way.

The range of viewing magnification should be a function of the resolution characteristics of the photography. As an example, photography that has 20 lines per millimeter resolution should not be viewed at 20X. Most operational photography is about 50 lines per millimeter, and the best possible operational

Table 4-1. Photographic Data Reduction Viewers

	OPTICAL		ELECTRO-OPTICAL
	DIRECT	PROJECTION	DIRECT
SCREENING			
Magnification	2X - 3X	2X - 8X	2X - 8X
Size	3'W x 2'H x 2'D	3'W x 6'H x 8'D	4'W x 4'H x 3'D
Volume	12 cu.ft.	144 cu.ft.	48 cu.ft.
Weight	100 lbs.	1000 lbs.	700 lbs.
DETAIL			
Magnification	2X - 200X	2X - 200X	2X - 200X
Size	3'W x 2'H x 2'D	3'W x 6'H x 8'D	4'W x 4'H x 3'D
Volume	12 cu.ft.	144 cu.ft.	48 cu.ft.
Weight	100 lbs.	1000 lbs.	700 lbs.
SPECIAL			
Magnification			
Size	NOT PRACTICAL	6'W x 6'H x 8'D	6'W x 4'H x 3'D
Volume		288 cu.ft.	72 cu.ft.
Weight		1500 lbs.	1000 lbs.

obtainable photography may have 200 lines per millimeter. The resolution of the human eye is approximately 10 lines per millimeter. Therefore, the limit of viewing magnification is from 5X (50/10) to 20X (200/10), but this is the extreme limit. The practical screening viewing range should be some factor of this limit. A subjective estimate for this factor is that it would be a little less than 1/2, or a magnification range of 2X to 8X.

A screening viewer should also have a film marking and/or and editing capability. Film marking is useful in recording some of the gross decisions made by the screening operator such as the marking of those frames that should be removed from the roll, or that are not to be reproduced because they may contain only clouds, open water or useless information. Film editing which is similar to marking can be used for correcting any textual errors in the data block, frame count (if some frames were removed), and for other types of pertinent data that should be recorded with the screened photography.

A coarse measuring system is not necessary, but may be helpful in screening certain specially collected photography.

All of the above capabilities may be accomplished either by an optical or an electro-optical viewer. However, in a screening viewer a very useful function is to be able to view a negative as a positive and have a readout of the photographic gamma required to photographically produce a similar positive image. This function can only be achieved with an electro-optical viewer. Other than this capability, and a possible reduction in size, an optical viewer is probably best for the screening function.

4.1.2 Detail Viewers

Detail viewers are used by the photointerpreter to aid in the extraction of information from various sensor materials.

Detail viewers are generally large magnification viewers. They can be either non-stereo or stereo, rear projection or direct viewing, monocular or binocular, optical or electro-optical. A large range of magnifications are usually available and can be accomplished in either step magnification or zoom magnification. The simplest detail viewer is a B & L zoom microscope with a light table.

The detail viewer should be capable of providing the photointerpreter with the least resolvable element on the photograph. Therefore, the highest magnification should be slightly lower than the highest resolution of the photography (200X) so as to provide the photointerpreter with more than he can actually use. The general requirement of most photointerpreters is to have a zoom magnification system so that the photointerpreter may zoom in on a point of interest. This zooming technique allows the photointerpreter to continually watch the point of interest as it is being magnified, even though he may only use the lowest and highest magnifications.

The detail viewer should be capable of viewing roll film, chip film and glass plates with film transport speeds that are relatively slow, and which would not damage the film in any way. Also, it should have an accurate measuring system with some computational ability to convert photographic measurements into useful ground measurements.

The data block should also be available as the photointerpreter may at times require all available information concerning a particular sortie.

The detail viewer probably should be a combination of a low magnification rear projection system and a high magnification direct stereo viewing system. The low magnification rear projection offers a quasi-screening function to the photointerpreter since he will not look in detail at all of the imagery. The high magnification direct stereo viewing will provide the most photographic information at the best possible resolution with the smallest amount of instrumentation. Stereo viewing requires some flexibility in differential magnification between viewing channels and some image rotation to perform relative orientation of the two stereo images.

The detail viewer should probably be an optical viewer as electro-optical viewers tend to degrade resolution. However, the screening function of a detail viewer can be very conveniently handled by an electro-optical viewing system.

4.1.3 Special Viewers

Special viewers are a catch-all but do satisfy a very important function in photographic data reduction. These viewers are used for change detection, image correlation of other sensors, image manipulation, and permit other possible techniques for the extraction of information from photography. Most of these viewers would probably be electro-optical viewers, because of their required versatility. These types of viewer will be classified by their use and will be individually discussed.

Change Detection Viewers

These viewers are designed to present in one mode or another those image areas that have changed between two different sorties. A viewer of this type was developed about 40 years ago to detect subtle changes in bacteria growth under laboratory conditions by superimposing a "before" photograph projected in red and an "after" photograph projected in green. Upon superimposition, no change will appear yellow, a "before" change in red, and an "after" change in green. This technique is still very practical for photography taken of the same area from the same exposure station; however, an aerial collection system cannot satisfy the same exposure station requirement. Therefore, a change detection viewer must have some rectification capability.

The resolution of change detection or the least element of change is usually relatively large, thereby permitting a low resolution viewing system. Electro-optical viewers can easily satisfy the rectification requirement and are generally capable of resolving the least element of change. As an example, a change detection viewer design could consist of two matched (sync and linearity) CRT/PM inputs and one video tube display. A display of the subtraction of the two video waveforms of each image being analyzed for change would indicate a misregistration due to tilts and changes. With the ability to rectify, an operator could minimize the misregistration by trial and error until only the changes are displayed. The Itek ARES viewer can easily perform this entire operation automatically.

Image Correlation Viewers

This type of viewer would be the most important viewer in a multisensor reduction system. Presently, a viewer of this type does not exist. As with the change detection viewer, the resolution requirement for this viewer is relatively low, and can be satisfied be an electro-optical viewing system.

Because of vastly different multisensor image collection systems (IR, SLR, photography) this viewer should be under computer control for image matching. Once common image areas are identified and matched each record could be displayed in a separate color (e.g., IR in Red, Visual in Green, and SLR in Blue) on a conventional TV color tube for interpretation. Once a photointerpreter has learned to interpret this type of color display, a very quick and accurate interpretation could be made.

Image Manipulation Viewer

This should be an electro-optical viewer which will allow manipulation of the electronic waveform with video amplifiers for extracting various types of information.

4.2 REFERENCE MATERIAL

Photointerpretation keys are seldom used in an operational environment because they are generally of a different area, difficult to handle, and difficult to update. In addition, the current format for photointerpretation keys is such that only when an area is almost completely identified is the key helpful. In brief, present photointerpretation keys are not compiled properly and are not easily accessible for photointerpretation.

Photointerpretation keys should be under computer control, so that a photointerpreter can ask a few pertinent questions, with some initialization parameters, and have displayed at an appropriate scale the most probable key. This operation would be similar in many respects to computer-aided managerial decisions that many large corporations are currently using. A better analogy might be the construction of a criminal's face by an artist from an eye-witness verbal description, basically a trial and error method.

4.3 OTHER COVERAGE

The use of other coverage is a storage and retrieval, and an adequate display problem. The chip concept for the solution of this problem creates a very difficult material handling problem, whereas the roll concept creates an awkward updating problem.

4.4 DATA BLOCK

The data block is very useful in the proper classification of imagery for storage and retrieval. Generally, the data block is not too valuable in photo-interpretation as a good photointerpreter can extract a majority of the data block information from the imagery. However, the data block is very valuable in some cursory mensuration techniques.

4.5 PHOTOGRAPHIC RECORDS

The available photographic records will be defined as those records that lie within the range of silver halide sensitivity, i.e., 3400 Å to 9000 Å. This range can be subdivided into three operable regions - 3400 Å to 4200 Å (ultra-violet); 4200 Å to 7000 Å (visible); and 7000 Å to 9000 Å (infrared).

4.5.1 Ultraviolet Region (3400 Å to 4200 Å)

The collection of electromagnetic energy reflectance in this region is altitude and optically limited, that is, energy in this region can only be imaged by certain lenses, and can only be recorded at low altitudes because of atmospheric attenuation. However, the variation in reflectance of various objects in this energy region is rather spectacular. As an example, vegetation is a complete absorber whereas most hard surface objects are almost always a complete reflector of ultraviolet. A low altitude photograph in this energy spectrum looks very much like a planimetric map since all vegetation is unrecorded.

4.5.2 Visible Region (4200 Å to 7000 Å)

This is the region in which the human eye is most sensitive, and in which most of the physiological studies have been conducted. This is also the region in which color film is sensitive.

Many studies have been conducted in attempting to determine the value between performing interpretation with color photography and black and white photography. In general, the results of most of these studies indicated that color photography was considerably easier to interpret with some improved detectability; however, with color film there is a considerable loss in image resolution and considerable difficulty encountered in processing the three-emulsion layer film and handling the processed film since the three-emulsion layer film tends to curl with age. As a result, the use of the additive color technique is being emphasized.

The additive color technique was originally demonstrated in 1866 by Thomas Young who used a three-color process. With the development of motion pictures, considerable effort was placed on a two-color additive color process. The optimum two-color process consisted of a 4200 Å to 5600 Å (cyan) filtered black and white image and 5600 Å to 7000 Å (orange) filter black and white image. The superimposition of these two records give excellent color with a minimum of effort. This combination is also suited for aerial photography since it collects less of the blue light (3900 Å to 4400 Å) which tends to be attenuated by the atmosphere.

With this two-color process, a color image is obtained by the superimposition of two appropriately filtered high resolution black and white images, thereby providing a truly optimum color photointerpretation system (high resolution color).

Every surface has a completely unique electromagnetic reflective characteristic for wavelengths from a few meters in length to wavelengths a few hundred angstroms in length. Some investigators have been promulgating the thesis that several narrow passband filtered photographs should be collected to further exploit the reflective characteristics of objects in the visible spectrum. However, the portion of the electromagnetic spectrum in which photographic techniques and the human eye is sensitive is very small with respect to the total. It would appear that it would be more practical to collect electromagnetic reflective characteristics over a larger span of the spectrum and reduce this collected data to the visible portion of the spectrum for analysis since the human eye is faster and far more accurate than any other device in sensing slight changes in the visible portion of the spectrum.

4.6 DATA REDUCTION FLOW

The flow of data reduction is fairly well defined up to the point of interpretation which is as follows:

1. Collection — Collection of all electromagnetic reflection from an area of interest in one form or another by various sensors, except for ELINT which is an electromagnetic radiation sensor.

2. Real Time Display — All electromagnetic reflection sensor systems can be displayed in one visual form or another. Two of the more feasible means of display are the CRT with a moving phosphor belt and the more common line-scan CRT with a rapid processing photographic viewer. The UV, IR, SLR, and visible portion of the spectrum are easily handled with each of the above systems; however, the photographic imaging system requires rapid inflight processing prior to viewing in real time.

The photographic collection system is unique in its geometric quality and in its resolving capabilities with respect to the other sensors. It is questionable whether this high quality sensor should be subject to a generally erratic, rapid processing system so that it may be quickly viewed in a real time mode with other sensors that are distorted and of low resolution. With this reasoning, it is suggested that real time analysis be confined to SLR, IR, the visible spectrum and UV which incidentally cover the electromagnetic full-spectrum. The visible spectrum could be spectrally filtered and displayed on a color TV tube for real time color analysis.

3. Recording (film processing for photography; signal processing for other sensors, and recording on film and film processing) — This stage of the data reduction is the most critical and, unfortunately, in many cases the weakest link. Little is known on how to process film to obtain maximum information (which may not be maximum resolution or contrast, etc.). This weak link also exists, and is possibly more severe in the photographic recording of IR, UV, visible spectrum, and SLR, as the entire success of a collection dependent upon the adjustment of the line scan CRT and the V/h setting on the film drive. With these sensors it would be advisable to record them in their original recorded form, that being an electrical waveform. Then, the electrical waveform could be monitored as it is being recorded on film to assure good reproduction.

4. Photographic Data Analysis — This stage contains all of the viewing reproduction, storage and retrieval, and other data handling equipments, and where proper equipment design and employment are of utmost importance.

5. PHOTOGRAPHIC OUTPUT PRODUCTS

Tactical reconnaissance photo materials are recovered in a variety of environments depending on the particular tactical situation. The recovery location may have located on it a full established fixed facility, a mobile facility which provides a semicontrolled environment in which equipment similar to a fixed facility is installed, a building which has been expediently converted and has installed in it much of equipment which is normally found in a fixed facility, or a field operation set up in tents or other provisional shelters. The degree of control over product quality and the rate of production will be governed by the environment and the installed equipment.

5.1 PHOTO PROCESSING

Film recovered from a photo reconnaissance mission must be processed. Even inflight-processed material must be washed and dried if it is to be retained. In a substantial operation where large amounts of film are received, continuous processing is required to meet the established schedules. Productivity and speed depend on the rate at which the processor operates. Figure 5-1 allows calculation of productivity based on film length for some representative speeds of machines in use today.

In some field operations it may not be possible to install continuous processors. Film then must be processed roll by roll in tank-rewind processors. These devices have two capacities - 300 feet and 600 feet. Rolls are processed one at a time, and a total time of 40 minutes is required for processing and washing. A separate dryer is required to provide a dry original negative; this operation entails 20 to 30 minutes.

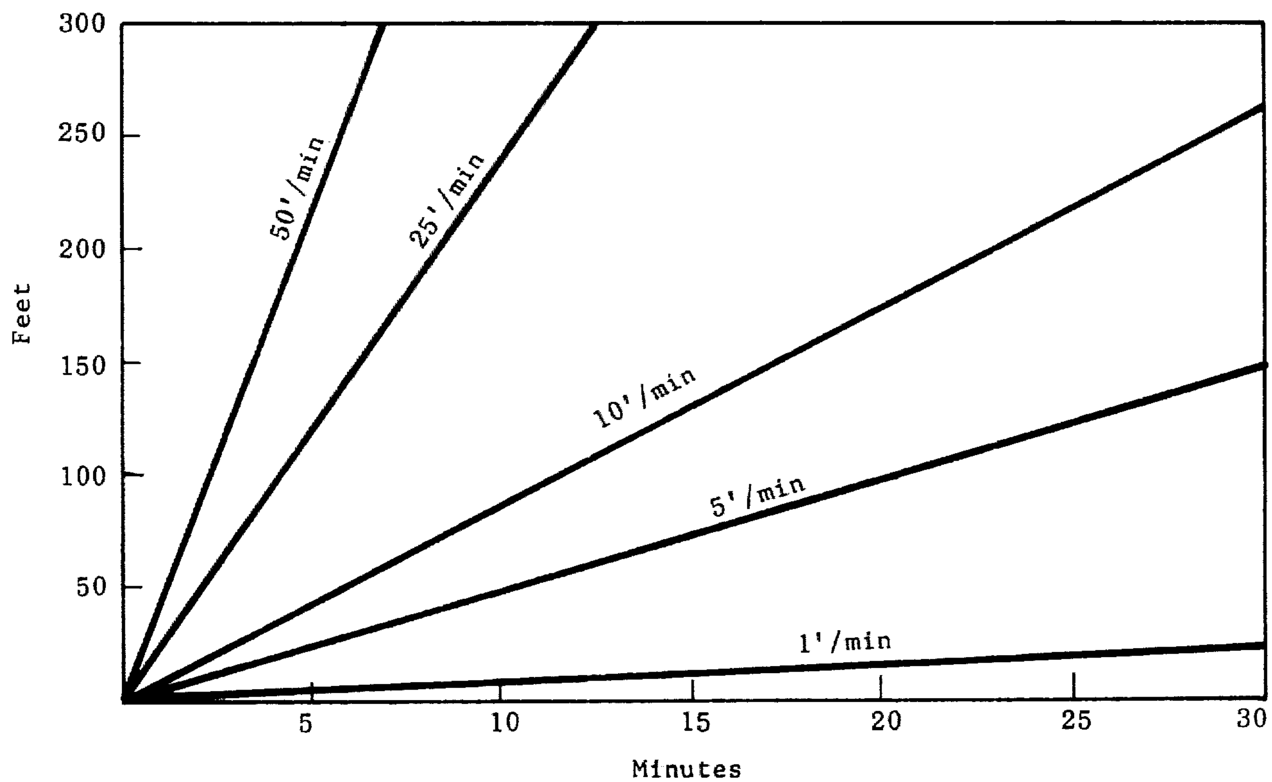


Fig. 5-1 — Film processing production chart.

Current aerial camera equipment accepts film rolls 500 to 6000 feet in length with intermediate increments of 1000 and 2000 feet. These cameras are usually installed and operated in multiples. In this case, and where many reconnaissance aircraft are recovered in a short period, the time to complete processing could be substantial unless multiple processing stations are available.

Any roll of film identified as having the most critical information is processed first. It may be important to determine the amount of time required to get the first frames of photography from this roll. If the film is processed in rewind tanks, the entire process from insertion through to the first frames coming off the dryer make the elapsed time to first product about 45 minutes. If continuous processors are used, total time to the first product will depend on total path length and film transport speed. Figure 5-2 presents a rapid means for determining these data. The range of path lengths and transport speeds used in the figure are representative of continuous processors available today.

Applications of special processing technique, e.g., Bimat, are finding increased use in tactical reconnaissance. A recent Air Force contract resulted in a Bimat-equipped van which enables processing and duplication of five-inch film as the van travels from the pickup point to the photointerpreters area. The results produced are adequate for most tactical reconnaissance photography, although not of the highest quality.

5.2 PHOTO DUPLICATION

Preparation of material for use by interpreters, strike crews, for briefing purposes, and for reference requires a variety of photo duplication equipment which can perform enlargement, reduction or same size prints from original negative materials. These duplicates can be either opaque or transparent positives, duplicate negatives and, depending on their use, duplicated on step-and-repeat or continuous duplicators.

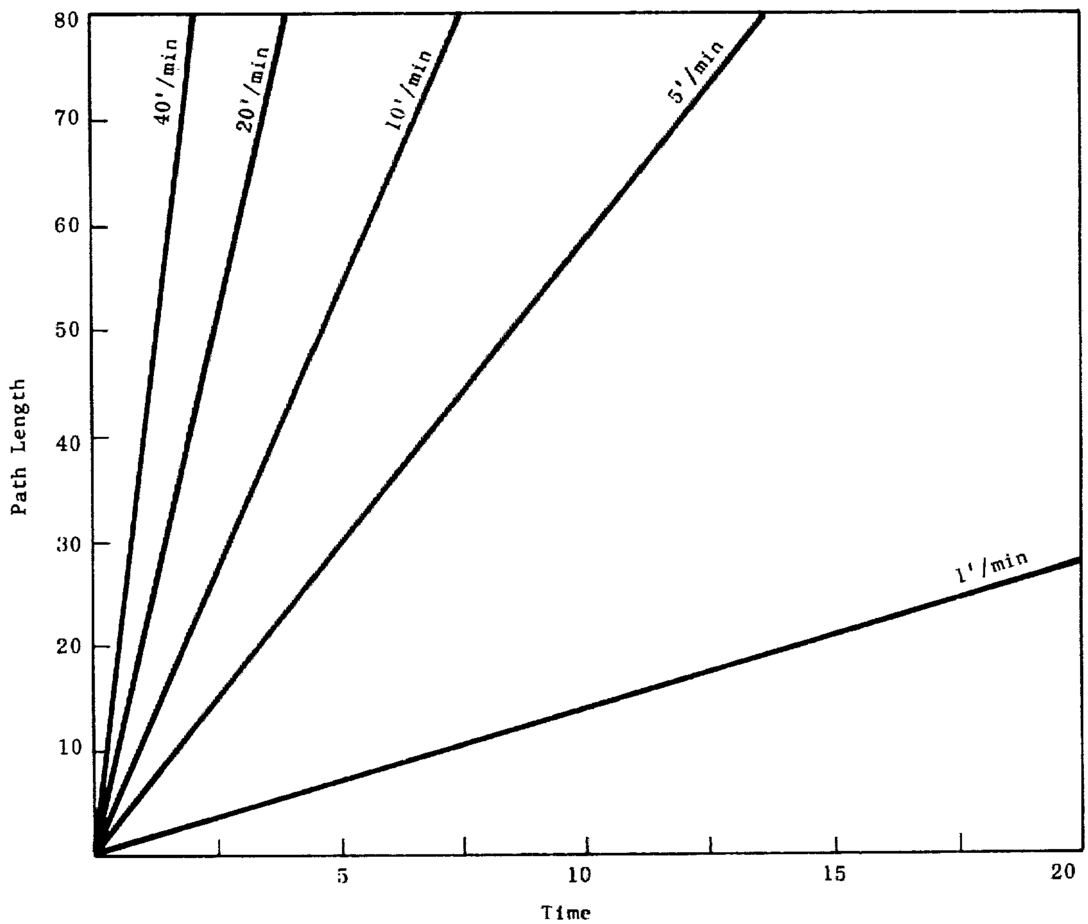


Fig. 5-2 — Time to first access.

5.2.1 Continuous Printing

The requirement to duplicate an entire roll of material calls for the use of continuous printers. A representative list with their operating characteristics is shown in Table 5-1. The type of printer used depends on the task to be performed, the environment and the quality of the output. Printing rates as well as quality vary with each device. Some devices, e.g., C-1B, are configured for field use, while others are only for fixed facility.

5.2.2 Step-and-Repeat Printing

This type of printer is employed when only selected areas of the photography are to be reproduced, either singly or in multiple copies. The most simple of these devices is the hand-operated contact or projection printer. Exposure times on such devices vary from approximately 1 to 30 seconds, which results in a manual production rate from 2 to about 20 prints per minute. A recently developed group of printers, using roll paper or film, has a more intense light source to permit very short exposure times and raise production to approximately 30 prints per minute.

5.2.3 Dodging

Dodging in various forms has generally been incorporated in most military duplicators. The older contact printers were equipped with argon glow lamps which could be extinguished individually to control the amount of light used to form the print image. In some printers an aperture was provided to insert translucent tissue at appropriate spots to selectively reduce light intensity. The advent of electronic dodging has provided an accurate control of light in printers. Military printers, such as the CP-10 (contact step-and-repeat), B-10A (projection step-and-repeat) and the SP-1070 (1:1 size continuous) included this capability. These duplicators are generally slower than their non-dodging counterparts with a resulting reduction in productivity.

5.2.4 Duplicate Processing

When duplicates are produced on a continuous roll of film or paper, processing can be accomplished in the same types of continuous processors described

Table 5-1. Operating Characteristics of Continuous Printers

Model/ Manufacturer	Type	Resolution	Rate	Film Size	Power	Weight	Size
SP107, Log Electronic	Continuous contact, auto dodging	160 1/mm	50-60 ft per min	70 mm 5 1/4 9 3/8	105-130 V 60 cps, 12A	450 lbs	40" x 25" x 68"
Concord (console) Eastman Kodak	Continuous contact	300-350 1/mm	85 ft per min	70 mm, 6.6" 1000 ft lengths	115 V; 60 cps 1000 w	660 lbs	48" x 29 1/2" x 70 1/2"
Concord (table top) Eastman Kodak	Continuous contact	300 1/mm	33 ft per min	70 mm, 6.6", 1000 ft lengths	115 V; 60 cps 500 w	350 lbs	42" x 38" x 22"
Niagara, Eastman Kodak	Continuous contact	300-350 1/mm	82 1/2 ft per min	70 mm, 9 1/2", 1000 ft lengths	115 V, 60 cps, 1000 w	1030 lbs	73" x 60" x 34"
C1B, Military	Continuous contact	45 1/mm	15 ft per min	9 1/2 roll black and white and color	115 V, 60 cps 400 w	300 lbs	27" x 37" x 19"
EN6A Military	Continuous contact	45 1/mm	15 ft per min	5 and 9" black and white and color	115 V, 60 cps 800 w	400 lbs	43" x 30" x 37"

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previously. Because of the sensitometric characteristics of the duplicating materials, they can be processed at about twice the rate of original film. The dried roll of duplicates must, after processing, be cut into individual segments. A variety of automatic cutters are available which can cut these rolls at rates up to 50 feet per minute.

The use of sheet paper or film requires tray processing. This procedure is tedious, time consuming and messy. A line of printer, processor and fixer usually requires three people with one processing line accommodating no more than two printers. After fixing, a lengthy wash is required; drying is accomplished on a drum dryer in a dehydrator cabinet. Several machines have been developed recently to overcome these problems. Eastman Kodak, Pako and Itek have developed devices which process these materials automatically enabling the entire operation from dry to dry to be accomplished by one man. These machines generally operate at from 2 to 10 feet per minute.

5.3 PRODUCTION VOLUME

Reconnaissance aircraft are currently equipped with a variety of cameras, each having its own characteristics, and each having different film capacities. Film capacities vary in width from 70mm to 9 1/2 inches, and in length from 100 feet to 12,000 feet, the latter in two reels of 6000 feet each. Cameras may be installed and operated in multiples or individually depending on the assigned mission. During periods of extreme activity, it is not uncommon for the total complement of aircraft to fly at least one mission each, using all cameras on each mission. In this circumstance, when film is not processed inflight, it is entirely possible for a tactical reconnaissance operation to produce from 20,000 to 40,000 feet of film per day. When this material must be processed and printed, as well as analyzed within a two-hour period (the accepted time limit for completing the processing and analysis of tactical reconnaissance material), it is evident that a large complement of machines and personnel must be available, and that the process must be accellerated by a combination of high speed processing/printing devices and automation or a combination of both.

5.4 PHOTO PRODUCTS

In addition to processed and titled original negatives, the tactical photo operation may produce a variety of products to support battle activities.

5.4.1 Photo Interpretation

In many photo activities, where time for reduction of photography to intelligence is extremely critical, interpretation will be accomplished from the original negative. Interpreters must be trained in this form of interpretation, but once proficiency is achieved, the results are nearly equivalent to those obtained working from positives.

Tactical interpreters, in general, have worked from positive prints. Where the reconnaissance system produces material of low resolution, paper prints are adequate to retain all available detail. Producing paper prints with continuous or step-and-repeat printers is rapid and requires only nominal control. With the advent of high acuity systems, a large percentage of the available detail in the negative can be lost printing on paper. As a result, tactical operations have generally converted to continuous printing on high resolution positive transparent materials. The resultant transparent positive is viewed by medium-magnification rear projection viewers, or directly with high magnification microscopes. In a limited number of cases, instead of continuous contact printing, the transparencies are either magnified or reduced to convert all materials to a standard handling size. This activity could result in the requirement for one or more duplicates requiring not only the printers, but the processing devices required to develop, fix, wash and dry the material. The machine requirement is directly dependent on the volume of materials received, the numbers and types of duplicates required, and the time available to produce the required products.

5.4.2 Reference Material

Duplicate transparencies or opaque prints are produced to be used as comparative reference with newly acquired coverage. In addition, copies of annotated photography and maps are produced as evaluated reference. Sizes of these products will vary with the particular reference system established.

Transparencies may vary in size from the recently established 70 by 100mm Unit Record (film chip) to a full frame of original photography. These records are indexed and stored in dossiers or in file drawers to be extracted for comparison when new cover is received. Often prints of complete or partial frames are made for storage in target dossiers as part of the total complement of target reference material. The index used can be the BE (Bombing Encyclopedia) Number, the Tactical Target Index Number, or the Target Data Inventory (TDI) Number.

5.4.3 Mission Folder Material

As a part of the mission folder organized to provide reference for the combat mission, photo reproductions of annotated maps and photos are produced. Response speed for reproduction of these materials must be minimized to support the "quick reaction" capability of combat aircraft.

5.4.4 Briefing Material

In addition to the intelligence extracted from aerial photographs, these photographs are used in briefings as additional aids. Often selected photographs are enlarged to considerable size to serve as detailed illustrations for the briefer. Prints of smaller dimensions are used in briefing packages for th senior command staff. Magnification of 10X are not uncommon in this application resulting in prints that are 40 inches square. This requirement imposes special problems in terms of equipment to print and process as well as the paper required for this product.

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6. HIGH RESOLUTION SIDE LOOKING RADAR

This section discusses the role of the radar sensor in an integrated multisensor system for tactical reconnaissance. A side looking radar can be used to obtain radar "pictures" of terrain features and cultural objects. In addition, it can automatically detect moving objects and objects of large cross-section and use this detection information to key the radar imagery of the information obtained from the other sensors. By repetitive cover over the same area of a tactical battlefield, changes in the location of enemy offensive and defensive equipment and construction can be noted by comparison of the latest imagery with that previously obtained. The proper choice of frequency can allow the penetration of foliage and camouflage. Unlike photography and infrared sensors, radar is essentially an all-weather sensor.

With conventional radar systems, resolution is achieved by radiating a beam sufficiently narrow that the width of the beam at the desired range gives the required azimuth resolution. Similarly, a conventional radar's range resolution is achieved by radiating a pulse whose width corresponds to the desired range resolution. However, by employing the relatively new techniques of synthetic array radar signal processing and pulse compression, very fine azimuth resolution, practically independent of range, is obtained along with fine range resolution compatible with high average power transmission; this discussion considers the optimum design of a radar sensor incorporated in a multisensor system for airborne tactical reconnaissance for the 1970 era. This is specifically interpreted as meaning that the flight tests of the production prototype will be completed in 1970. A reasonable extrapolation of the state-of-the-art is made based upon current technology.

Electronic or coherent optical signal processing techniques may be employed to process the synthetic array radar raw data to obtain imagery maps or to process the data for moving target indication. With the present state-of-the-art, electronic processing has proved less efficient than coherent optical processing in terms of the weight and power required for processing at a specified data rate (in resolution elements per second). Further developments in storage media and electron beam technology may make electronic processing attractive in the 1970 time era. Even with the present state-of-the-art, electronic processing can be used for moving target indication while in flight, although the number of range resolution elements is restricted.

There appear to be very good reasons to perform inflight signal processing to obtain moving target indications since this indicator can be used as an alerting and keying device for the radar imagery and other sensors. However, there appears to be little reason for doing inflight image processing just for the purpose of presenting the output to the aircraft observer. This is principally because the observer does not have available the amount of time required to absorb the information at the sensor output data rates from even one of the imagery sensors. Therefore, the principal reason for doing inflight processing of imagery is to shorten the time involved in transferring the imagery from the aircraft to the carrier and then to the reconnaissance analyst. It is not clear whether this time saving is commensurate with the additional amount of airborne equipment required, with the resulting problems in weight, power, complexity, reliability, and cost.

In analyzing the data link operation we must consider the types of information which is valuable to transmit to the priority analyst in real-time. Obviously the MTI keying information is of this type. Also, the other keying information obtained from the other sensors is of this type.

When operating at high altitude it is possible to transmit the radar signal raw data directly to the carrier where it can be recorded and processed to form an image. When operating at low altitudes, however, it is not possible to obtain direct transmission unless a relay aircraft is used. Without the use of relay aircraft, it is necessary to record the raw data on film, develop the film, and then scan the film data with a flying spot scanner and read out over the data link when the aircraft is at the proper position. This requires a relatively wide band link unless some selection is done of the data which is to be transmitted back.

The requirements of low altitude and high altitude missions place different requirements upon the performance of a synthetic array reconnaissance radar. For low altitude missions the coverage is usually restricted by the shadowing effect at low grazing angles, while for high altitude missions the coverage is usually restricted by the amount of recording capacity that can be included in the radar system. The maximum range for high altitude missions can be set by the amount of average power, the grazing angle, or ambiguity considerations.

For low altitude, short range missions which map preselected targets, it is possible to employ a conventional radar and still obtain reasonable azimuth resolution. In the high altitude, wide coverage mission, however, reasonable azimuth resolution can only be obtained by synthetic array radar techniques. For the limited amount of coverage obtained on low altitude missions normal photointerpretation techniques can be employed for target recognition. In the wide coverage, high altitude missions, the amount of data per mission could saturate the reconnaissance analyst unless some data selection is performed. This data selection can best be done by change detection techniques which call attention to those areas where there are changes in radar return.

Because of weather attenuation, the useful radar frequency range is K-band and below. Even at K_a-band there is fairly severe weather attenuation and back scattering when light rain is present. At X-band almost all of the atmospheric attenuation, weather attenuation, and clutter effects have disappeared. However, the K-band frequency range has better contrast between such low reflectance targets as concrete, dirt, grass, etc. For low altitude, short range missions, the effect of weather can be ignored and this would indicate that K-band would be the best operating frequency to obtain good radar imagery. However, for long range high altitude missions X-band is to be preferred.

To penetrate dense foliage and camouflage requires the use of low radar frequencies, for example, 1-meter RF wavelength.

The time scales of importance in radar sensor design are fifteen minutes and two hours. The fifteen minute figure pertains to obtaining information in time to change the mission of the next reconnaissance sortie or to change the armament and mission of the attack force on the next flight. This timeliness is especially important for fleeting targets in a battlefield environment. Because of the flight time and data recovery times involved, the fifteen minute figure can only be met by the use of a data link to send priority information. Because of data link bandwidth considerations, only selected data can be transmitted, and because of the interpretation times involved, only data which is not subject to long interpretation will be valuable.

For the radar sensor, the moving target indication information falls in this category of priority information. Therefore, a real-time inflight processor for moving target indication should be employed and the output of this processor should be both presented to the observer on the aircraft and sent by data link to the carrier. On the carrier the priority analyst will be presented with this moving target information along with other alerting and keying information from other sensors in order to make a decision for the next strike and subsequent strikes.

Another form of operation where near real-time processing will be valuable is for battlefield surveillance. To best utilize the radar in a timely manner, it is necessary to fly at high altitudes and maintain continual data link contact with the carrier. By the use of repetitive surveillance missions the imagery data which is sent via data link to the carrier can be processed and compared to previous imagery by change detection methods. To make maximum use of this information for programming attack missions, the delay in this processing and change comparison must be kept to times on the order of fifteen minutes for fleeting targets.

The bulk of imagery data, especially on wide coverage missions, will be physically recovered on the carrier. Film processors and signal processors that obtain the output imagery used for data and target interpretation should operate so that output images are available in under an hour, which means that most of the reconnaissance information can be obtained in under two hours. In cases where high quality photography has been obtained of the same areas being covered, the radar will not be used for detailed interpretation but for keying large cross-section targets and indicating changes in the radar imagery. This keying data will enable a photointerpreter to inspect in detail these locations on the photography.

6.1 SYNTHETIC APERTURE RADAR

Synthetic array radar is one of the most advantageous technique for airborne reconnaissance. In that it is a new technique, it is described in detail in this section. Functional elements of a radar system are shown in Fig. 6-1.

Conventional radar systems achieve azimuth resolution by radiating a beam sufficiently narrow that the width of the beam at the desired range gives the required resolution. Similarly, in conventional radars, range resolution is achieved by radiating a pulse whose width corresponds to the desired range resolution. The result of these conventional techniques is a radar whose range resolution is essentially independent of range but whose azimuth resolution deteriorates with range, since a constant angular resolution is achieved.

In many instances, a short pulse technique is adequate for the achievement of useful range resolutions. However, in many cases the linear azimuth resolution desired cannot be achieved with particular parameter values (antenna size).

Improvement of the azimuth resolution by conventional techniques is accomplished by narrowing the radiated beam. Since the radiated beam is proportional to wavelength and inversely proportional to the length of the antenna aperture, much effort has gone into systems using shorter wavelengths and longer antennas. Obviously, for airborne mapping applications, a limit is reached on the length of antenna which can be carried in an aircraft. For this reason, means to achieve fine resolution without the necessity for long physical antennas were sought, which resulted in the development of the synthetic antenna technique.

The synthetic antenna technique uses motion of a significantly smaller antenna together with signal analysis operations to generate a synthetically long antenna. The analysis of the operations involved shows that a linear azimuth resolution can be achieved which is independent of range and of frequency, and which depends only upon the aperture of the physical antenna used. Moreover, contrary to the conventional radar case, finer resolution is associated with smaller physical apertures, the theoretically achievable resolution being, in fact, equal to approximately one-half the physical aperture.

The reasoning leading to a synthetic antenna is essentially as follows. In a linear array the beamwidth of the array factor is inversely proportional

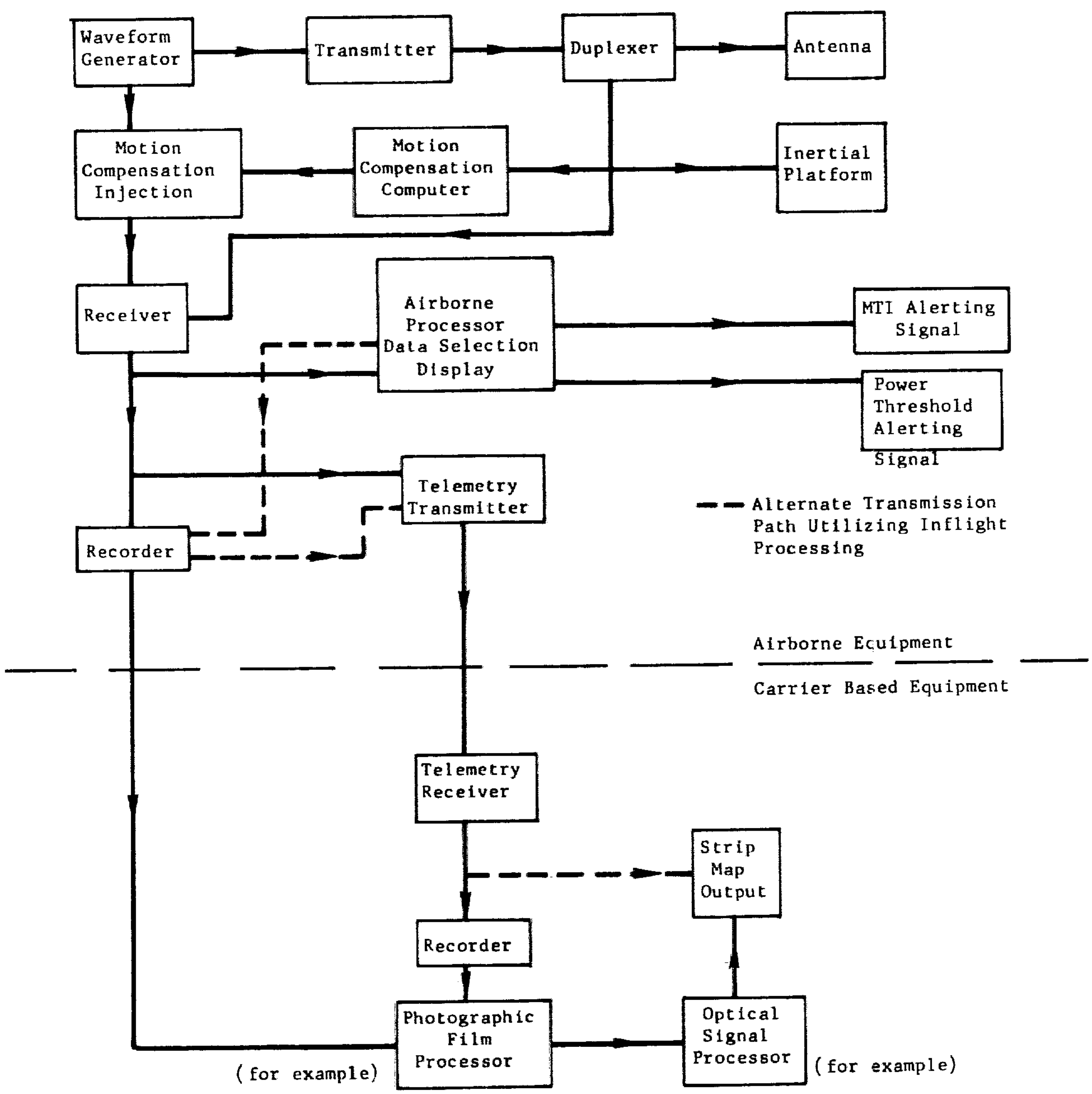

Fig. 6-1 — Functional elements for radar system.

to the length of the linear array, so that one achieves narrower array factors by using longer arrays; in a physical linear array, each of the elements of the array exists physically, and each element transmits and receives signals simultaneously. The signals from the radiating members of the array are combined so that appropriate vector summation of their signals gives the radiated beam pattern associated with the array.

In the synthetic antenna case, however, only a single radiating element is used. This element is moved so that it occupies, in turn, each of the positions of a linear array. At each of these positions, a signal is transmitted and the radar echoes are received. The received signals are put into storage and subsequent operation on this data is used to combine these signals in a manner appropriate to synthesize a long aperture antenna. To do this, the operations must preserve the essential vector character of the signals so that a coherent radar system preserving both phase and amplitude is required.

It is evident that, if the signals are in storage, some degrees of freedom available in the synthetic antenna case which are not available in the case of a real physical linear antenna. Since the data is in storage, a synthetic antenna can be generated which is focused at all ranges. In generating synthetic antennas focusing becomes necessary as the desired length of the synthetic antenna is increased. For antenna lengths shorter than some critical value, little is gained by focusing. However, for synthetic antenna lengths longer than this critical value, focusing is required in order to achieve the resolution corresponding to that length. Hence, two types of synthetic antennas are considered, namely, focused and unfocused.

An additional benefit derived is that a synthetic antenna of a given length gives a resolution element finer by a factor of two than that achievable with a physical antenna array of the same length. This arises because path length differences, both in transmission and reception, are effective in generating the synthetic antenna pattern, whereas only path length differences during reception are effective in the physical antenna case.

Finally, antenna lengths of the order of tens of feet are practical in airborne systems. In the case of synthetic antennas, array lengths of thousands of feet are possible since these antenna lengths are achieved by transporting a small antenna along the synthetic array. The length of the synthetic antenna achievable depends only upon the product of beam width of the antenna and range to the target. Thus, it is evident that wider beams are needed to achieve longer synthetic antennas. This is contrary to the conventional case in which physically long antennas are required to produce narrow beams.

The notion of the synthetic antenna beam first received attention prior to 1953. Since 1953, however, much more intensive activity has been devoted to synthetic antennas. Many systems have been built and flight-tested since that time, and flight test results of successful systems are available. Some flight test results are shown in Section 6.1.6.

6.1.1 A Comparison of Several Azimuth Resolution Techniques

This section will compare the resolution performance capability of the three means for achieving azimuth resolution, namely:

1. The conventional technique: In this technique, azimuth resolution depends upon the width of the radiated beam.
2. The unfocused synthetic antenna technique whereby the synthetic antenna length is made as long as the unfocused technique permits.
3. The focused synthetic antenna technique, whereby the synthetic antenna length is made equal to the linear width of the radiated beam at each range.

As is shown in the sections which follow, the linear transverse resolution for the conventional case is given by:

$$\text{Resolution}_{\text{conv}} = \frac{\lambda R}{D} . \tag{6.1}$$

For the unfocused case, the resolution is given by:

$$\text{Resolution}_{\text{unf}} = \frac{1}{2} \sqrt{\lambda R}, \tag{6.2}$$

whereas for the focused case, the resolution is given by:

$$\text{Resolution}_{\text{foc}} = \frac{D}{2} . \tag{6.3}$$

In the above expressions, λ is the wavelength of the radar signal transmitted, D is the horizontal aperture of the antenna, and R is the radar range.

Fig. 6-2 is a plot of the resolution for each of these cases as a function of radar range. This plot is for an antenna aperture of 5 feet and a wavelength of 0.1 foot.

Conventional Azimuth Resolution — The conventional technique for achieving azimuth resolution has been that of radiating a narrow beam. In this case the resolution of a target depends upon whether the target is included within the radiated beam. While some techniques exist for resolving targets somewhat less than a beamwidth apart, it will be assumed that the resolving capability of an antenna is equal to the width of the radiated beam at each range.

The computation of the linear azimuth resolution for the conventional case is well-known. The appropriate expression is obtained by noting that the width of the radiated beam in radians is given by the ratio λ/D, whereas the linear width of the beam at range R is the product of this beamwidth by range. These considerations lead to the result described by Eq. (6.1).

For a given wavelength and antenna aperture, the fineness of resolution deteriorates in direct proportion to range. For a specified antenna aperture and range, the linear resolution can be improved by using a shorter wavelength. Conversely, with the wavelength fixed, an increase in antenna aperture is required to improve resolution.

A consideration not evident from the above discussion but pertinent from antenna theory is that Eq. (6.1) applies only to the far-field pattern of an antenna. The beginning of the far-field occurs at a distance R_{min} for which

$$R_{min} = \frac{D^2}{\lambda} . \tag{6.1.1}$$

It will be noted by substitution of Eq. (6.1.1) that the finest resolution achievable using the conventional technique is given by

$$\text{Minimum Conventional Resolution} = D \tag{6.1.2}$$

The Unfocused Synthetic Antenna — The simpler of the synthetic antenna techniques is that which generates an unfocused synthetic aperture. In this case, the coherent signals received at the synthetic array points are integrated with no attempt made to shift the phases of the signals before integration.

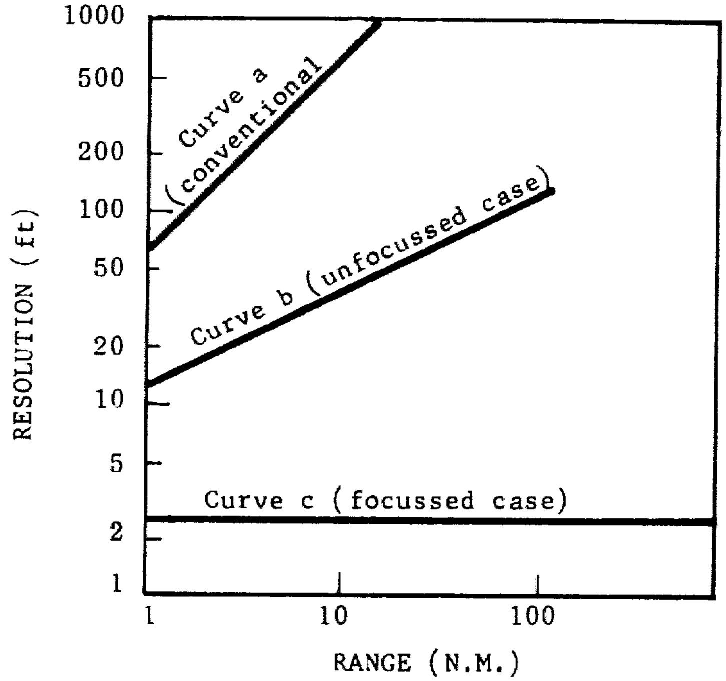

Fig. 6-2 — Azimuth resolution for three cases: (a) conventional, (b) unfocused, (c) focused.

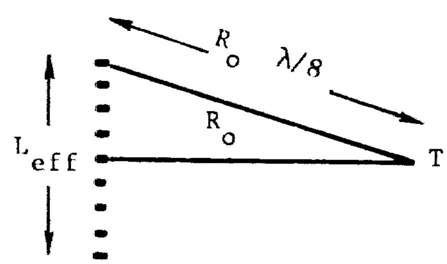

Fig. 6-3 — Geometry for unfocused synthetic antenna.

This lack of phase adjustment imposes a maximum length upon the synthetic antenna length which can be generated. This maximum synthetic antenna length occurs at a given range when the round-trip distance from a radar target to the center of the synthetic array differs by $\lambda/4$ from the round-trip distance between the radar target and the extremities of the synthetic antenna array.

The pertinent geometry is shown in Fig. 6-3. In this figure, R_o represents the range from a radar target to the center of the array, L_{eff} represents the maximum synthetic antenna length for which the distance from the target to the extremities of the synthetic antenna does not exceed $R_o + \lambda/8$.

From this geometry,

$$\left(R_o + \frac{\lambda}{8}\right)^2 = \frac{(L_{eff})^2}{4} + R_o^2 . \qquad (6.2.1)$$

If this expression is solved for L_{eff}, subject to the assumption that $\lambda/16$ is small compared to R_o, the result is

$$L_{eff} = \sqrt{R_o \lambda} . \qquad (6.2.2)$$

Because of coherence, the relative phase of signals received from a target depends on the round-trip distance to it. Consequently, the beamwidth of the synthetic antenna is half that of a conventional array of the same length, i.e.,

$$\beta = \frac{\lambda}{2L_{eff}} \text{ radians.} \qquad (6.2.3)$$

Multiplying this beamwidth by range results in the resolution given by Eq. (6.2).

As shown in Eq. (6.2), the transverse linear resolution is independent of the antenna aperture size. For the unfocused case, fineness of resolution is increased by the use of shorter wavelengths, but in comparison with the conventional case, the improvement in fineness of resolution varies as the square root of λ rather than directly as λ.

<u>The Focused Case</u> — An expression for the resolution achievable in the focused case was given by Eq. (6.3). It is significant that the azimuth resolution achievable for this case depends only upon the synthetic antenna aperture

and that, in contradistinction to the conventional case, finer resolution is achievable by using small rather than large antennas.

Also, significant for this case is the fact that the achievable resolution for a given antenna size is independent both of the range and of the wavelength used. A graph of Eq. (6.3) is also shown in Fig. 6-2. Inasmuch as the resolution achievable in this case is a constant, this curve is a straight line parallel to the range axis.

In order to achieve the resolution indicated by Eq. (6.3), a synthetic antenna length given by Eq. (6.3.1) is required; namely,

$$L_{eff} = \frac{\lambda R}{D} . \qquad (6.3.1)$$

The consideration used in arriving at Eq. (6.2.2) indicated that unless additional processing were applied to the signals, antenna lengths such as those implied by Eq. (6.3.1) could not be achieved. The processing required is that of an adjustment of the phases of the signals received at each point of the synthetic antenna which makes these signals co-phase for a given target. If this is done, the restrictions which limited the maximum antenna length to that given by Eq. (6.2.2) are no longer pertinent, and the new limitation on the length of synthetic antenna achievable becomes simply the linear width of the radiated beam at the range of the target. Note that Eq. (6.3.1) is an expression for the maximum length in this case.

In some cases a resolution coarser than D/2 is sufficient. Then a fraction α of the maximum focused synthetic antenna length can be used. Eq. (6.3.1) becomes

$$L_{eff} = \frac{\alpha \lambda R}{D} \qquad (6.3.2)$$

and the achievable resolution is

$$\text{Resolution}_{foc} = \frac{D}{2\alpha} .$$

In those situations for which the synthetic antenna length given by Eq. (6.3.2) is less than or equal to the synthetic antenna length for the unfocused case as given by Eq. (6.2.2), only a limited improvement in resolution is achievable for the focused case. However, if a resolution finer than that given by Eq. (6.2) is desired, then focusing must be used, and in this sense the use of focusing, in effect, removes the restriction on synthetic antenna length which would otherwise apply.

6.1.2 Ambiguity

The basic mechanism employed in synthetic aperture radar is to operate on a "phase history" that can be predicted for each target in the antenna beam. Predictability, properly accounted for in the signal processing, will permit the obtaining of resolution much finer than conventional beamwidth limited considerations would indicate. Let us consider, for the moment, the phase history that will be obtained from a point target with a side-looking, coherent radar.

A side-looking radar is an airborne radar that has the main lobe of the antenna beam oriented normally to the velocity vector of the vehicle. A coherent radar is distinguished from a conventional radar by a clock employed in the radar set that permits the measurement of the total round-trip phase distance to a target (modulus 2π). The diagram shown in Fig. 6-4 shows the airplane on the left of the picture with the antenna beam depicted. A target, whose minimum range is r_o, can be thought of as traversing the path shown as Target Path relative to a stationary airplane. The change in $\underline{a}$ observed as the target moves along the target path is proportional to the phase output from the coherent radar. This radar is easily calculated by

$$(r_o + a)^2 = r_o^2 + x^2,$$

or

$$r_o^2 \left(1 + \frac{2a}{r_o}\right) = r_o^2 + x^2.$$

Reduced to a first order approximation,

$$a = \frac{x^2}{2r_o} .$$

The approximation here assumes that the distance $\underline{a}$ is much smaller than r_o which is clearly a valid assumption when the antenna beam width is on the order of a few degrees and the range r_o is several miles.

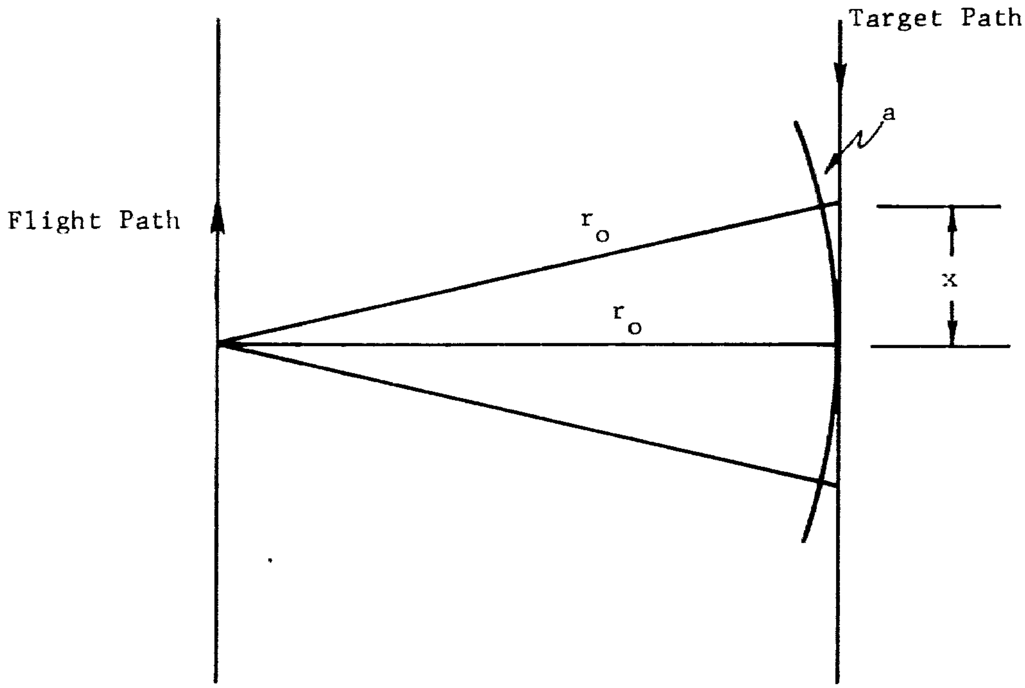

Fig. 6-4 — Side looking radar pattern from aircraft.

When the distance a is converted to a round-trip phase distance, the following result is obtained:

$$\phi = \frac{2\pi\ x^2}{\lambda\ r_o}. \tag{6.4}$$

where λ is the radar wavelength. A final change is made by our establishing a time origin at the instant the target is exactly broadside the aircraft; and then the distance x is merely the product of aircraft velocity and time. Thus, the phase history is expressed as

$$\phi\ (t) = \frac{2\pi\ v^2\ t^2}{\lambda\ r_o}\ . \tag{6.5}$$

If required, a frequency history could be specified as the time derivative of Eq. (6.5), or

$$\omega\ (t) = \frac{4\pi\ v^2\ t}{\lambda\ r_o}\ .$$

The maximum value that ω can obtain is when the target just enters or just leaves the beam. In terms of Eq. (6.4), this maximum value is

$$\omega_{max}\ (t) = \frac{4\pi\ x_{max}}{\lambda\ r_o}\ \frac{dx}{dt} \tag{6.6}$$

$$= \frac{4\pi\ v\ x_{max}}{\lambda\ r_o}\ .$$

A maximum value for x is obtained by our considering the nature of the antenna characteristics. The beamwidth of the antenna is roughly the ratio of the radar wavelength to the aperture length. Therefore, the distance x_{max} is

$$x_{max} = \frac{\lambda\ r_o}{2D}\ ,$$

where D is the antenna length. Thus we obtain

$$\omega_{max} = 2\pi\ \frac{v}{D}\ ,$$

or in terms of frequency measured in cycles per second,

$$f_{max} = \frac{v}{D} . \tag{6.7}$$

The above discussion has led to a basic consideration that can cause ambiguity. It is well established that unique recovery of a sampled signal can be accomplished only if the sampling frequency is at least twice as great as the bandwidth of the signal being sampled. When the sampling frequency is actually less than twice the bandwidth, spectrum folding occurs, and it becomes impossible to distinguish between different frequency signals in the sampled spectrum. In other words, ambiguous signals are generated by the folded portion of the spectrum.

In synthetic aperture radar, the data processing is unable to separate signals from the folded portion of the spectrum from the undistorted portion of the spectrum. System pulse repetition frequency (PRF), therefore, must be set at a sufficiently large value to permit ambiguous recovery of the spectrum from any target illuminated by the radar antenna. It is important to observe here that the bandwidth of the signals being sampled is not merely the ratio of the vehicle velocity to the antenna aperture length as shown by Eq. (6.7). The bandwidth is in reality twice this value because information is collected both before the vehicle is broadside to the target, and after this time. When the target is in the forward half of the antenna beam, the velocity is closing, (i.e., the airplane is moving toward the target). During this period of time, the frequency shift is positive. On the other hand, when the target is in the after portion of the beam the target is receding and the doppler shift is negative. Here is a case where it is important to be able to distinguish between positive and negative frequencies - a task that is very difficult to accomplish. To assist in this measurement, a frequency offset is employed. The offset is set at a value such that the lowest negative frequency is translated to zero frequency. This amount of offset frequency will translate the entire spectrum of received signals to positive frequencies, and there will be no difficulty encountered in separating the different portions of the spectrum of the return signal. The amount of this offset must be at least as great as f_{max} determined by Eq. (6.7). Therefore, the actual maximum frequency to be sampled by the system PRF is in reality 2 f_{max}, and the minimum PRF is

$$\mathrm{PRF} \geq \frac{4v}{D} \tag{6.8}$$

In case the PRF is less than the above quantity, the data processing system will be supplied with false signals that are indistinguishable from bonafide signals.

Another problem that is related to ambiguity generation sets an upper limit on the PRF. When the inner-pulse period is shorter than the round-trip propagation time for the required range interval, two pulses can impinge on the ground at the same time within the region illuminated by the antenna beam. When this operation occurs, signals from targets widely separated in range will arrive at the radar receiver simultaneously. No really workable method of separating these range signals has been demonstrated. Therefore, the inter pulse period must be kept greater than a value corresponding to the round-trip distance across the range interval being mapped. This consideration leads to

$$T \geq \frac{2 \Delta R}{c},$$

or

$$\mathrm{PRF} \leq \frac{c}{2 \Delta R}, \tag{6.9}$$

where c is the propagation velocity.

The inequalities Eq. (6.8) and (6.9) are now combined to show the boundaries for the permissable range of PRF:

$$\frac{4v}{D} \leq \mathrm{PRF} \leq \frac{c}{2 \Delta R}. \tag{6.10}$$

When it is possible to place the PRF within the above boundaries, no difficulty will arise from ambiguity considerations. In some cases, the permissable range of PRF might become very small, or it might not be possible to satisfy the above expression at all. These cases occur because the required resolution is very small, and hence the antenna aperture must be small, the velocity of the vehicle is very large, or a very wide range coverage is necessary. If one or more of these considerations force the boundaries on the PRF to the same value, i.e.,

$$\frac{4v}{D} = \frac{c}{2 \Delta R},$$

the radar is called ambiguity limited, and there is no freedom available in the selection of various system parameters. A most important restriction imposed by ambiguity limited performance is on the radar antenna area. Solving the above equation for the length of the antenna, we find that

$$D = \frac{8 v \Delta R}{c} \tag{6.11}$$

A relationship for R can be derived which shows that R depends on the minimum slant range to the target, the radar wavelength, the vertical antenna aperture and the depression angle. Consider the diagram shown in Fig. 6-5. The law of sines relates the quantities shown in this figure by

$$\frac{R_{min}}{\sin \phi} = \frac{R}{\sin \alpha}.$$

As an approximation, $\sin \alpha$ is the ratio of the radar wavelength to the height of the antenna. Therefore, ΔR can be expressed as

$$R = \frac{R_{min} \lambda}{h \tan \phi},$$

where h is the vertical aperture of the radar antenna. When this expression is substituted into Eq. (6.11), it is possible to solve for the product Dh, the area of the radar antenna:

$$Dh = A_{min} = \frac{8vR_{min} \lambda}{c \tan \phi} \tag{6.12}$$

Equation (6.12) is an expression for the minimum antenna area. This area has been dictated by ambiguity considerations, and if the antenna is smaller than specified by Eq. (6.12), the received signal will contain ambiguous returns. Note that from this equation the shape of the antenna is not dictated by the ambiguity consideration, but rather the area is fixed. Therefore, the particular ground coverage or longitudinal resolution is not in itself fixed by ambiguities,

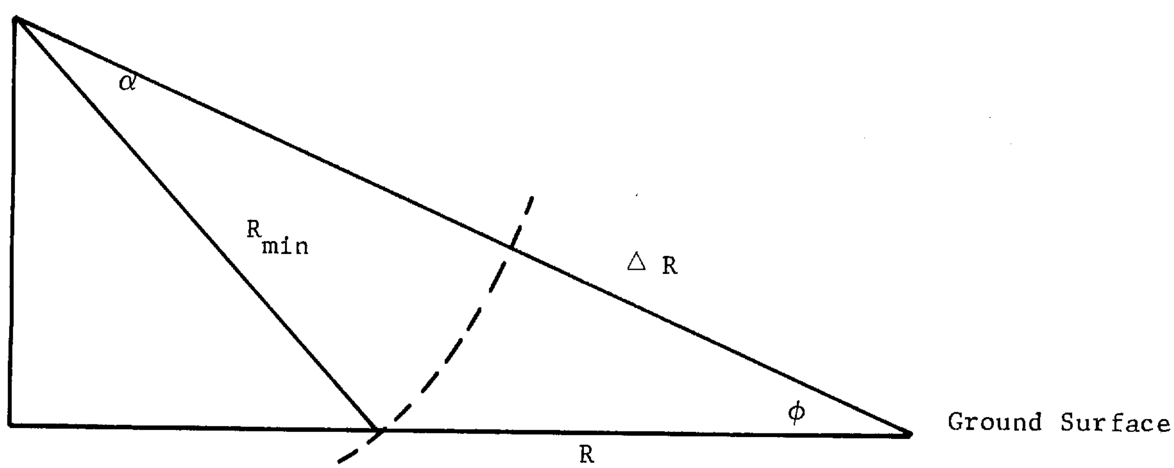

Fig. 6-5 — Calculation of R.

but these two parameters are related in a more complex manner. When the area is fixed and the antenna is lengthened, the height must be reduced proportionally. This reduced height will permit the illumination of a greater range interval on the ground. On the other hand, longitudinal resolution can be no smaller than one half the physical length of the antenna. Increasing the range coverage of an ambiguity limited synthetic aperture radar can be accomplished only at the cost of longitudinal resolution. Likewise, improved longitudinal resolution can be obtained only at the cost of range coverage.

The above brief description of the ambiguity problems in synthetic aperture radar is only intended to point out the physical reasons for these effects. There has been no intent to show the system degradation if ambiguities are permitted to appear in the results. This subject area has been of great interest and extensive use has been made of the ambiguity theory developed by Woodward, Siebert, and others. Much of this material has been published and appropriate references to these works are shown below.

1. Woodward, P. M., Probability and Information Theory, McGraw-Hill, New York, 1953.

2. Siebert, W. Mc., A Radar Detection Philosophy, Institute of Radio Engineers, Transaction of the Profectional Group of Information Theory, Vol. IT-2, September, 1956.

6.1.3 The Radar Equation for Synthetic Aperture Radar

The radar equation for a synthetic aperture radar is somewhat altered from its conventional form. This modified form is derived quite easily, and the derivation is shown in this section. The conventional radar equation will be developed first. When a peak transmitted power P_p is radiated toward a target at range R through an antenna of area A, the power density at the target is

$$\rho = \frac{P_p A}{R^2 \lambda^2},$$

where λ is the radar wavelength. A target of cross-section σ will in turn reflect a portion of this power toward the receiving antenna. The power density at the receiving antenna is:

$$\rho_r = \frac{\rho\ \sigma}{4\pi R^2},$$

and finally, the total power intercepted by the receiving antenna is the product of the antenna area and this power density. Generally, the receiver and transmitter will use the same antenna, so that the signal power is expressed as

$$S = \frac{P_p\ A^2\ \sigma}{4\pi\ R^4 \lambda^2}.$$

The parameter of interest here is usually concerned with the strength of the received signal when compared to the locally generated noise. Since the noise power generated in the receiver is represented by the product k T B where

k = Boltzman's constant,
T = Effective receiver temperature,
B = Receiver bandwidth,

the ratio of peak received signal power to average noise power is

$$\frac{S}{N} = \frac{p_p\ A^2\ \sigma}{4\pi\ R^4\ \lambda^2\ k\ T\ B} \tag{6.13}$$

At this point in the development no new ideas have been presented. Now, several ideas from synthetic aperture radar theory shall be incorporated that will significantly modify the appearance of the radar equation. First, it is important to recognize that the nature of the data processing amounts to a phase rotation of the received signal followed by an integration. Therefore, in computing the signal-to-noise ratio, the power received from a given target after signal processing must be an integration of Eq. (6.13) over a specified period of time. Since a synthetic aperture radar is a pulsed radar, the integration can be replaced by a summation over the required number of pulses. The signal is coherent, and the phase of each return is corrected so that the signal elements all add in phase. Thus, the time integration of signal over $\underline{n}$ pulses would result in a signal that is a factor $\underline{n}^2$ greater than the signal power received on a single pulse. However, noise power will also increase after integrating n samples. Noise, being a random signal, will only increase by a factor n in power. Therefore, a net gain of a factor of n will be obtained from the data processing, and the signal-to-noise ratio after processing will be

$$\frac{S}{N}\, p = \frac{P_p\, A^2\, \sigma\, n}{4\pi\, R^4\, \lambda^2\, k\, T\, B} .$$

The problem now is to determine what the number n must be. Certainly n can be expressed as the product of integration time and system PRF. Another modification at this point is to replace the bandwidth term by the reciprocal of the pulse length τ. With these two changes, the radar equation can be written as

$$\frac{S}{N}\, p = \frac{P_p\, \mathrm{PRF}\, \tau\, A^2 \sigma\, t_i}{4\pi\, R^4\, \lambda^2\, k\, T} = \frac{P_a\, A^2\, \sigma\, t_i}{4\pi\, R^4\, \lambda^2\, k\, T} ,$$

where t_i is the integration time, and P_a is the average transmitter power.

The value of t_i is found by considering the synthetic aperture. A given resolution δ from a target at range R indicates an angular resolution from the synthetic aperture of

$$\beta_L = \frac{\delta}{R} .$$

The -4 db beamwidth of the synthetic aperture is the ratio of the radar wavelength to twice the length of the synthetic aperture, or

$$\beta_L = \frac{\lambda}{2L} .$$

Therefore,

$$L = \frac{R\, \lambda}{2\, \delta} .$$

Further, the time required to fly a distance L (the integration time) is the ratio of L to the airplane velocity. This time is

$$t_i = \frac{R\, \lambda}{2\, V\, \delta} .$$

The radar equation now reduces to

$$\frac{S}{N}\,p = \frac{P_a\,A^2\,\sigma}{8\pi\,R^3\,\lambda\,V\,\delta\,k\,T} \tag{6.14}$$

One final consideration deals with the parameter σ. A terrain mapping radar is a sensor that detects far more than widely scattered targets as is the case in an air search radar. Specification of a target cross-section does not want to be concerned with the nature of specific targets such as trucks, tanks, buildings, and so forth. The matter of importance is that of being able to generate a background signal against which targets can be observed. Another important facet here is to be able to detect the absence of this background or the presence of a specular reflector. An example is the problem of detecting a road or an airplane runway. Hard surfaced roads and runways are nearly specular reflectors. To observe this type of installation, it is necessary to be able to detect with good clarity the grass that surrounds the specular reflector so that these interesting target complexes will appear as the absence of background. Therefore, our problem in specifying a target cross-section is not that of requiring sensitivity to detect a certain sized target such as a vehicle but rather to detect with a reasonable signal-to-noise ratio the backscattering from grass or similar ground cover at the maximum radar range.

Experimental analysis of this problem has been conducted in the United States (see R. L. Cosgriff, W. M. Peak, and R. C. Taylor, "Terrain Scattering Properties for Sensor System Design" (Terrain Handbook II) Engineering Experiment Station Bulletin, Ohio State University, Columbus, Ohio). Results of this analysis has shown that backscattering from ground cover can be expressed as a fraction of the resolution area projected onto the line of sight to the radar. In other words, σ can be written

$$\sigma = \gamma\,\delta^2\,\tan\,\phi\,, \tag{6.15}$$

where γ is a number less than unity, and ϕ is the grazing angle. It has been found that γ for short cut grass is approximately 0.02. In practical cases for the computation of performance at maximum radar range, the angle ϕ is merely the minimum depression angle of the radar. As a final step, the substitution of Eq. (6.15) into Eq. (6.14) yields:

$$\frac{S}{N} p = \frac{P_a A^2 \gamma \delta \tan \phi}{8\pi R^3 \lambda v k T} . \tag{6.16}$$

The radar equation for synthetic aperture radar points out several of the remarkable characteristics of this type of radar. Probably the most notable change is the range cubed characteristic of the radar. In conventional radars, the signal-to-noise ratio varies inversely as the fourth power of range where in the synthetic aperture system the signal-to-noise ratio varies inversely as the cube of the range. Therefore, there is a great savings in required transmitter power to obtain a given level of performance.

Parameters that do not appear directly in the usual radar equation are the resolution δ and the velocity of the vehicle $\underline{v}$. Here observe that the performance varies inversely as the speed of the vehicle and directly as the resolution. Therefore, fine resolution performance from a radar in a high-speed vehicle will require more transmitter power to obtain a given signal-to-noise ratio than would be required to deliver the same level of performance in a slower vehicle. This effect can be considered as being more than offset by the ambiguity limitation. Recall that the minimum antenna area is proportional to velocity. Therefore, in a strictly ambiguity limited situation the value of antenna area dictated by Eq. (6.12) could be substituted into Eq. (6.16) to indicate the signal-to-noise performance that includes the ambiguity consideration. This substitution might be well justified if all radars were to be ambiguity limited. In general, however, a radar limited in performance by ambiguity considerations is rarely found. Separation of Eqs. (6.12) and (6.16) is important in most cases.

6.1.4 Recorder Design Considerations

Data Storage Techniques — There are available a number of recording techniques which include magnetic tape, CRT writing on film, and direct electron beam writing on film, thermoplastic and electrostatic recording materials. Only electron beam recorders (including indirect CRT recording) have successfully recorded and read out information over tens of megacycles bandwidth with good reproduction quality.

The direct electron beam recording technique which has received the most attention in recent years is electron beam recording on thermoplastic material. Electron beam recording on other materials in which local changes in the index of refraction, polarization, thickness, etc., are induced have been studied to only a limited degree. Electron beam techniques also have been tested in which an electrostatic charge pattern is written on a material such as selenium, after which readout processing similar to that used in xerography can be used. None of these approaches of direct electron beam recording, however, has progressed to the point where they can be proposed with confidence for system application in a short time period. Electro-optical recording techniques employing cathode-ray tubes, on the other hand, have been tested and proven successful. Other methods of recording may hold more promise for the future, but are not considered competitive at the present time.

<u>CRT Recording on Photographic Film</u> — A cathode ray tube-film recorder consists of a high resolution CRT with its associated electronics, film spools and a film drive with its electromechanical drive control. Inputs consist of timing signals from the synchronizer, receiver coherent video, an aircraft along track velocity signal and various control signals. Two different optical configurations can be employed to transfer the CRT trace to a photographic film. One uses an optical lens system with a conventional CRT face plate, while the other eliminates the lens system by placing the photographic film in direct contact with a set of fiber-optics which is imbedded in the face of the CRT. The principle advantage in using fiber optics is that a greater percentage of the light generated by the phosphor actually reaches the film. This produces increased exposure, allowing slower film to be used to improve the resolution. A sketch of a recorder is illustrated in Fig. 6-6.

<u>Recorder Parameters</u> — The recorder parameters are determined from the aircraft along track velocity $\underline{v}$, the required resolution δ and the transfer characteristic of the CRT - film combination chosen. This transfer characteristic relates the input signal to the actual resolution on the film measured in terms of special frequency for a given contrast level.

For a specified minimum contrast ratio, let the highest spacial frequency that can be resolved f. Then the resolution in range on the film, in the

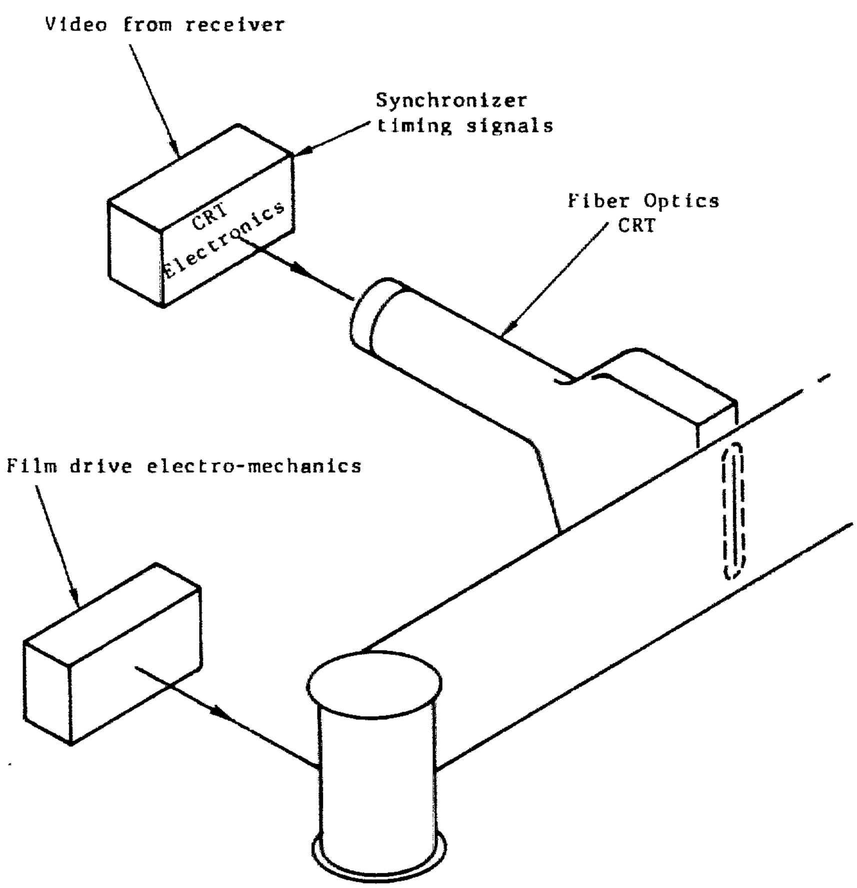

Fig. 6-6 — Recorder configuration.

width dimension of the film, is Δ_r = d/f if one resolved line pair is allowed for each pulse length. The total range interval recorded on one film is then R = Wf δ_r, where

ΔP = total recorded range interval,

W = usable width of the film,

and δ_r = actual range resolution (corresponding to one pulse length).

To avoid signal ambiguities, the portion of the signal doppler history which is used for processing usually goes from zero doppler to some maximum doppler frequency f_d where

$$f_d = \frac{2vL}{\lambda R}$$

Defining δ_a to be the -4 db azimuth resolution, then

$$f_d = \frac{v}{\delta_a}$$

since

$$\delta_a = \frac{\lambda R}{2L}$$

If an offset f_a from zero doppler is used then the maximum doppler frequency that must be recorded would be $f_d + f_a$.

The speed of the film in the recorder v' is expressed in terms of the maximum doppler frequency f_d and the maximum resolvable spacial frequency $\underline{f}$.

$$v' = \frac{f_d}{f} = \frac{v}{f\ \delta_a} .$$

The length ℓ of the signal history which is to be processed is then related to the synthetic array length L by the scale factor v'/v:

$$\ell = \frac{v'\ L}{v} = \frac{L}{f\ \delta_a} = \frac{\lambda\ R}{2f\ \delta_a^2} .$$

6.1.5 Optical Data Processor

In one mechanization of fine resolution radar using the synthetic antenna technique, a coherent optical data processor is the key component. This processor accepts as its input a signal history film which is the initial output of the radar system and operates upon it to expose a second film which becomes the fine resolution radar map. The signal film format is one in which signals from increasing range occur across the width of a film while successive returns from a given target occur along the length of the signal film. The signals are recorded upon this film range-trace-by-range-trace, side-by-side, to build up the signal history film.

The format of the output film is similar in that targets at increasing range are also located along the width of the film. However, as a result of the processing, successive points at a given range are radar images of successive points at that range along the radar flight path.

It is the function of the optical processor to operate upon the signal history film in such a manner as to, in effect, generate a long synthetic antenna. The result of this operation is a resolution whose fineness is that corresponding to the length of synthetic antenna generated.

To understand the operation of the optical processor, a brief discussion of the nature of the signal history recorded as the aircraft carrying the radar flies past a given target is in order. This signal history resembles a linearly frequency-modulated signal. In fact, this signal consists of a sequence of samples of the Doppler frequency generated by flying past the target under consideration. Upon first entering the beam, the Doppler frequency shift has its highest value. This Doppler frequency shift decreases to zero as the radar reaches the broadside position, and the Doppler shift becomes negative as the aircraft continues to fly past the target.

If the signal is recorded in this manner, one cannot distinguish positive from negative Doppler shifts. Hence, it is usual to generate an offset frequency sufficiently high that the Doppler shift plus the carrier frequency do not pass through zero while the target is in the radar beam. In this manner, a linearly frequency-modulated signal which does not pass through zero is generated and recorded from each target in a radar beam. The signals recorded in this manner from a single target resemble a slice taken from a zone plate. A zone plate has the characteristic of behaving like a lens with a multiplicity of focal lengths, i.e., it has self-focusing properties. This property is made use of in the design of the optical processing equipment.

Let us assume that a radar target, instead of being illuminated and re-radiating the signal, were a coherent transmitter. Then the signals incident at any instant of time upon the synthetic antenna would be very similar to the signals recorded in the radar pulse-by-pulse as the radar flies by a target. Hence, one may consider the recorded signals from a given target in question.

At first glance, it might seem that information needed to image a target is lost in this process. Actually, such is not the case. From a knowledge of the geometry of the radar configuration (range measurement and scale factor change) a location can be ascertained for a small source of light which can be used to illuminate this signal history such that the signals emerging from the signal history thus illuminated duplicate both in amplitude and in curvature the amplitudes and curvatures of the microwave signals. If one takes into account the change in scale factor and the change in wavelength in going from radar frequencies to optical frequencies, it is evident that one can place an optical system beyond the illuminated signal history so as to create an image of the radar target.

In essence, the optical processor behaves as indicated above. However, several additional problems have to be considered.

The discussion above has concerned itself with creating the limits of a single point at a single range from operations on the target signal history. The actual signal history consists of signals from different ranges, and these create wavefronts with different radii of curvature at the signal history film. Consequently, the optical system must cause a wavefront to be incident upon the target signal history whose curvature as a function of range appropriately duplicates in analog fashion the geometry of the radar world.

There are several ways to create this curvature. One technique uses a conical lens between a narrow slit and the signal history film.

In addition to having targets at different ranges, the target histories at a given range will be overlapping from targets at the same range but different azimuths. In such cases, a detailed examination of the behavior of the system will show that for a given segment of signal history the target histories from the target at one azimuth will be appropriately illuminated and will cause that spot to image whereas signals from targets at the same range but different azimuths will converge to points at a different azimuth. Hence, the self-focusing properties of the target histories serve to separate targets at the same range but with different azimuths.

Thus far, the problem of keeping the range elements separate has not been discussed. It has been stated that the signals from a given target are found on a line along the signal history film. In order to keep these separate lines (range intervals) separate, the optical system following the signal history consists of a combination of spherical and cylindrical lenses. The combined power of the cylindrical and spherical lenses is such as to cause imaging in one direction in the output plane, thereby keeping the range elements separate. Thus the optical system required to operate upon the target signal histories consists essentially of the following sequence of elements.

1. a narrow slit in combination with a conical lens to illuminate the target history film with a coherent wavefront having the appropriate curvature as a function of range;
2. the signal history film together with a transport to move this film across an aperture in the optical system;
3. a combination of spherical and cylindrical optics to image the target signal histories and to keep the range elements separate;
4. an output slit and camera for recording the fine resolution radar map.

The description of operation given above has considered the optical system as an analog to the radar world. Alternatively, the signal processing can be considered as one in which synthetic antennas are generated. In this case, the sequel of signals on this target history film from a given target can be considered as being the signals which the elements of a linear array at that point would receive. These signals have a phase shift associated with them which points out the fact that different points along the synthetic array are at different ranges from the radar target. If a focused radar system were built, the phases of these signals would have to be readjusted before vector addition. It is the function of the conical lens to make the appropriate phase correction to the signals before the addition. Then the signals from each point on the synthetic array will then be added cophase.

The function of the spherical and cylindrical optics can be viewed as performing a line-by-line (constant range) integration of the signals from the synthetic array positions.

Either point of view results in the same optical configuration. A schematic diagram of an optical processor appropriate for generating synthetic antennas is shown in Fig. 6-7. Examples of the appearance of signal history are given in Figs. 6-8 and 6-9.

The synthetic antenna technique was conceived prior to 1953. The earliest flight test results using the optical processor were conducted in 1957. Since that time, a number of successful systems employing these principles have been built and demonstrated.

6.1.6 Summary

The discussions have shown that the resolution capabilities of conventional focused and unfocused antenna systems differ markedly in their characteristics. The fineness of resolution, other parameters being fixed, varies directly as λ for the conventional case, as the square root of λ for the unfocused case, and is independent of λ for the focused case. Dependence of the fineness of resolution on antenna size has been shown to improve for larger apertures in the conventional case, to be independent of aperture in the unfocused case, and to improve with smaller apertures for the focused case. Dependence of the fineness of resolution on range has been shown to deteriorate directly as range in the conventional case, as the square root of range in the unfocused case, and to be independent of range in the focused case. Evidently, as the requirement for finer longitudinal resolution increases, one may be led to consider in turn the conventional, the unfocused and the focused case, in that order.

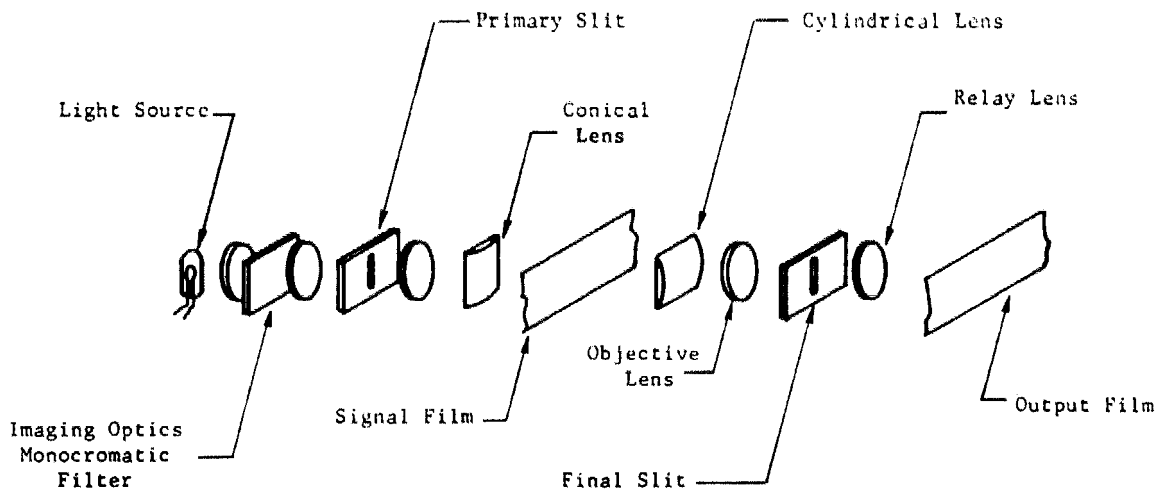

Fig. 6-7 — Schematic diagram of a synthetic aperture radar, optical signal processor.

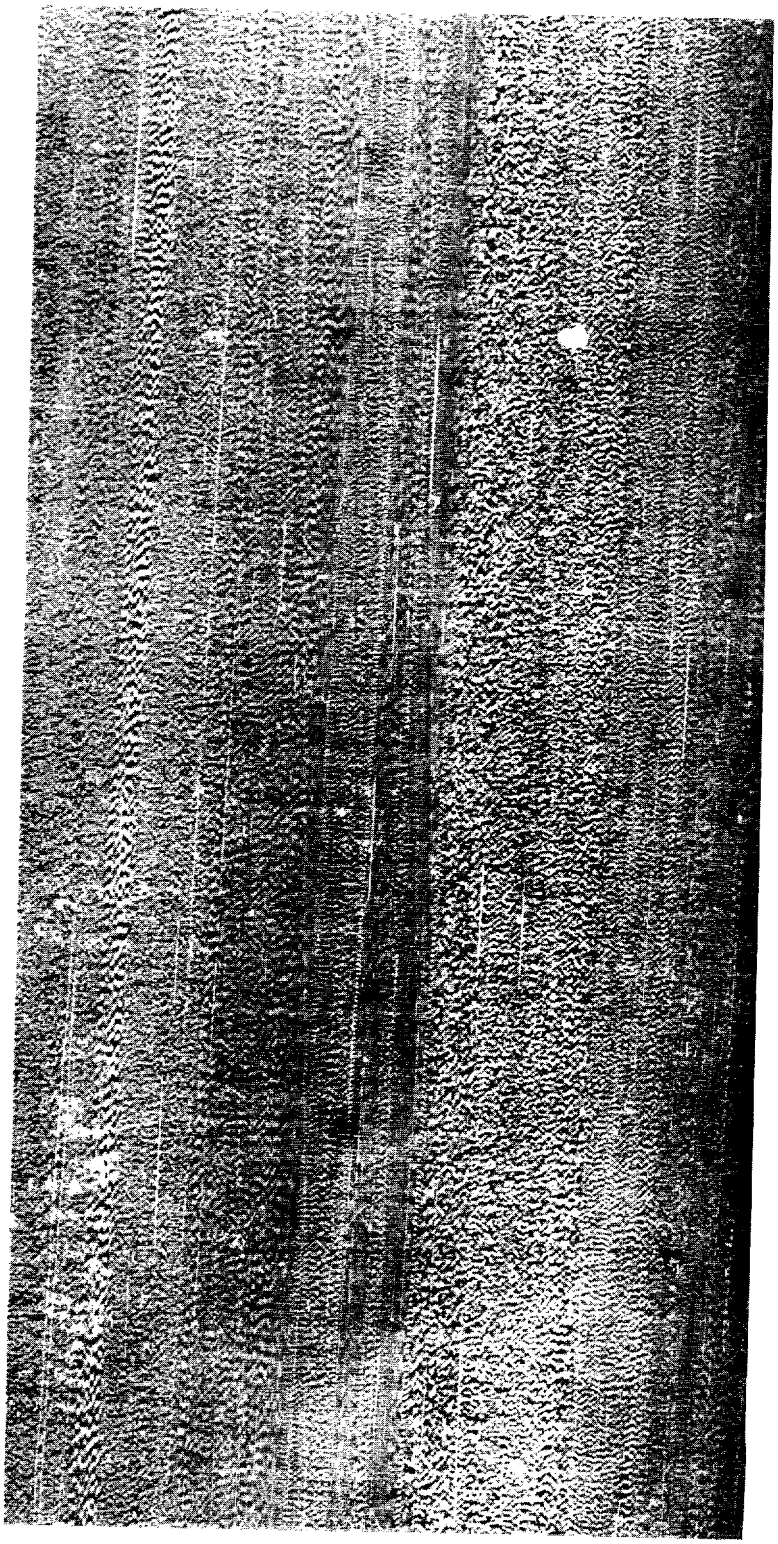

Fig. 6-8 — Appearance of signal history.

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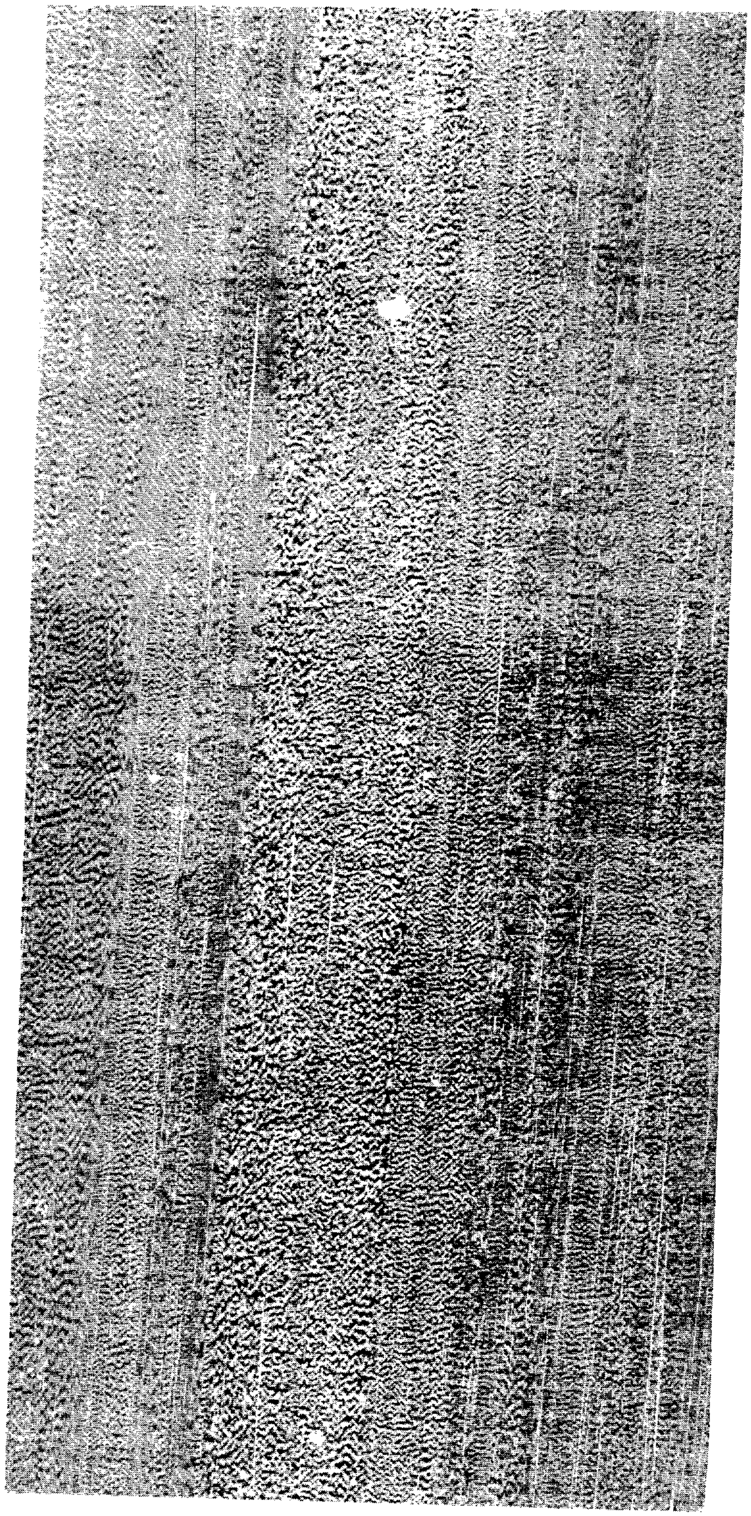

Fig. 6-9 — Appearance of signal history.

Data processing used to obtain the improved performance of a focused system is a linear operation performed on a phase history that can be predicted for each target in the antenna beam. This phase history or frequency history must be recorded and operated on by the data processing. Unambiguous recording of this signal can be obtained only if the system PRF is greater than twice the bandwidth of the spectrum of the return from a typical target. This consideration sets a lower bound for the radar pulse repetition frequency. A contrasting upper bound is set by the range interval desired to be interrogated by the radar. Ambiguity limitation becomes a problem when the lower limit of PRF is equal to, or greater than, the prescribed upper limit of PRF. In such a case, the system is said to be ambiguity limited and from ambiguity considerations a minimum effective antenna area for the radar antenna is specified. The restricted minimum antenna area is a cost that must be borne if the advantages of a fully focused synthetic aperture radar are to be obtained.

When the focused synthetic array radar is used, a marked improvement is found in signal-to-noise performance over conventional radar. The most striking improvement in this case is that the signal-to-noise ratio varies inversely as the third power of range in a focused synthetic aperture system, while the signal-to-noise ratio varies inversely as the fourth power of range in a conventional radar. This performance is obtained because the synthetic aperture system essentially constructs an antenna for each range the radar is observing. The length of this antenna is proportional to the range of the target. In effect, the area of the transmitting antenna is fixed and the area of the receiving antenna is proportional to the range of the target. The improved gain of this synthetic receiving antenna yields an overall result in the signal-to-noise expression that the signal-to-noise power ratio varies inversely as the cube of range rather than the conventional fourth power of range.

A system like a synthetic aperture radar is capable of collecting a fantastic amount of data in a very short period of time. The problem of recording the data for later data processing is a severe one. The most practical technique available today is that of cathode-ray tube recording on photographic film. Approximately 1000 independent events per linear inch of cathode-ray tube face can be recorded with such a system. The consideration of resolution, recording density capability, range interval, and usable width of film dictates the amount of film that must be used in recording synthetic aperture radar data.

Optical data processing essentially transforms an unfocused image captured in a radar space into a focused image in the optical data system. This technique of data processing has been utilized with synthetic aperture radars since the earliest days of focused radar systems. The technique has proven quite successful, and with optical data processing, it is possible to perform a task that would require a tremendous amount of analog electronic equipment with a relatively simple desk-top size data processing unit.

Several figures are attached to indicate the type of performance that can be obtained from a focused, synthetic aperture radar. Figs. 6-8 and 6-9 are photographs of unprocessed raw data film as recorded directly from a cathode-ray tube-type recorder. A careful examination of these films will show in many places the linearly frequency modulated target patterns which we discussed earlier. The range direction on these pictures is in both cases across the short dimension of the photograph. Observe that the linearly frequency modulated target returns run normal to the range dimension and the essential data processing that takes place in these systems is an operation in the longitudinal direction. Figs. 6-10, 6-11 and 6-12, are various photographs made with synthetic aperture radar. Examination of these pictures will indicate the order of fine detail that can be obtained with the focused synthetic aperture radar system.

6.2 MOVING TARGET INDICATION (MTI)

Moving target indication radar covers many phases, including the detection and recognition of moving targets and the determination of coordinates, velocity, and direction. The presence of moving objects is an important clue in the recognition of target complexes and in determining fluid military situations. It is therefore desirable to have real-time airborne processing for MTI so that it can serve as an alerting function, and can aid in selecting sensors for limited spot coverage. An "ideal" MTI processor, for use with a high resolution map display, would super-impose upon the display arrows indicating the magnitude and direction of the target velocity vector at the correct position. A MTI processor design should come as close to this ideal as possible with the input data available.

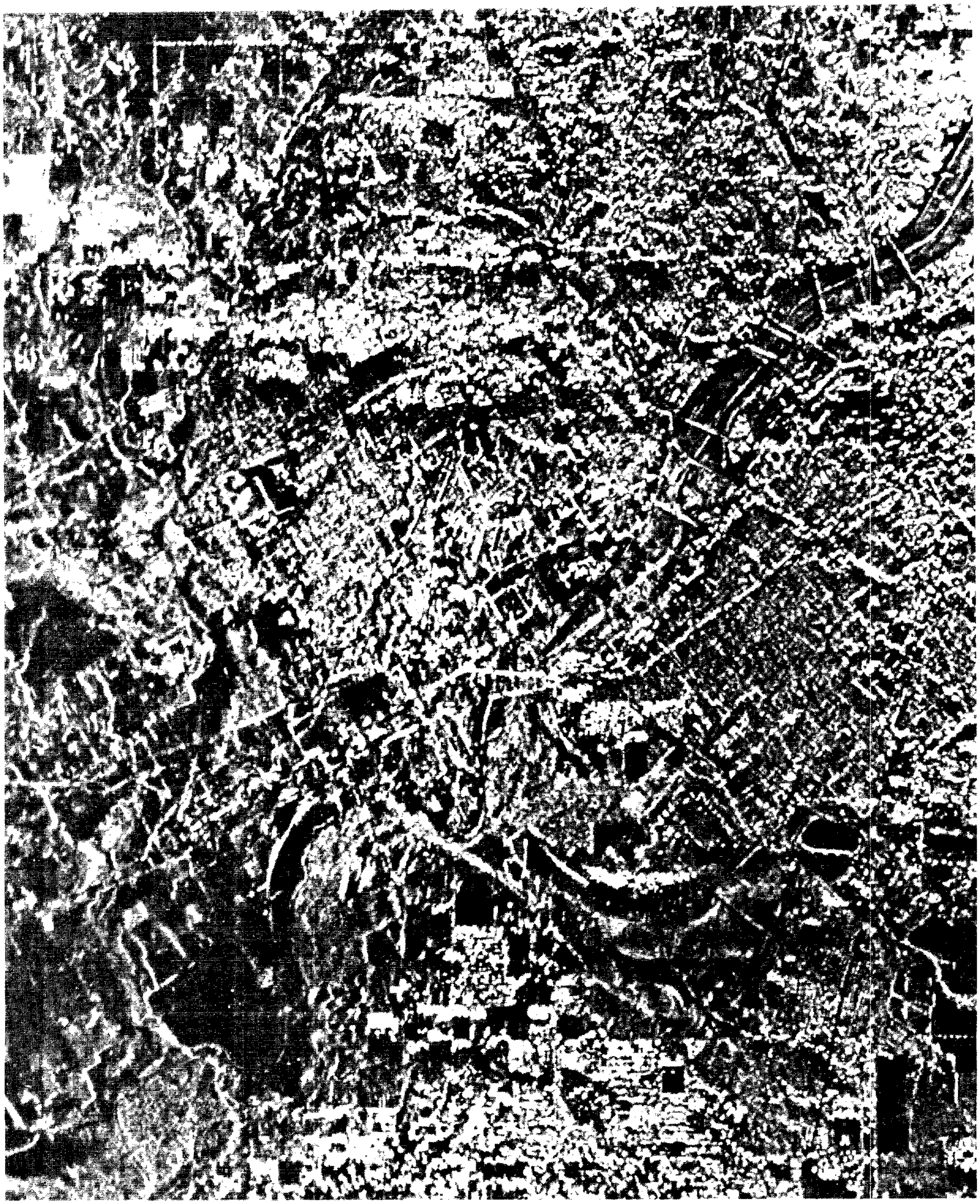

Fig. 6-10 -- Photograph made using synthetic aperture radar.

Fig. 6-11 — Photograph made using synthetic aperture radar.

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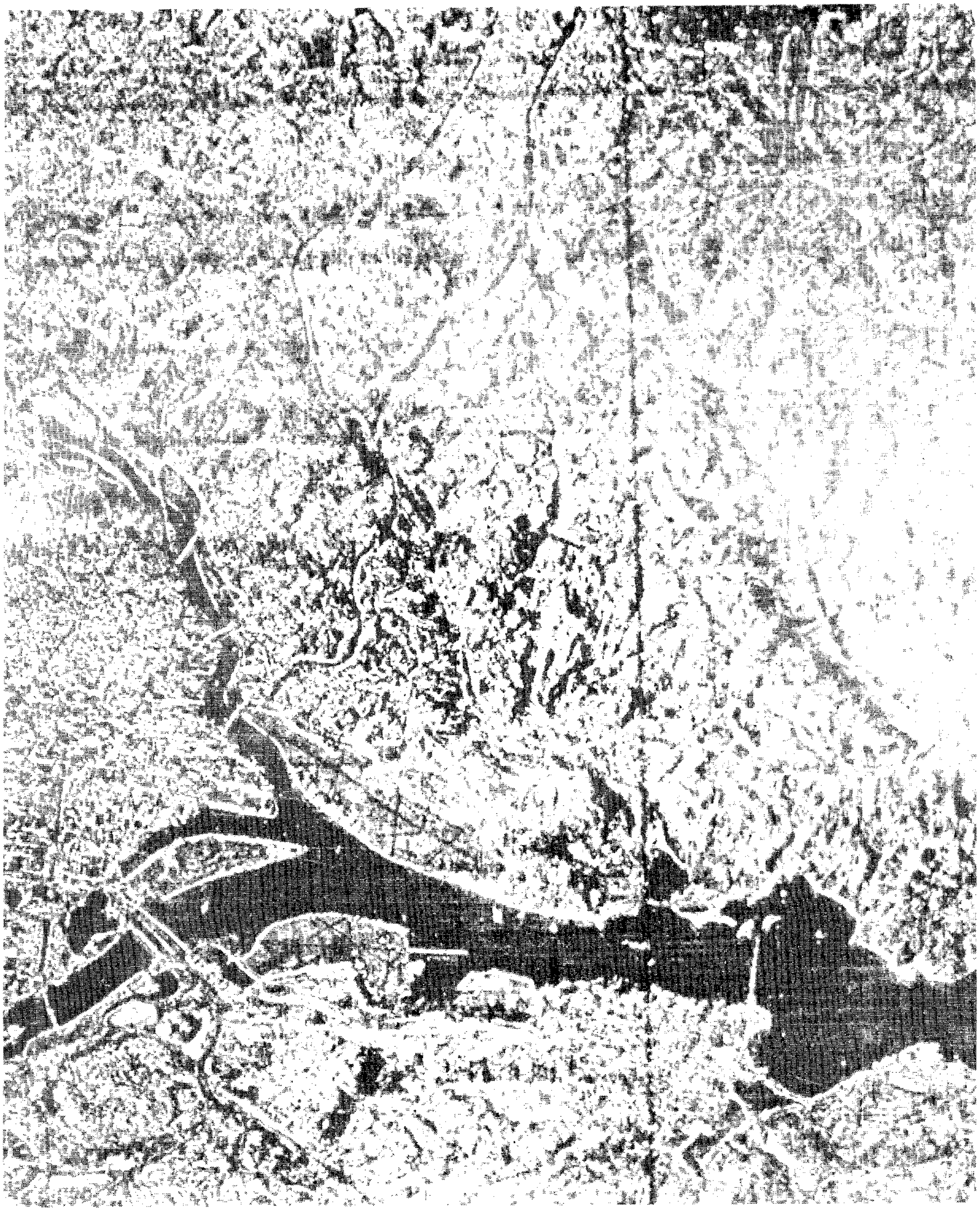

Fig. 6-12 — Photograph made using synthetic aperture radar.

There is a conflict in the optimization of radar parameters for the detection and resolution of both fixed and moving targets. MTI considerations alone would dictate a forward looking radar to minimize doppler spread of the ground return and thus would maximize the number of targets in the clear region. On the other hand, to minimize the integration time required for a given resolution for fixed targets, a side looking radar would be used. However, by making use of the displaced phase center technique, it is possible to adequately cancel the clutter even for a side looking radar, and still detect moving targets with velocities much smaller than the maximum velocity spread over the real beam. This MTI technique is compatible with the simultaneous generation of a high resolution map, and this high resolution feature greatly reduces the area of ground clutter with which the moving target competes. It is expected that this type of MTI will have been thoroughly proven out by the post 1967.

The techniques used for a MTI processor are practically identical to those used for the airborne processor for the high resolution radar map. In fact, it is entirely feasible to design a processor which is compatible with both of these functions. This electronic processor would be used as a relatively gross resolution airborne monitor of the radar mapping performance. However, it may prove desirable to have an electronic processor for the MTI function alone. For the alerting function, MTI signals can be generated with azimuth and range position data so that the area of interest can be mapped (by the radar and other sensors) with fine resolution.

For example, the parameters for an alerting MTI radar system can be:

squint angle	= 45 degrees
range resolution	= 100 feet
azimuth resolution of clutter path	= 100 feet
range measurement accuracy	= 100 feet

The azimuth placement accuracy of a moving target depends upon the radial velocity uncertainty, which for vehicles averages around 30 feet per second, and for men, 3 feet per second. That is,

$$\triangle \theta = \frac{\triangle V \psi}{V \cos Y},$$

where

$\Delta\,\theta$ = angular uncertainty,

$\Delta\,V$ = velocity uncertainty,

V = velocity of aircraft and

ψ = squint angle.

For

$\Delta\,\psi$ = 30 feet per seconds and ψ = 45 degrees,

$\Delta\,\theta$ = 0.014 radians for V = 3000 feet per seconds, and

$\Delta\,\theta$ = 0.035 radians for V = 1200 feet per seconds

The maximum angular uncertainty, however, will never be larger than the beamwidth of the physical antenna and, by complex data, processing can be held to a tenth of this beamwidth even for large velocity uncertainties. The azimuth distance placement error derived from the above equations is plotted versus range in Fig. 6-13.

The alerting time, defined, as the time between MTI detection and the crossing of the target in the broadside direction is given by

$$T_a = \frac{R \cos \psi}{V} .$$

For

zero = 10 nautical miles, ψ = 45 degrees

zero = 3000 feet per seconds, T_a = 143 seconds.

The limit on clutter cancellation ratio for the displaced phase center technique is set by equipment limitations and, based upon the performance of present cancellation techniques, is estimated to be approximately -30 db. This is shown for illustrative parameters in Fig. 6-14. Note that if there is considerable ted for illustrative parameters in Fig. 6-14. Note that if there is considerable internal motion of the ground clutter (for example, wind blown foliage), the clutter cancellation ratio is considerably worse than -30 db. What these numbers mean in terms of actual detection of moving targets is illustrated in Table 6-1. Obtaining fine resolution can be, by itself, an efficient clutter

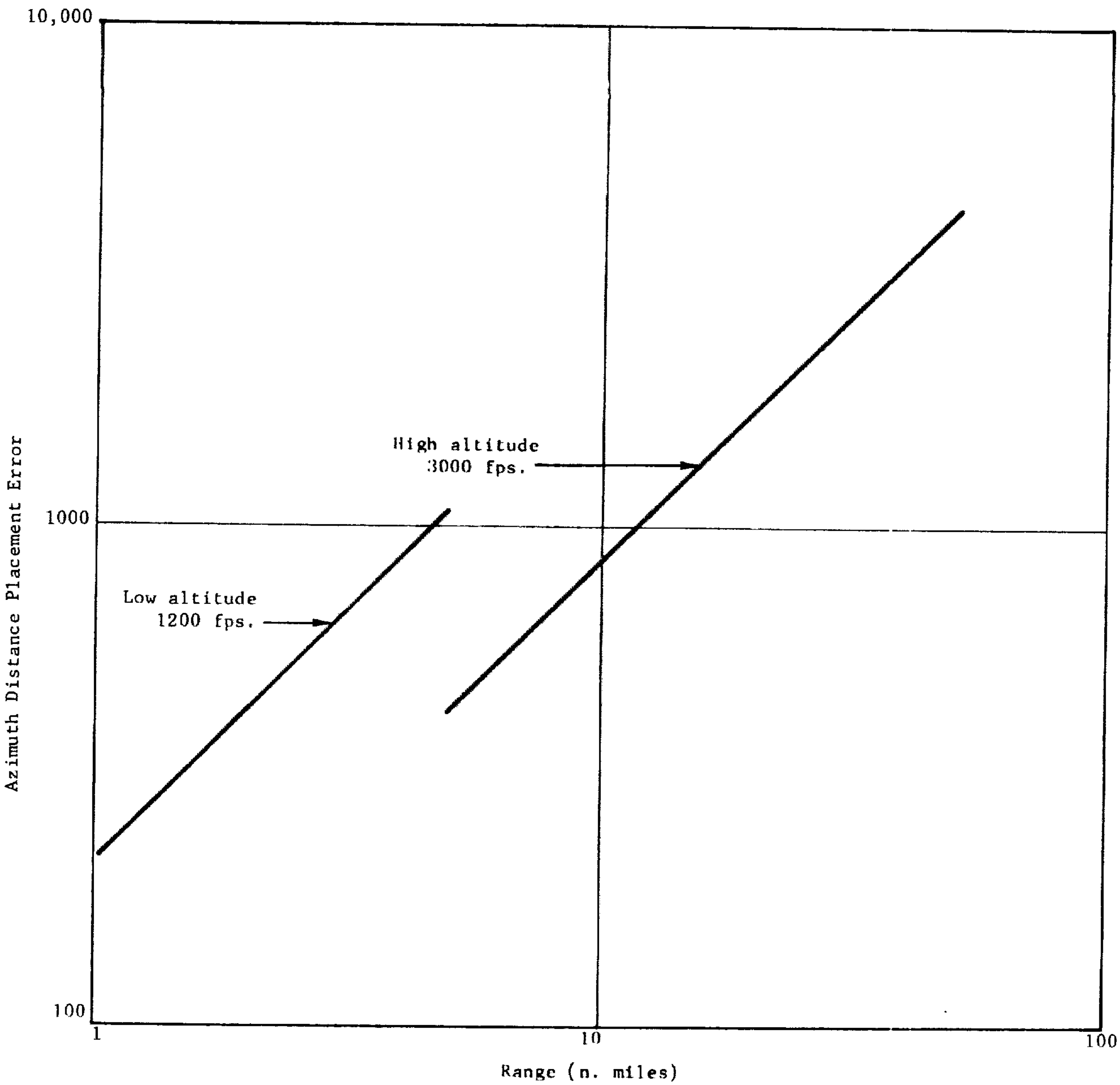

Fig. 6-13 — Azimuth distance placement error vs range (MTI operation velocity uncertainty = ±30 fps).

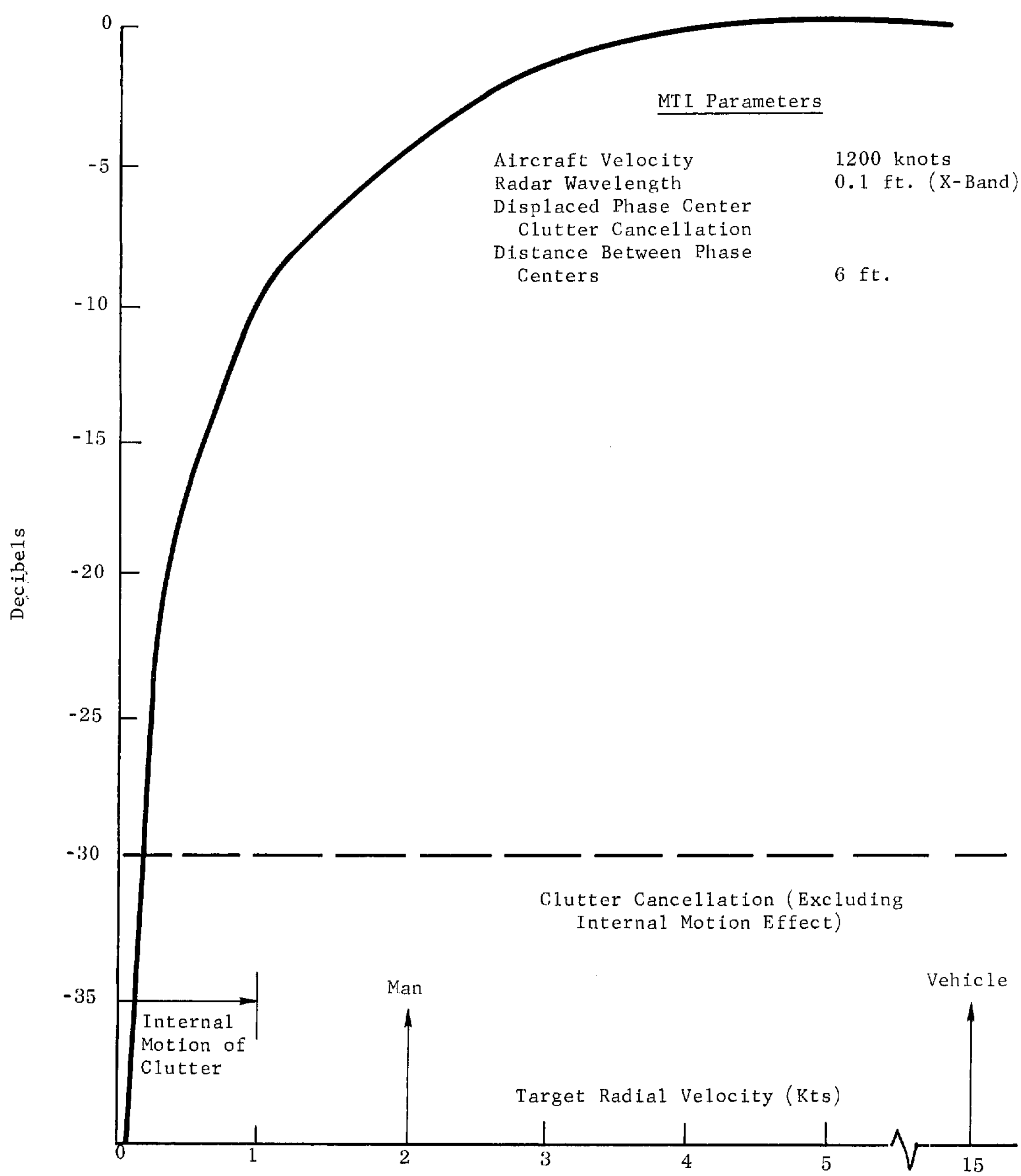

Fig. 6-14 — Signal cancellation for slow moving targets.

Table 6-1. Target Radar Cross-Sections

	Actual Radar Cross-Section (sq. ft.)	Typical Radial Velocity Due To Own Motion	Effective Cross-Section After Clutter Cancellation (sq. ft.)
Vehicle	10-1000	15 kts	10-1000
Man	1-10 (est.)	2 kts	0.35-3.5
Grass 100' x 100'	20[1]		0.02-2
25' x 25'	1.25[1]	0-1 kt[2]	0.001-0.12
Average 100' x 100'	100[1]		0.1-10
Terrain 25' x 25'	6.25[1]	0-1 kt[2]	0.006-0.62

MTI Parameters

Aircraft Velocity = 1200 kts
Radar Wavelength = 0.1 ft (X-Band)
Displaced Phase Center Clutter Cancellation
Distance Between Phase Centers = 6 ft
Maximum Cancellation (Equipment Limitations) = -30 db
Combination of MTI with High Resolution Discrimination

(1) 6 degree Grazing Angle: η = -17 db Grass
η = -10 db Average Terrain

(2) The 1 knot velocity is for internal motion due to movement induced by wind.

discrimination tool since the target of interest has only to compete with a very small area of ground. Typical vehicles have a cross-section which is greater than a 25 by 25-foot area of average terrain, and this ratio is increased an order of magnitude by MTI techniques even with one knot internal motion. Detection of moving men, on the other hand, is not possible under all conditions when there is internal motion of the ground clutter. Calculations indicate that, with displaced phase center MTI in conjunction with high resolution on the order of 10-20 feet, it should be possible to detect moving men from a tactical reconnaissance aircraft under many conditions. It is reasonable to expect the development and testing of techniques to do this by the post 1967.

6.3 CROSS-SECTION THRESHOLD INDICATOR

It is feasible to use a cross-section (power return) threshold indicator in conjunction with either the ground mapping or the moving target function of a fine resolution synthetic array radar. This indicator would serve as an alerting and location device. Since normal ground return exhibits a large fluctuation of power return, the false alarm rate would probably be large unless the information obtained by the device was coupled with other indicators such as correspondence to an IR output.

6.4 EXAMPLE PARAMETERS

It is, of course, not possible to choose specific system parameters for a radar for a tactical reconnaissance aircraft without first defining the system requirements fairly exactly. However, various tactical reconnaissance high resolution radar system designs have been considered at Conductron, and the list of parameters shown in Table 6-2 illustrate the principle feature of such a radar for post 1967.

Table 6-2. Examples of SLR Parameters

System Type	Fine Resolution Coherent SLR
Aircraft Velocity	Mach 3
Altitude(1) (ft.)	60,000
Maximum Range(1) (n. miles)	75
Range Interval Coverage(1) (n. miles)	15 one side 30 total
Design Resolution(2) (ft.)	15
Transmitter	
Radiation Frequency(3)	X-Band
Average Power (watts)	500
Peak Power (KW)	360
Pulse Expansion Ratio (variable)	47-140
Pulse Length (Actual)	1.4 μ
Pulse Length (Effective)	10-30 μ
Basic PRF (kc)	1
Antenna	
Physical Length (ft.)	6
Physical Height (ft.)	1
Receiver RF	33-100
Bandwidth (mc) Video	33-100
Noise Temperature °K	1000°K
System(4)	
Estimated Volume (cu. ft.)	15
Estimated Weight (lbs)	750
Estimated Power (watts)	4500

Table 6-2 (Continued)

(1) High altitude mode.

(2) Variable resolution, five feet, resolution for spot coverage to 50 miles.

(3) For general mapping, low frequency option for foliage penetration at short ranges.

(4) Including MTI and Pattern Recognition, but excluding displays and Data Transmission.

SPECIAL HANDLING

SPECIAL HANDLING

7. INFRARED

In reconnaissance, the use of optical scanning devices that operate in the infrared region of the spectrum has increased in recent years. Like photography, infrared thermography produces a permanent record, but of data that cannot be recorded by a camera working in the visible spectrum.

In effect, a camera observes the differences in light reflected from a scene, and records this information graphically in a coordinate system which is similar to that of the human eye. An infrared scanner, on the other hand, records differences in the emission of thermal energy or heat, and records this information in graphic form after it has been converted to visible light. The output of an infrared scanner is a thermograph, or heat map. As in photography, one is concerned with the ground resolution of an infrared system, and also in the temperature resolution, i.e., temperature differences.

Since the fundamental quantity being detected is differences in heat (emissivity), the detecting element must be capable of sensing small differences in temperature.

Since an infrared system, unlike a camera, is not dependent on reflected sunlight, it will work as well at night as during the day time. It also has better haze penetration than a camera, but it is not an all-weather device.

The interpretation of infrared thermographs employs many standard photo interpretation techniques, but new techniques are also required. For example, the sea presents large areas of uniform temperature and emissivity, and hence is usually an ideal background for detection of ships. Sharp thermal differences are common at river outlets, Gulf Stream boundaries, underwater thermal fronts, and where tidal currents flow over shallow banks. Ships' wakes are usually discernible because of their straight line character. Wakes of submarines operating at 150 to 300 foot depths have been detected by infrared systems, particularly when the submarine performs a maneuver. The intensity of the infrared radiation of ships is highly variable because of such factors as solar heating, wind velocity, air and water temperature differences, the mode of propulsion, and exhaust product disposal. (For example, in one test, a hot spot on the deck appeared on some infrared recordings but not on others. The commanding officer commented that it was the habit of the ship's baker to bake after the evening movie.)

One degree of temperature difference permits satisfactory reconnaissance of natural land scenes, even for such unusual missions as ice thickness studies and ice crevasse detection. Solar heating, air temperature and wind histories determine contrast. Contrast is frequently reversed at night because water, for example, does not cool as rapidly as land surfaces. A solid cloud cover overhead reduces contrast because it affects cooling and allows the ground to reflect the thermal radiation from relatively warm clouds rather than from the cold sky. Clouds between an infrared system and the ground block the radiation, and occasional incipient clouds or thermal turbulence will mar thermal maps.

Manmade objects seldom match the thermal characteristics of natural objects and hence are easily detected. Furthermore, human activity requires the expenditure of energy which usually dissipates into thermal energy. Tanks, cars and even men are detectable, but the detection of the latter usually requires prior knowledge. The cooking of food provides thermal sources which can sometimes be detected even under dense foliage because of holes in the foliage. Multiple coverage (overlap or repeat scans) can significantly increase the probability of detection by increasing the probability of "source-hole" alignment.

The trade-offs considered in designing infrared systems are somewhat analogous to those considered in designing a photographic system. The designer is concerned with resolution (both angular and temperature), angular coverage, and the V/h rate which, when combined with resolution and angular coverage, determines the system bandwidth or data rate.

In a photographic system, the resolution is fundamentally limited by the Rayleigh limit, i.e., the system is aperture limited. In a given set of circumstances, however, image blur may impose a more severe limit than aperture (or lens-film resolution).

In infrared system design, where a large aperture is also desired, limitations are not imposed by the Rayleigh limit but by a photon or energy limit.

7.1 SCENE CHARACTERISTICS

All objects, manmade or natural, emit energy if they are at any temperature above absolute zero. As the temperature increases, the amount of energy emitted increases but the wavelength of the radiation decreases. Hence, an object at $5000^{\circ}K$ emits radiation over a wide band of wavelengths, from the far infrared (around 80 microns) up to well beyond the visible spectrum. At this temperature, the radiation is highest at the red end of the visible spectrum. However, it radiates a great deal of energy in all wavelengths of the visible spectrum and thus would appear to be white hot. A cooler object of $1000^{\circ}K$ would have its peak radiation around 2 1/2 microns. However, it would emit enough radiation in the visible portion of the spectrum to appear to be red hot. In other words, it would be visible to the human eye. As the temperature of the emitter decreases, the peak wavelength shifts toward longer wavelengths. Hence, a room temperature object that is $293^{\circ}K$ or $20^{\circ}C$ peaks at about 10 microns, which is well beyond the visible spectrum. For reconnaissance use, many of the objects of interest are emitting most of the radiation at rather long wavelengths. A room temperature object is emitting a small but detectable amount of radiation in the 4-micron region, but as noted, it peaks in the 10-micron region. Hence, if one is interested in relatively cool objects, that is, objects which are a few degrees above the ambient temperature, it is desirable to use detectors which are sensitive to the 10-micron region of the spectrum.

The atmosphere imposes an additional constraint. The atmosphere is reasonably opaque to radiation in the 4 to 8-micron region of the spectrum. Fairly good atmospheric windows exist between 2 to 4 microns and between 8 to 14 microns.

Working in the infrared region of the spectrum imposes a problem in selecting window materials. For one thing the window itself will heat up if used in a high performance aircraft and appear as a heat source to the infrared system. For this reason, an opening in the bottom of the aircraft should serve as the "window".

7.2 DETECTION METHODS

The method of detecting thermal radiation is an important factor in infrared system design, and is discussed briefly here since it affects the optical system. Photographic films are not satisfactory since the radiation at room temperature would fog the film at the instant of manufacture, unless the film were manufactured at temperatures below one degree Kelvin, which, of course, is impractical. Detection devices which permit imaging a scene on a detector other than film have been evolved. These include the Baird Atomic evaporagraph and the Westinghouse thermicon (thermal vidicon). However, neither of these devices are capable of handling an adequate information rate with sufficient sensitivity to provide the tenth of a degree to one degree temperature resolution required for aerial reconnaissance. It seems unlikely that this sort of a detection method will be developed to an adequate degree to meet the reconnaissance requirements of the next generation of equipment.

The only feasible method of detecting thermal radiation is to scan the scene with single or multiple element detectors and reconstruct the scene in a manner similar to the early television technique of the Nipkow disc. Usually the detector and imaging optics are held stationary and a rotating flat mirror moves the line of sight of the instrument. In aerial reconnaissance, scanning in the second direction is accomplished by the aircraft motion, while in ground-based reconnaissance systems the rotating mirror is slowly tilted. The resultant electrical signal from the detector is used to modulate a light source which, in turn, is imaged on standard photographic film with a scanning system similar to the infrared optics.

Table 7-1 summarizes pertinent information on several detectors which have been used successfully in infrared systems. Ideally, all thermal radiation should be used for maximum sensitivity. However, as noted in the table, different detectors respond in different regions of the spectrum, and their information rate varies. Also, working in the longer wavelengths increases the cooling requirements of the detector, since the detector must be cooled below a point where its own noise affects performance. Presently, the germanium mercury detector appears to offer the best combination of characteristics for an infrared system.

Table 7-1. Thermal Detection Regions

Spectral Windows (Microns)	Detector Cooling Requirement (Degrees Kelvin)	Detector Material	Average Photon Rate for 300 K Photons / sec. cm^2 ster	Average Rate Difference Photons / sec. cm^2 ster degree	Theoretical S/N*
1.0 - 2.5	240	PbS	1.14×10^{12}	9.85×10^{10}	0.845
3.0 - 4.1	200	InAs	7.72×10^{14}	3.53×10^{13}	12.7
4.4 - 5.5	80	InSb	7.08×10^{15}	2.87×10^{14}	34.2
8.0 - 14.0	25	Ge:Hg	3.10×10^{17}	7.65×10^{15}	137.
16.0 - 25.0	4	Ge:Cu	3.35×10^{17}	2.87×10^{15}	49.7

*(1×10^6 samples per second, 1 milliradian square field of view, 1 degree Kelvin temperature difference and 100 cm^2 viewing aperture with a single detector.)

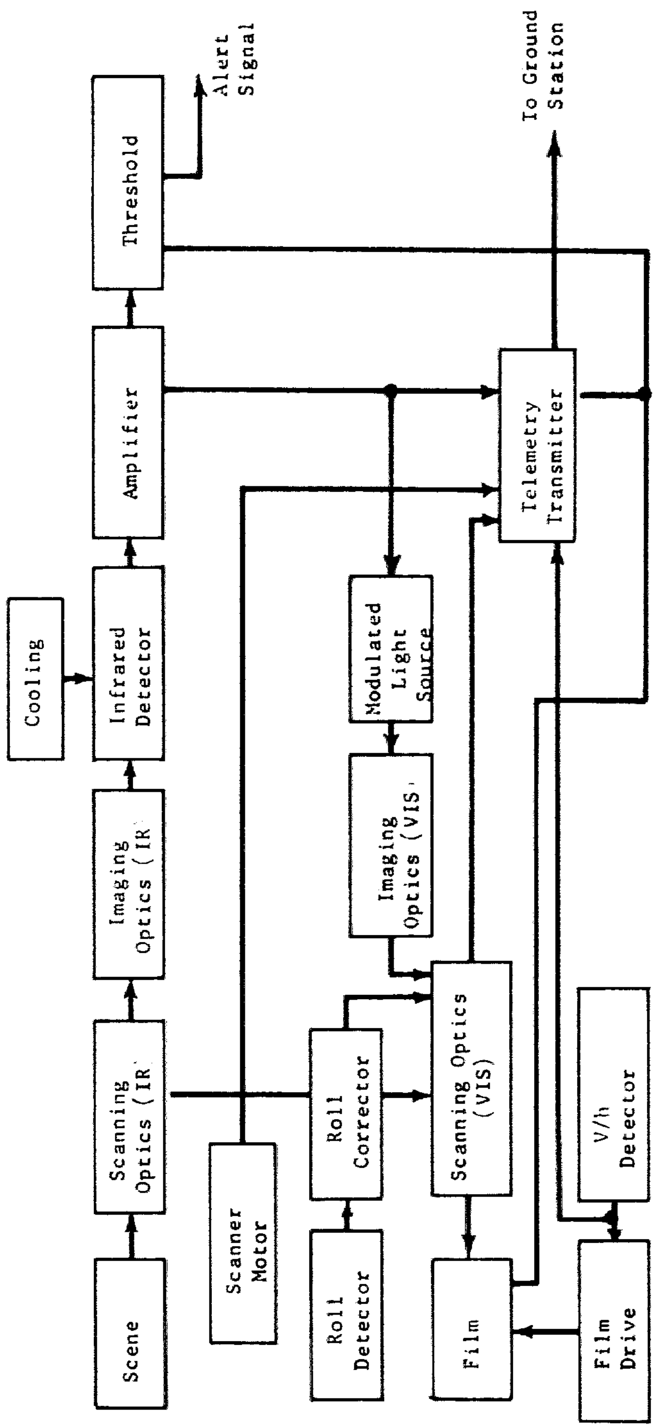

Fig. 7-1 — Functional elements for infrared system.

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It is sensitive in the 8 to 14-micron region of the spectrum, and its information rate is high. It has a short time constraint - something less than a microsecond - and the signal-to-noise ratio is excellent.

Within the next few years the performance of infrared detectors should be within a factor of three of the theoretical limits imposed by the random arrival of photons. (This condition is referred to as BLIP - Background Limited Infrared detection). The average photon rate for a $300^{\circ}K$ black body is given in Table 7-1 as well as the rate difference for one degree Kelvin temperature difference. The maximum theoretical signal-to-noise ratio is given for a typical reconnaissance requirement and system. The system is assumed to cover a field of view of one milliradian on a side, a million such viewing elements per second, a one degree temperature difference, a radiation collecting aperture of 100 square centimeters and a single detector.

System performance is usually measured in the number of elements viewed per second, system resolution (angular size of the field of view), and temperature difference required for a signal-to-noise ratio of one NETD (Noise Equivalent Temperature Difference).

7.3 FUNCTIONAL ELEMENTS

Fig. 7-1 shows the essential functional elements of the system. The scene is scanned and imaged on a cooled infrared detector. The electrical signal is amplified and converted to an equivalent intensity light signal which is imaged on to film via roll-compensated scanning optics. The film is moved forward at a speed proportional to V/h. Scanner position, roll compensation, V/h, as well as the electrical signal from the infrared detector, must be telemetered in order to reconstruct the image on the ground. By setting a threshold, intense infrared signals can be converted to an alerting signal for recording on film or activating other sensors.

The design of the scanning optics is determined by the angular coverage required and the V/h limits. As V/h increases, rotational speeds must be increased proportionally. Generally, flat optical surfaces are used because they can best be mounted without excessive image distortion. Prisms can also be used. However, the choice of material is limited, particularly when working in the 8 to 14-micron region.

In designing the imaging optics, reflective systems are generally used since they cover the wide spectral region without severe chromatic aberration. As indicated previously, the imaging requirements generally do not approach the diffraction limit or Rayleigh limit. The twenty-fold increases in wavelength over those utilized for photographic systems, make the optical tolerances less severe. Since the radiation collecting area requirements are large, the diffraction limit is more significant. In some designs the detector itself is placed in the image plane (where the resultant image size, a function of scale - focal length divided by altitude - is compatible with the detector area). In most cases the imaging optics form an image which is transferred by a field lens to the detector. In other words, the field lens images the entrance aperture on the infrared detector. The field lens is usually designed to work in the spectral region of the particular detector. Cone condensers can also be used in place of the field lens.

The spectral filters are usually placed close to the detector to optimize image quality by eliminating unwanted radiation from the scene. The filter may be an integral part of the detector assembly.

Infrared detectors suitable for reconnaissance must have short time constants to handle the high information rates required. The bit rate or data rate of an infrared system is given by the formula $D_r = VS/h\,\theta^2$, where D_r is the data rate in bits per second, V is the ground speed, h is altitude, S is the cross-track angle in radians, and θ is the angular resolution in radians. At a V/h of two radians per second (approximately Mach 1 at 500 feet), a resolution requirement of one milliradian (corresponding to six-inch ground resolution at 500 feet at nadir), and a scan angle of 120 degrees or roughly two radians would result in a data rate of four million bits per second or four megacycles. The data rate is directly proportional to V/h and to scan or cross-track angle, but increases as the square of the angular resolution. Hence, a requirement for a 1/2 milliradian resolution with the same set of parameters previously given would require a 16 megacycle width. Thus, it can be seen that the response time or time constant of an infrared detector must be very short - less than a microsecond if the number of detectors in the system is to be kept in reasonable bounds. A single detector system where the detector has a time constant of less than a microsecond could handle a one megacycle data rate. The signal-to-noise ratio tends to improve if the detector is not pushed too hard in terms of response time. It is generally agreed that present single detectors should not be pushed beyond a one megacycle data rate, and even this is considered a rather severe rate. Hence, if one considers the problem of infrared reconnaissance at V/h rates greater than two radians per second with resolution requirements of 1/2 milliradian or better, multiple detector systems are required.

At present, infrared detectors used for high information rates are either intrinsic or extrinsic photo detectors. Chemically deposited materials such as PbS and PbSe exhibit time constants which are too long and further require considerable electronic compensation for data rates. Intrinsic semiconductor crystals such as InAs and InSb have been developed in photodiode form for wavelengths to seven microns. Longer wavelength response is obtained with extrinsic detectors such as copper or mercury-doped germanium. Since these detectors exhibit low absorption, integration chambers are required to achieve multiple paths through the crystal. At the present state of the art, these detectors are the preferred choice. However, intrinsic detectors such as HgTe are being investigated and may be available in the next few years.

Cooling to cryogenic temperatures is required for most detector operation. Thermoelectric cooling can be utilized for temperatures down to 200°K. Gas cooling is employed below 200°K by liquefying mechanisms. Liquid nitrogen from storage containers, as well as cryostats utilizing high pressure nitrogen to achieve 77°K, are used for this purpose. Similarly, neon, hydrogen and helium are used for lower temperatures. The use of cryogenic solids such as methane has also been explored.

In addition to cooling, infrared detectors require low noise preamplifiers because the signal levels are near the Johnson noise. Such preamplifiers are well within current technology.

Due to detector time constant and capacitance associated with high resistance, high frequency boost is sometimes required. If multiple detectors are used, some form of keyed or subliminal agc is required to equalize response. Recent systems have employed a threshold to perform an alerting function such as marking the edge of the film. On certain missions such as submarine wake detection, temperature gradient is more significant and some degree of low frequency suppression is used.

Several display methods are used with IR systems. An "A" scope display is sometimes utilized. Because information from previous scans is needed for a more adequate understanding, film recording and rapid development are a necessity. Recording techniques other than film may be used for "instantaneous" display and may be satisfactorily developed by 1967. Updating a video display requires considerable equipment and has an extremely limited time span compared to a "hard copy" process.

Film recording is usually accomplished with a modulated light source, such as a glow tube, and scanning optics that are mechanically coupled to the infrared optics through a roll compensation mechanism. The film speed is controlled by the V/h detector. Electronic scanning and compensation through the use of a CRT, while allowing less mechanical parts, introduces more stringent linearity, resolution, dynamic range and roll, pitch, and yaw compensation requirements.

Magnetic tape recording is presently used in certain applications, but requires more ground equipment and better equipment accuracy to allow for signal degradation during recording and playback. For high data rates, video recorders beyond the present state of the art would be required.

As with other sensors, the design of an operational infrared system is also limited to space available in the aircraft. A typical system would scan over 120 degrees. A 180-degree system is feasible; however, information gathered beyond 120 or 140 degrees is of questionable value.

Angular resolution of less than a milliradian and temperature resolution of 0.1 degrees Kelvin are feasible. Such a system would weigh about 200 pounds and require about 1000 watts of power (400 cps three-phase). The overall size would be about 1.5 by 1.5 by 3 feet.

7.4 INFRARED RECONNAISSANCE SYSTEM DEVELOPMENT

The development of infrared scanners of the type envisioned for the multisensor mission is less than a decade old. From 1950 to 1960, the infrared reconnaissance system evolved very slowly as a low altitude, low resolution, low V/h device, with expanding capability only in terms of spectral coverage at longer wavelengths. Resolutions of several milliradians, temperature sensitivities of 1°C, and V/h capabilities of 0.050 radians per second were typical requirements.

Operation in the lead sulphide spectral band (1 to 3 microns) was succeeded by use of cooled lead selenide detectors in the 3 to 5-micron band and finally by copper-doped germanium and mercury-doped germanium detectors in the 8 to 14-micron band.

Until several years ago, the angular resolution requirement remained in the range 2 to 3 milliradians although temperature sensitivities as low as 0.1°C (with entrance aperture completely filled) had been reached. Indium antimonide and lead telluride detectors were developed allowing operation in the 4.5 to 5.5-micron window. The AN/UAS-5, AN/AAR-9, and AN/AAD-2 scanners are representative systems of this era.

Systems described within the past year or so (the AN/AAS-18 and AN/AAS-10) have resolutions exceeding 1 milliradian with a V/h capability to over 2 radians seconds and noise equivalent temperatures of 0.25°C. Many useful and high quality examples of terrain imagery have been produced by the existing systems when operating at the lower altitude.

However, if one considers a reconnaissance mission with a contemporary high-speed high-altitude aircraft at an altitude of 50,000 feet, an angular resolution of 1 milliradian would resolve ground structure of the order of 50 feet. Imagery of objects whose size is much less than the width of an airstrip would be seriously degraded. To achieve ground resolution comparable to that obtained with a 1 milliradian system at 5000 feet, the instantaneous angular resolution requirement becomes 0.1 milliradian. Because of the inverse squared dependence of noise equivalent temperature difference on resolution, the sensitivity of the system would have to be increased by a factor of 100 to preserve temperature resolution comparable to that obtained at the lower altitude. Otherwise, a noise equivalent temperature difference of 0.3°C would become 30°C, and terrain imagery would be impossible because the temperature differences associated with terrain features are in the 1 to 10°C range. In addition, the increased data-gathering rates imposed by the higher resolution may impose requirements that will render the past generation systems unsuitable for generalized tactical reconnaissance.

Faced with these technical requirements, it appears mandatory that single channel detection systems, which have been satisfactory at the lower altitudes and speeds, be replaced with multi-element detector arrays followed with multi-channel electronics in order to cope with the requirements of sensitivity, data rate, and scanning speed. Multi-element sensors having of the order of ten detectors have been designed and flown with excellent results.

In summary, infrared surveillance systems have not been widely used in operational aircraft reconnaissance. The traditional single-detector channel systems have not been able to satisfy the requirements of resolution and bandwidth imposed by present high speed aircraft operating under generalized mission-profile requirements. However, recent advances in the development and fabrication of multiple detector arrays offer a potential for infrared reconnaissance systems that has not been previously realized. The parametric analysis in the next section establishes the relations that would be used in setting forth system specifications.

7.5 INFRARED PARAMETRIC ANALYSIS

This analysis is based on a panoramic scan at right angles to the vehicle track by an array of detectors. The output format is of the strip map type. In actuality, the detector array is stationary and the scan action is produced by a mechanically rotating reflector, assumed to be a single element mirror for the present purpose. This mode of scan is also called the "sweep broom" type.

7.5.1 Diffraction Blur Circle

The minimum diameter D of the entrance aperture of the optical system necessary to provide the desired angular resolution is

$$\theta_d = \frac{2.44\,\lambda}{D},$$

where θ_d is the angular diameter of the central maximum of the diffraction pattern and λ is the wavelength. This is the least requirement on aperture irrespective of sensitivity requirements. At a wavelength of 10 microns, and at an angular resolution of 0.1 milliradian, the least optical aperture is about 10 inches.

7.5.2 Minimum System Focal Length

On the basis of the minimum detector size Δd which can be fabricated and the desired angular resolution $\Delta \theta$, the minimum focal length f is found from

$$f = \frac{\Delta d}{\Delta \theta} .$$

Doped germanium detectors suitable for use in the 8 to 14-micron atmospheric window can be made as small as 0.004 inch in size.

7.5.3 Noise Equivalent Bandwidth

The noise equivalent bandwidth Δf, or the single channel bandwidth with a single-element scanning mirror is given by

$$\Delta f = \frac{\pi \quad V/h}{(1-\alpha) \; n \; (\Delta \theta)^2}$$

where

V = velocity of the aircraft,
h = aircraft altitude,
n = number of detector channels,
$\Delta \theta$ = angular resolution of a single detector, and
α = fractional overlap of successive sweeps.

It can derived from

$$\Delta f = \frac{1}{2 \Delta t}, \quad \frac{\Delta \theta}{\Delta t} = \frac{2 \pi}{T}, \text{ and } T = \frac{(1-\alpha) \; n \; h \; \Delta \theta}{V}$$

where Δt = detector dwell time for a point source

and T = scan period of rotation during which time the aircraft advances $(1-\alpha) n h \Delta \theta$.

If the fractional overlap can be neglected,

$$\Delta f = \frac{\pi \quad V/h}{n \; (\Delta \theta)^2}$$

Doped germanium detectors have maximum useful bandwidths of the order of 1 megacycle per second. To conform to this requirement, it is necessary to increase the number of channels as V/h increases with high speed aircraft or as the angular resolution is decreased for high altitude operation. With single channel systems, Δf may become prohibitively high.

7.5.4 Total System Bandwidth

The total system bandwidth Δf_T is increased by the number of detector channels operating in parallel according to

$$\Delta f_T = n \Delta f .$$

7.5.5 Average Information Data Rate

This is defined here as the number of scanned resolution elements swept in a period of rotation and it does not comprise the out-of-scan elements during retrace. It is given by

$$DR = \frac{V \quad S}{h(\Delta \theta)^2 \ (1-\alpha)}$$

where S is the cross-track angle, and the other symbols are as defined above. It includes the redundant elements scanned twice because of overlapping of successive sweeps.

The number of once-scanned resolution elements is found by application of the factor $1-\alpha$, where α is the overlap, and the information rate for these is given by

$$DR_o = \frac{V}{h} \frac{S}{(\Delta \theta)^2} ;$$

this is the same rate as for no overlap.

7.5.6 Noise Equivalent Power

The noise equivalent power (NEP) of the detector is given by

$$NEP = \frac{\sqrt{A \Delta f}}{D^*}$$

where A is the detector area in cm^2, Δf is the noise equivalent bandwidth, and D^* is the photodetector figure of merit normalized to unit frequency bandwidth and unit area. For doped germanium detectors, the peak D^* may approach

$$10^{11} \left[\frac{\text{cm cps}^{1/2}}{\text{watt}} \right].$$

7.5.7 Noise Equivalent Temperature Difference

The noise equivalent temperature difference (NETD or ΔT_N) is an important parameter describing the performance of an infrared surveillance system. It represents that temperature difference of a blackbody radiator with respect to the ambient reference temperature and which provides for a signal-to-noise ratio of unity. The radiator completely fills the field-of-view of a single detector. ΔT_N is found as follows.

The NEP from the Section 7.5.6 is written

$$NEP = \Delta P = \frac{\partial P}{\partial T} \Delta T_N ,$$

since two adjacent fields-of-view are at different temperatures ΔT_N apart and the change in power at the detector is ΔP. But,

$$P = e_o e_E \frac{\pi D^2}{4} (\Delta \theta)^2 N$$

where

e_o, e_E = optical, electronic efficiencies,

D = diameter of the entrance aperture (cm),

$\Delta \theta$ = the angular resolution,

N = the apparent radiance $\left(\frac{\text{watts}}{\text{cm}^2\text{-sr}}\right)$.

The apparent radiance is found by weighing the Planck blackbody radiance function $W/\pi\ (\lambda, T)$ where T is absolute temperature and λ is the wavelength, by the normalized spectral response of the detector D^*/D^*_{max} and by τ (λ), the combined atmospheric and filter transmittance. Integration over the spectral interval gives

$$N = \int_{\lambda_1}^{\lambda_2} \frac{D^*}{D^*_{max}} \tau(\lambda) \frac{W}{\pi} (T, \lambda) \, d\lambda \quad \left(\frac{\text{watts}}{\text{cm}^2\text{-sr}}\right).$$

Further, introducing the bandwidth

$$\Delta f = \frac{\pi \ V/h}{n (\Delta \theta)^2},$$

and the detector area

$$A = (f \Delta \theta)^2 ,$$

and by doing some algebraic manipulation, it is found that the NETD is

$$\Delta T_N = \frac{4 f \sqrt{\frac{\pi}{n} V/h}}{(\Delta \theta)^2 D^2 e_o e_E \int_{\lambda_1}^{\lambda_2} D^* \tau \frac{\partial W}{\partial T} d\lambda} .$$

The integral in the denominator has been evaluated at a background reference temperature of 288°K in the 8 to 14-micron region with doped germanium to be

$$3 \times 10^6 \left(\frac{\text{cm cps}^{1/2}}{°\text{K}}\right).$$

7.5.8 <u>"Push Broom" Scan</u>

In this type of scan, there is no rotation of the detector array. The number of detectors, n, is given by the ratio of the cross-track angle S to the angular resolution $\Delta \theta$. The downward-looking field-of-view, in conjunction with the aircraft motion, maps a strip along the vehicle track. This type of scan is more suited to low altitude operation where the requirement on angular resolution is less severe. Otherwise, in a high altitude aircraft the number of detectors can be prohibitively large.

It can be shown that the expression for NETD in the section above for the "sweep broom" scan is also applicable to the "push broom" scan if the quantity π under the radical is replaced by S/2.

7.5.9 Signal-to-Noise Ratio, "Sweep Broom" Scan

The determination of target signal follows along the methods used in the analysis of NETD. Analogous to ΔT_N, $\Delta \theta$, and NEP, we find the target temperature difference ΔT_S, the angular subtense of the target at the entrance aperture $\Delta \omega$, and the signal power S. Following through the analysis, it can be shown that the signal-to-noise ratio is

$$S/N = \left(\frac{\Delta \omega}{\Delta \theta}\right)^2 \frac{\Delta T_S}{\Delta T_N} \text{ where } \Delta \omega \leq \Delta \theta .$$

Alternatively, the target temperature difference can be expressed in terms of the equivalent apparent radiance difference.

Introducing the expression for ΔT_N as developed previously,

$$S/N = \frac{(\Delta \omega)^2 \, \Delta T_S \, D^2 \, e_o e_E \int_{\lambda_1}^{\lambda_2} D^* \, \tau \, \frac{\partial W}{\partial T} \, d\lambda}{4f \sqrt{\frac{\pi}{n}} \, V/h} .$$

7.6 DESIGN PARAMETER SUMMARY ILLUSTRATING TWO MULTI-CHANNEL SYSTEMS

The parametric analysis of the previous section was applied to the determination of the system parameters illustrating two multi-channel systems. Tables 7-2 and 7-3 summarize the more important numerical values characterizing each. Each illustrates an internally consistent set of system parameters for a multi-channel system.

In both examples, the angular resolution for a low altitude mission was taken to be 1 milliradian. It is obtained by a 10 by 10 summation of the

Table 7-2. Summary of Design Parameters, Design No. 1

Altitude (ft)	Speed (ft/sec)	V/h (sec^{-1})	Ang. Res. (millirad.)	Number Channels	Single Channel Bandwidth (mc)	System Bandwidth (mc)	NETD (°K)
500	1,000	2	1	10	0.32	3.2	0.74
1,000	1,000	1	1	10	0.16	1.6	0.52
2,000	1,500	0.75	1	10	0.12	1.2	0.45
8,000	2,000	0.25	1	10	0.04	0.4	0.26
10,000	2,000	0.2	1	10	0.03	0.3	0.22
20,000	2,000	0.1	0.1	100	0.16	16.0	5.2
40,000	2,000	0.05	0.1	100	0.08	8	3.7
60,000	2,000	0.033	0.1	100	0.05	5	3.0

Total Field: 0.6 deg.
Detector Size: 0.005 in.
Focal Length: 50 in.
Entrance Aperture: 10 in.
Blur Circle: 0.1 millirad.

Scan Mirror: 2 element, cont. rotating, 100 rev/sec

Combined Optical-Electronic Efficiency: 20 percent (assumed)

Detector Array: Linear, staggered

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Table 7-3. Summary of Design Parameters, Design No. 2

Altitude (ft)	Speed (ft/sec)	V/h (sec^{-1})	Ang. Res. (millirad.)	Number Channels	Single Channel Bandwidth (mc)	System Bandwidth (mc)	NETD (°K)
500	1,000	2	1	20	0.16	3.2	0.72
1,000	1,000	1	1	20	0.08	1.6	0.51
2,000	1,500	0.75	1	20	0.06	1.2	0.44
8,000	2,000	0.25	1	20	0.02	0.4	0.26
10,000	2,000	0.2	1	20	0.016	0.3	0.23
20,000	2,000	0.1	0.2	100	0.04	4	1.8
40,000	2,000	0.05	0.2	100	0.02	2	1.3
60,000	2,000	0.033	0.2	100	0.013	1.3	1.0

Total Field: 1.2 deg.
Detector Size: 0.005 in.
Focal Length: 25 in.
Entrance Aperture: 6 in.
Blur Circle: 0.15 millirad.

Scan Mirror: 2 element, cont. rotating, 50 rev/sec

Combined Optical-Electronic Efficiency: 20 percent (assumed)

Detector Array: Linear, staggered

0.1 milliradian resolution of an individual detector element in the case of Design No. 1, and a 5 by 5 summation of the 0.2 milliradian resolution of an individual element in Design No. 2.

In both designs, the single channel bandwidth is well below the 1 mc maximum for doped germanium. However, in Design No. 2, the system bandwidth at 20,000 feet may present difficulties in recording. Hence, the resolution in Design No. 2 was increased by a factor of 2 to reduce both the system bandwidth and the noise equivalent temperature difference for the high altitude missions.

Tables 7-4 and 7-5 summarize calculations for both designs, of the relationship of that temperature contrast required for an arbitrary signal-to-noise ratio of 7 and the associated linear size at the full field-of-view. At low altitude missions below 10,000 feet, both designs are equivalent with respect to the required temperature contrast for S/N = 7 and with respect to resolution. At altitudes above 20,000 feet, the rendition of nominally occurring terrain contrast would be marginal with Design No. 1 but more easily achieved with Design No. 2 with a decreased but still adequate resolution. These designs are not considered as optimum final configurations but indicate the relationship of the various parameters.

Figs. 7-2 and 7-3 are plots of the fraction of the total field at the ground covered by an object of given size for various altitudes with an angular field of 0.1 milliradian. They may be used to estimate the reduction of signal-to-noise with objects of linear size less than the total field.

Table 7-4. Temperature Contrast for Signal/Noise of 7.
Design No. 1

Altitude (ft)	Temp. Contrast (°C) S/N = 7	Linear Size with Full Field At: 0° Nadir (ft)	45° Nadir (ft)
1,000	3.6	1	1.7
2,000	3.2	2	3.4
8,000	1.8	8	13.4
10,000	1.5	10	16.8
20,000	36.	2	3.4
40,000	26.	4	6.7
60,000	21.	6	10.1

Table 7-5. Temperature Contrast for Signal/Noise of 7.
Design No. 2

Altitude (ft)	Temp. Contrast (°C) S/N = 7	Linear Size with Full Field At: 0° Nadir (ft)	45° Nadir (ft)
1,000	3.6	1	1.7
2,000	3.2	2	3.4
8,000	1.8	8	13.4
10,000	1.5	10	16.8
20,000	13.	4	6.7
40,000	9.	8	13.4
60,000	7.	12	20.1

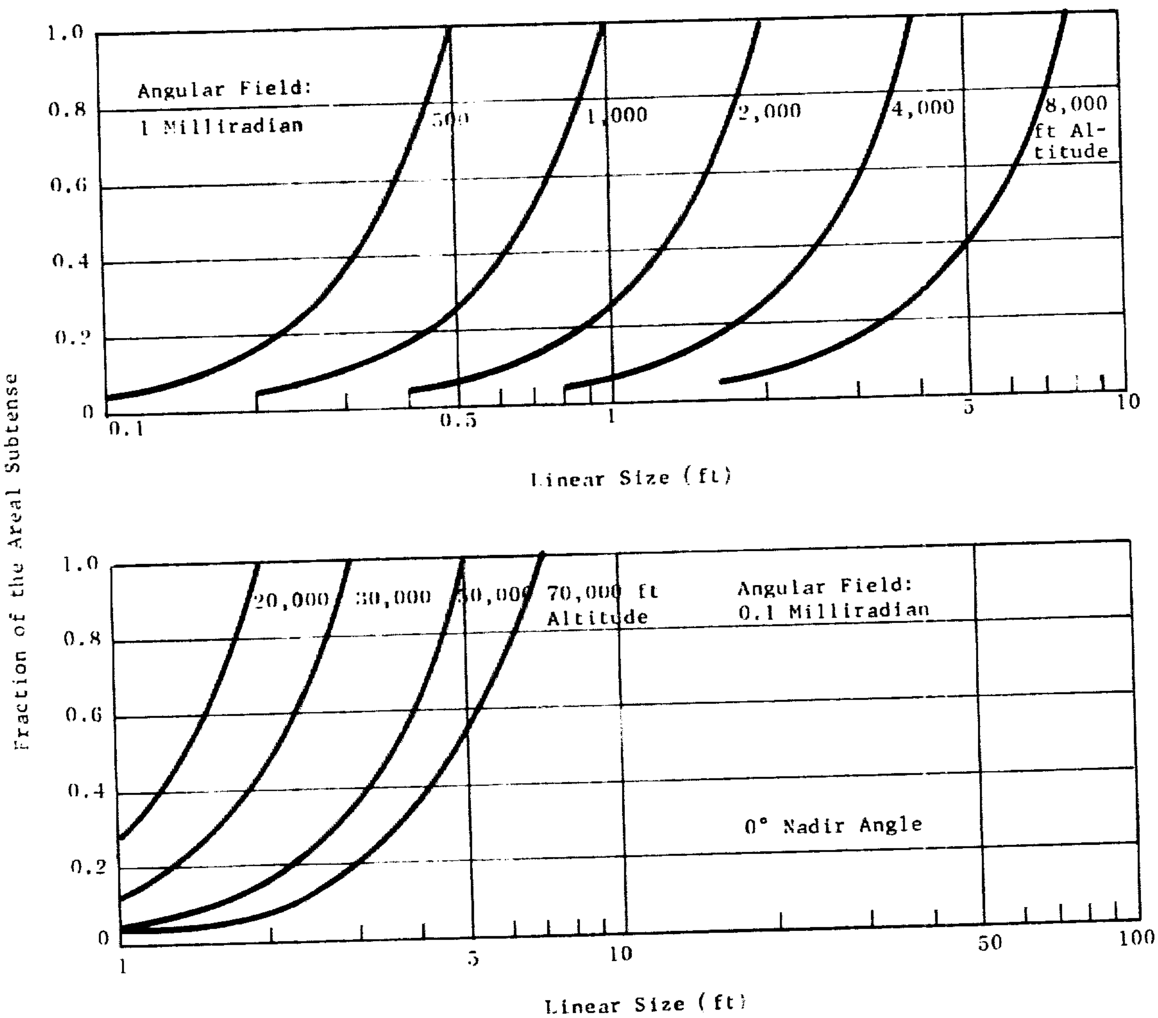

Fig. 7-2 — Fraction of the total field versus linear size for several altitudes (0° nadir angle).

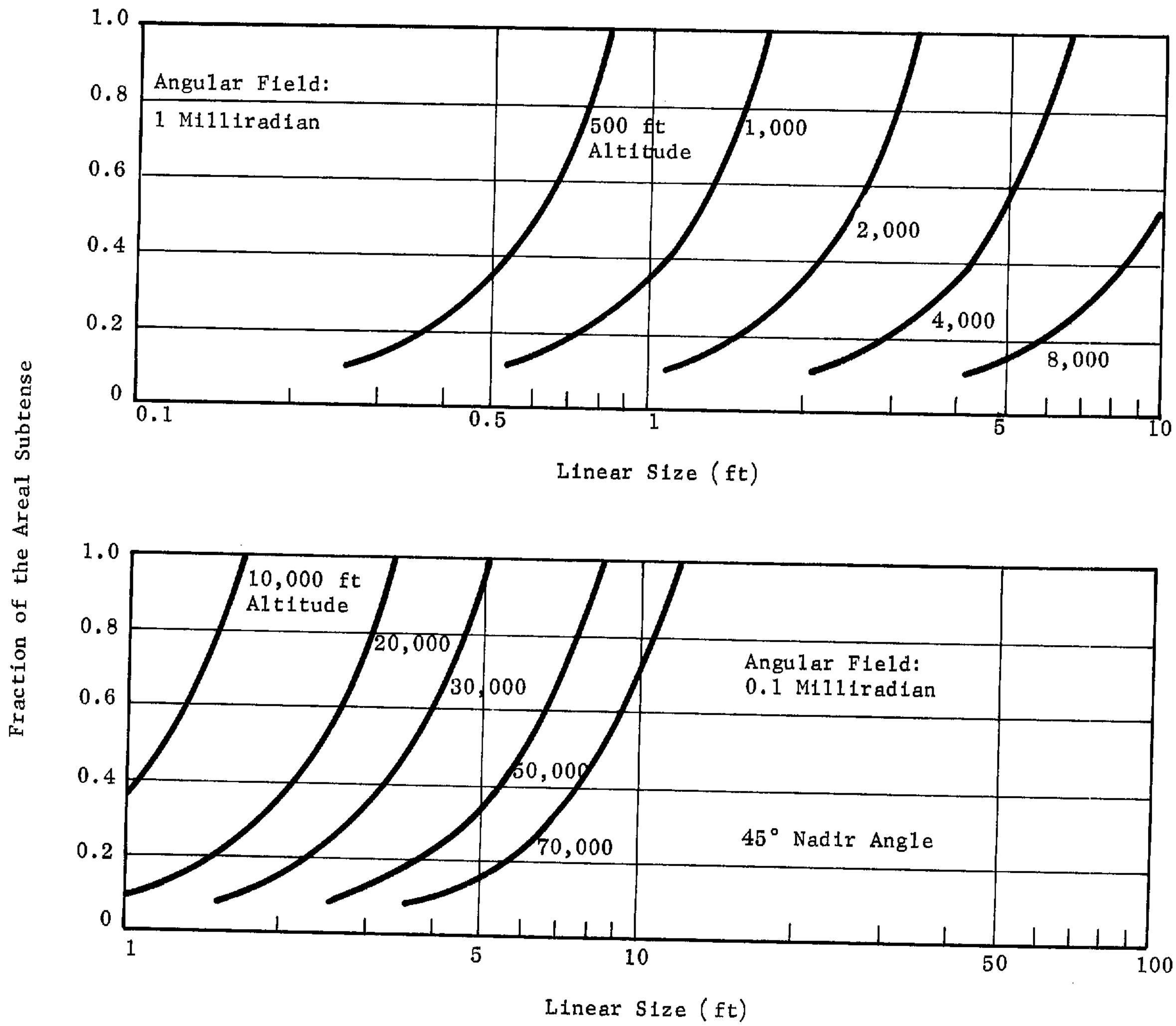

Fig. 7-3 — Fraction of the total field versus linear size for several altitudes (45° nadir angle).

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8. TACTICAL ELINT

The principal operational function of tactical ELINT (electronic intelligence) is to provide order of battle intelligence to the tactical commander. In the initial reconnaissance mission this is akin to a mapping operation. In subsequent missions, the most useful information lies in the changes observed in the order of battle. We are here considering, of course, only airborne ELINT collection systems.

In order to perform the intelligence function, the ELINT system must yield data on the location and classification of emitters in the combat area. By classification is meant the identification of the emitter function, such as early warning, fire control, and GCI. In some cases, identification by specific emitter type is feasible.

8.1 EMITTER CHARACTERISTICS

In order to have a frame of reference for understanding the operation of an ELINT system, the emitters will be considered against which such a system must operate. Technically, these may be classed as radars, guidance links, data links, and communication links including broadcast. From a functional point of view, they may be classified by an association with specific force units as shown in Table 8-1.

These emitters are distributed in frequencies from a few tens of megacycles up to approximately 20 gigacycles. However, the distribution is far from uniform, and is related to the function of the emitter. Communications and data links lie mostly in the region between 100 and 2000 megacycles. Radars on the other hand are distributed from as low as 70 megacycles to as high as 18 gigacycles. Fig. 8-1 shows the principal region of the spectrum occupied by Sino-Soviet radars.

Table 8-1. Functional Classification of Emitters

Air Defense

- Early Warning Radars (EW)
- Ground Control Intercept Radars (GCI)
- Height Finder Radars (HF)
- Ground Control Approach Radars (GCA)
- Ground-to-Air Data Links
- Ground-to-Ground Data Links

Surface-to-Air Missiles

- Acquisition Radars (ACQ)
- Tracking Radars
- Track-While-Scan Radars (TWS)
- Missile Control Guidance Links
- Ground-to-Ground Data Links

Anti-aircraft Artillery

- Fire Control Radars (FC)

Infantry Ground Operations

- Surface Search Radars
- Battlefield Surveillance Radars

Surface Artillery

- Tank Radars

Command Posts

- Command Communication Links

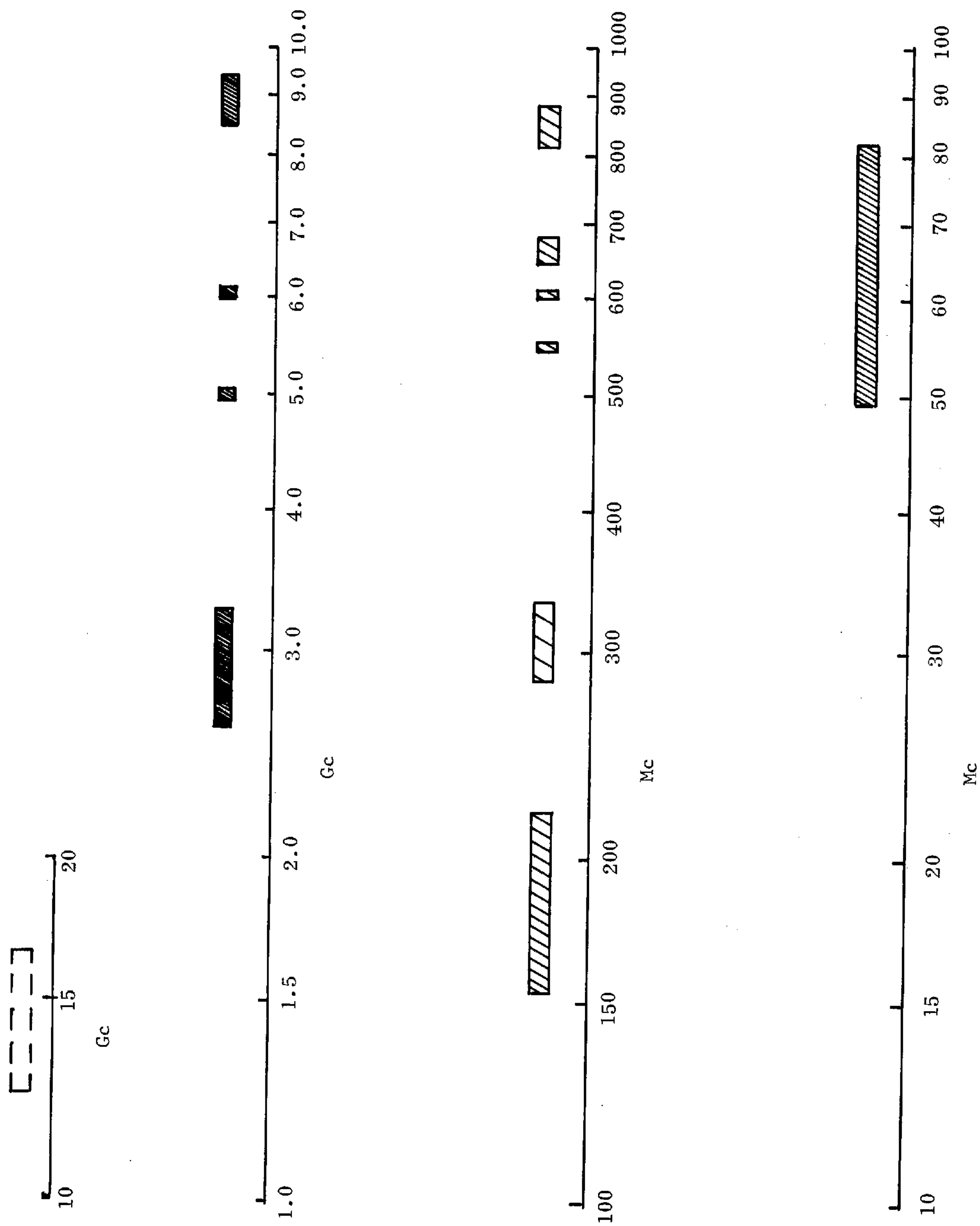

Fig. 8-1 — Soviet radar spectrum occupancy.

These various classes of emitters radiate signals that differ widely in the specific characteristics, and hence can be distinguishing among the different classes. Almost all of the radars are pulsed. The ratio of the pulse duration to the interval between pulses seldom, if ever, exceeds 1 percent - more typically, it is about 0.1 percent. Pulse durations range from about 0.2 microseconds to 10 microseconds. Since the range resolution of a pulsed radar is largely determined by the sharpness of the leading edge of the pulse, the frequency bandwidth of the radar signals usually exceeds 1 megacycle. Thus, if there are several radars actively illuminating an ELINT receiver, it is quite possible that they may overlap in frequency, or at least be so close together as to be unresolved by the frequency filter of the receiver. On the other hand, their low duty factor (ratio of pulse duration to pulse interval) insures that the pulses from different radars will usually be separated in time. Most radar transmitters are designed to provide position and velocity information concerning their targets. Range is measured by the travel time of the radar pulse, while the one or two regular coordinates of the target are determined by reference to the radiation pattern of the radar antenna. The radar usually contains a single highly directional main lobe with a cluster of much smaller minor lobes distributed over the remainder of the spherical sold angle. By virtue of the radiation from these so called minor lobes, it is possible for a sensitive receiver to detect a radar signal even though the main lobe is directed elsewhere.

Some exotic radar types differ from the conventional pulsed radars mentioned above. These may be CW radars (continuously radiating a signal), or they may be pulsed radars with a fine structure inside the pulse. Others may have a deliberate randomness in the sequence of pulse intervals or in the frequency of radiation from one pulse to the next.

Data links may be found in the low hundreds of megacycles where in general the transmissions are not highly directional, or in the 1000 to 2000 megacycle region where a fairly high degree of directivity is used. The primary modulation is usually FM, but the modulation structure may take on a wide variety of forms. The information will usually be encoded in a digital format, but may be quasi-analog as in the case of pulse position modulation. These bandwidths tend to be narrow compared with radar bandwidths, while the duty factors are high, and in many cases up to 100 percent. Therefore, signals must be separated on a frequency basis rather than on a time basis as in radar.

Other communication links include voice or analog transmission which are distinguishable from the data link type transmission by modulation characteristics.

8.2 BASIC ELINT FUNCTIONS

The basic functions of an ELINT system may be listed as collection, analysis, interpretation, and reporting. Collection is the reception of a signal with sufficient fidelity to permit analyzing and recognizing it against a background of noise and other signals. This function generates requirements of receiver sensitivity, bandwidth, antenna coverage, and angular resolution. The analysis function includes signal recognition by specific characteristics such as frequency and modulation structure. Interpretation covers the association of a number of signals to yield additional information. For example, the association of signals identified as emanating from the same emitter but having been received at different points along the flight track permits approximate determination of the location of the emitter. A rather different sample of interpretation is the comparison of the signal characteristics with a stored "library" of signal characteristics for the purpose of making a priority decision. Reporting is the manner in which the collected, analyzed, and/or interpreted information is delivered for use. It may simply be recorded for subsequent processing, or it may be displayed in the aircraft, or it may be transmitted in real time for use at a distant point.

8.3 BASIC SYSTEM COMPONENTS

The major classes of equipment components that make up an airborne elint system, and their relation to the basic functions, will now be examined, following the flow of information from the signal environment to the output records and displays, the first component is the antennas. These serve the collection function of the signals, and assist in the analysis and interpretation by sensing the direction of arrival. To provide frequency coverage sufficient to collect all the signals of interest requires a plurality of antennas. The requirement for direction sensing without time sharing results in a second multiplicity of antennas for each frequency range; if direction sensing by mechanical scanning is allowable, then one antenna per band is sufficient.

Associated with each antenna is a receiver whose function is to acquire the signal, and amplify it to sufficient level to permit further processing. The sensing of the signal frequency is also performed in the receiver.

The output of the receivers are fed to one or more signal analyzers or recognizers. These components may consist of such elements as analog filters, discriminators, or time-gate sequences. Alternatively, they may consist of analog-to-digital quantizers followed by digital processing circuitry to perform the recognition and analysis functions.

The analyzers and recognizers are followed by a general purpose logic and storage component which may take the form of a general purpose computer. This component will perform the tasks of data association and interpretation and will provide temporary storage during periods of peak signal traffic. It will prepare the output information in a form suitable for the reporting output device. For example, it will organize digital information in the proper format for a magnetic recorder, it will generate analog commands for onboard display devices, and it will format signals for input to the modulation unit of a real time data link. In addition, if the elint system possesses real time adaptivity, this component will generate the necessary commands to the collection and signal analysis portions of the system.

The output devices consist of magnetic tape recorders, diagrammatic or alphanumeric visual displays, or voltage generators to interface with a real time data link.

8.4 DATA FLOW REDUCTION

The raw signal environment, by which is meant the totality of signals arriving at the aircraft, is prodigious. In a field army tactical environment, an aircraft flying at 1000-feet terrain clearance will receive between one and two million pulses per second from pulsed radars. The redundancy in this raw information is very high, and permits the use of collection by sampling.

Analysis shows that a sample of about 0.2 percent is adequate to provide near-unity probability of interception at a rate sufficiently high to yield good emitter site locations, and to limit delay in alerting to new signals to a few seconds. Since the object of the sampling is to reduce the data rate, it is necessary to perform this function as near the input end of the elint system as possible. Accordingly, it is done within the antennas or the receivers, or a combination of both. This means that the parameters defining the sample description space, i.e., direction of arrival, frequency, and signal strength, must be those capable of being sensed by the antennas and/or the receivers. Sampling in each of these dimensions can be implemented by the following scanning processes - direction of arrival by a rotating antenna, frequency by a scan receiver, and signal strength by a fixed signal strength threshold set in the receiver which accepts signals only from the main lobe of the radar transmitter in which case the scan is generated by the radar transmitter itself. In principle it is possible to use a combination of these processes to arrive at the desired sample ration. In determining the optimum sampling process, tradeoffs must be considered among such performance features as probability of intercept, search rate, sensitivity and resolution in both frequency and angle.

The total data reduction process then proceeds as follows:

1. Reduction of the raw data by a sampling process in the system collectors.
2. First degree association which means pulse train recognition for pulsed radars and modulation pattern recognition for data link or collection signals.
3. Second degree association which means derivation of emitter location by association of the direction of arrival of a family of signals defined in the first association process.

Thus, the final output for single flight may consist of one or a few pages of printout listing the detected emitters by grid coordinates and type classification.

8.5 TYPICAL SYSTEM

Fig. 8-2 is a functional block diagram of a typical system. Frequency coverage is not continuous over the spectrum, but is as shown in Table 8-2.

Table 8-2. Frequency Coverage for ELINT Detectors

Band	F_{min} (Gc)	F_{max} (Gc)
1	0.1	0.2
2	0.4	0.9
3	2.5	3.5
4	3.5	7.0
5	7.0	12.0
6	12.0	20.0

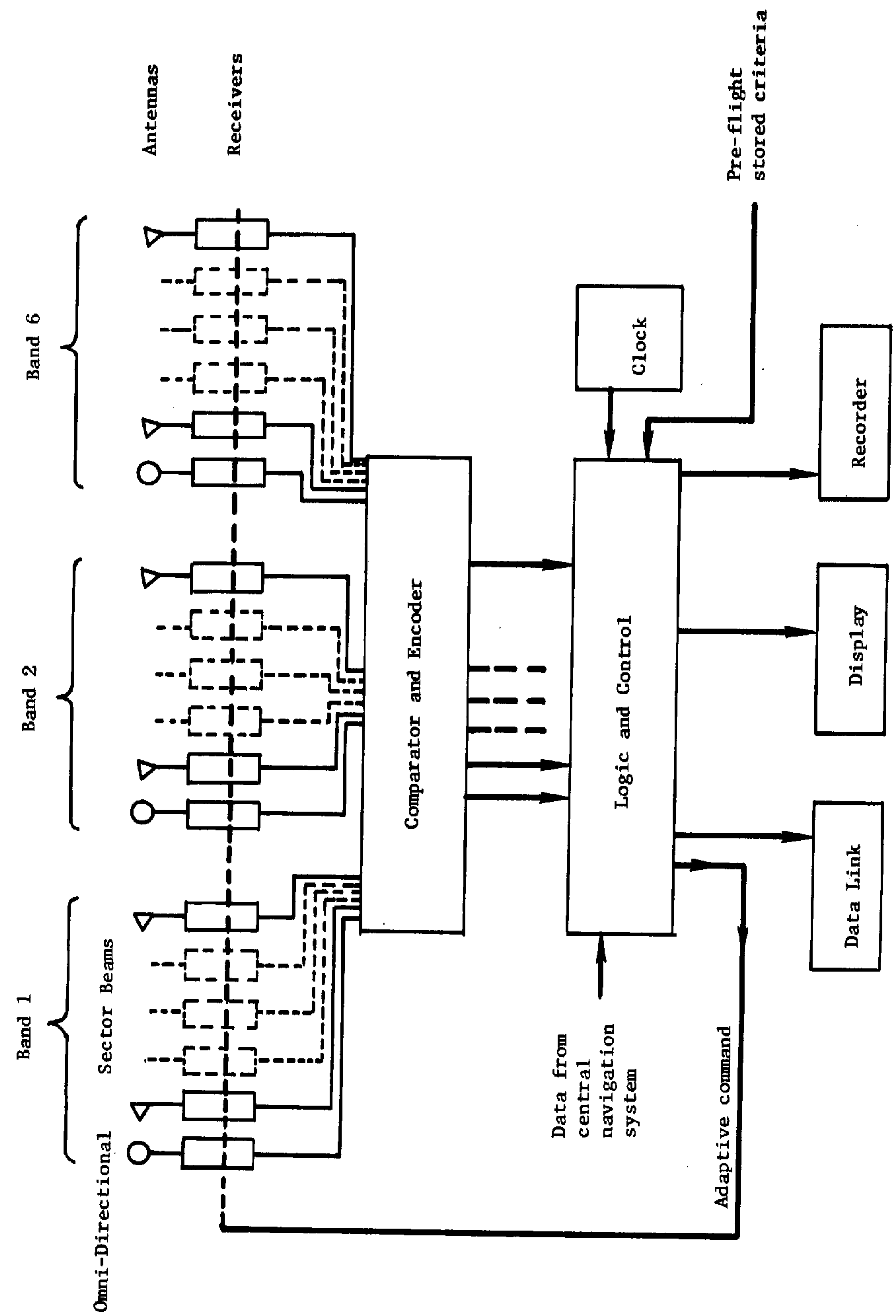

Fig. 8-2 — Typical system.

The spectrum is divided into six bands in each of which there is a set of scanning superheterodyne receivers. All bands are scanned simultaneously. Complete azimuthal antenna coverage is provided with an angular resolution of ±6 degrees in the side looking quadrants and ±10.5 degrees in the forward and aft quadrants (this resolution is somewhat degraded in the lowest frequency band). The scan period is five seconds and provision is made for stopping the scan on command from the logic and control component.

Consider now the block diagram. The signals from the frequency receiver, whose antenna pattern is omnidirectional in azimuth, and the signals from the several directional channels are fed to a central digital encoder. Comparison among the directional channels yields a unique direction specification. The amplitude and duration of the pulse are measured and digitally encoded, and all of this information is delivered to the central logic and control unit where it is formed into a single digital descriptor, and associated with a time of arrival. A sufficient number of pulses are kept in temporary storage to permit the measurement of pulse repetition interval. A single descriptor including this parameter is then formed. This descriptor is then compared with a set of descriptors stored in the logic and control unit prior to the beginning of the mission. These stored descriptors relate to priority emitter types. If a match between the acquired signal and the stored criteria is obtained, the descriptor of the acquired signal is retained in storage for the purpose of site location. When sufficient samples of this signal over a range of arrival directions has been obtained, a computation is performed yielding site location in aircraft coordinates. This information is then used for display or is transmitted for use by other sensors, or is transmitted in real time by a data link to a distant point. In addition, it enters the stream of data going to the magnetic tape recorder.

In the event that no match is obtained between the acquired signal and the stored criteria, the pulse train descriptor is recorded "as is". If no pulse train association is made, the individual pulse descriptor is recorded. Finally, the logic and control unit may, as a result of comparison with stored information, generate a command to stop the scan of one of the bands for an extended sample of the particular signal then being received.

Such a typical system would have the following performance.

1. Detection of all active emitters within the radio horizon. Maximum delay from emitter turn-on or horizon crossing to time of detection is five seconds.

2. Location, by triangulation, of all emitters by post-flight processing with an equivalent circular error probability (CEP) of 5 percent of lateral range from the flight track.

3. Location, by triangulation, of priority emitters in flight. The equivalent CEP is a function of the relative bearing of the emitter at the time of data "cut-off" at which the location determination is made.

4. Classification of emitters by functional type - in flight for priority emitters, and post flight for all emitters. Association of a functional type with each location.

SPECIAL HANDLING

SPECIAL HANDLING