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7 MAY 1980 (FOUO 5/80) 1 OF 1

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USSR Report

SPACE

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CONTENTS

SPACE SCIENCES

Atmospheric Research Conducted on 'Salyut-4' 1

APPLICATIONS

Contemporary Problems in Satellite Oceanology 9

Hopes and Realities of Oceanology from Space 22

Remote Methods of Studying the Earth's Surface and the Atmosphere of the Earth in the Microwave Band 44

On the Further Development of Methods of Studying the Earth from Space 59

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ATMOSPHERIC RESEARCH CONDUCTED ON 'SALYUT-4'

Moscow VESTNIK AKADEMII NAUK SSSR in Russian No 2, Feb 80 pp 60-65

[Article by O. A. Avaste, doctor of physical and mathematical sciences, and U. K. Veysmann, Ch. Y. Villman and K. A. Eerme, candidates of physical and mathematical sciences: "Studying the Atmosphere from 'Salyut-4'"]

[Text] Optical investigations of radiation from the atmosphere, noctilucent clouds and the underlying surface of the earth occupied a prominant position in the flight program of the "Salyut-4" orbital station. On previous flights of Soviet manned spacecraft, methodological experience in performing this type of research was acquired and some data were accumulated. While planning experiments for "Salyut-4" it was decided to give special attention to making systematic measurements that could give a more nearly complete representation of the energy-spectrum, spatial and temporal characteristics of radiation from the atmosphere, noctilucent clouds and the earth's underlying surface.

Let us examine some of the results that were obtained using the "Micron" infrared teleradiometer (Figure 1) that was installed on "Salyut-4" during both the first mission (January-February 1975, with Crew Commander A. A. Gubarev and Flight Engineer G. M. Grechko) and the second (May-July 1975, with Crew Commander P. I. Klimuk and Flight Engineer V. I. Sevast'yanov). The study of mesospheric irregularities is one of the urgent problems in modern atmospheric physics. Among these irregularities are noctilucent clouds, which are a unique type of grouping of polydispersed particles (the average diameter of the particles is about 10^{-5} cm) in the mesopause; that is, at an altitude of about 75-85 km above the earth's surface. When conditions are favorable, quite thick fields of noctilucent clouds form in the mesopause in the medium and high latitudes during the summer (in the Northern or Southern Hemisphere, respectively). The area of these fields ranges from millions to tens of millions of square kilometers. A solid band of noctilucent clouds sometimes covers half or even more than half the globe in the appropriate latitudes.

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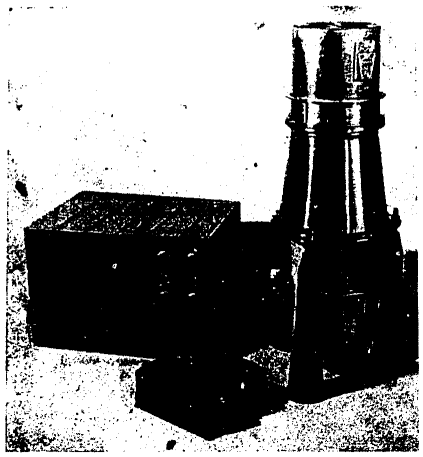

Figure 1. General view of the "Micron" teleradiometer complex.

Figure 2 depicts the projections on the earth's surface of several fields of noctilucent clouds ("Salyut-4," 3-4 July 1975). As is obvious, the noctilucent clouds were observed during the course of nine consecutive "Salyut-4" orbits (2,992-3,000). The apparent discontinuities between sections of the field of clouds that were registered on adjacent orbits are related to the geometrical conditions of the access to them for observation from "Salyut-4."

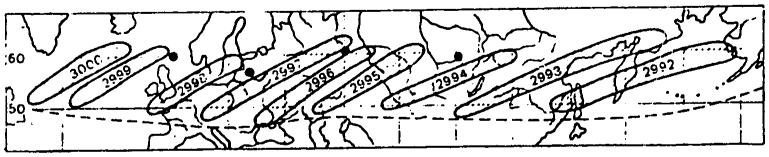

Figure 2. Projections of fields of noctilucent clouds observed from "Salyute-4" on 3-4 July 1975. (The orbit number is shown in the crosshatched ovals, the broken line indicates the projection of the entire probable area of propagation of the field of noctilucent clouds at the moment of observation, and the black circles designate the ground stations that conducted observations of noctilucent clouds at this time.)

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Investigations of noctilucent clouds from ground facilities have already been conducted for more than 90 years. In the last 10-15 years there has appeared a need for extra-atmospheric investigations. The concept of detecting noctilucent clouds from space was put forth in 1962, after which the photometry conditions and methods were discussed by a number of investigators. The first visual observations of noctilucent clouds from space were made by Soviet Pilot-Cosmonaut V. I. Sevast'yanov on the "Soyuz-9" in 1970.

We can regard the purpose of extra-atmospheric investigations of noctilucent clouds to be the determination of their fields' spatio-temporal characteristics on a global scale, a more precise definition of the spectrum of scattered radiation, the determination of the physical parameters of the groups of component particles in the layer of noctilucent clouds, and the establishment of the relation between these phenomena and other atmospheric phenomena and processes. The main problem is to determine the physical mechanism or set of mechanisms involved in the formation of noctilucent clouds.

The first calculations of the extra-atmospheric spectral brightness of noctilucent clouds were made in 1969, at the Estonian SSR Academy of Sciences' Institute of Physics and Astronomy. The brightness of noctilucent clouds in the near infrared band of the spectrum was also evaluated. From the calculations it was ascertained that the cloud's optical thickness had a maximum at the wavelength of 0.35 μm, while for $\lambda \geq 3\,\mu$m it became inversely proportional to λ^4. The theoretical work showed that when analyzing measurements of the brightness of noctilucent clouds it is necessary to allow for the emissions of OH and O_2. A detailed analysis of the organization of the extra-atmospheric experiment revealed the advisability of making the measurements under twilight conditions; that is, close to the terminator and on azimuths close to the Sun's azimuth. Since it is difficult to maintain a sighting line at the level of the noctilucent cloud layer, it is desirable to scan the atmosphere at altitudes of 0-100 km. The vertical sections (scans) of the atmosphere obtained in this way can also be used to solve the inverse problem of atmospheric optics (to calculate the vertical patter of the scattering coefficient) and, thereby, to investigate the distribution of the atmospheric aerosol.

The results of scanning a twilight segment with noctilucent clouds, on the 1.9 μm wave length, is shown in Figure 3. As is obvious, the noctilucent clouds' brightness near the sighting line's perigee H_0 = 79 km exceeds the brightness of the background by approximately half an order of magnitude. It should be mentioned here that all the profiles had a secondary maximum, or plateau, at λ = 1.35 μm for sighting line perigee values of about 55 km. Figure 4 shows the results of measurements of the diurnal atmospheric aureole on the λ = 1.35 and 1.9 μm channels in the absence of noctilucent clouds, when the effect under discussion

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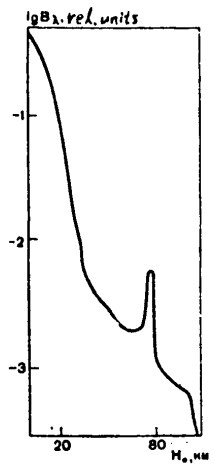

Figure 3. Distribution of horizon brightness in the presence of noctilucent clouds.

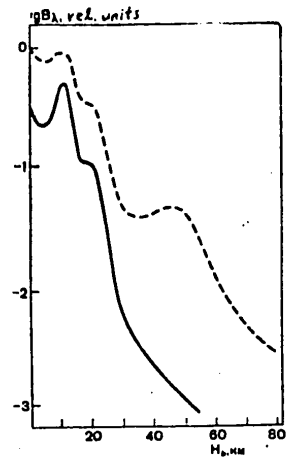

Figure 4. Distribution of horizon brightness in the absence of noctilucent clouds. (Solid line -- $\lambda = 1.9\mu m$; broken line -- $\lambda = 1.35\mu m$.)

was most clearly expressed. This can be explained by the effect of the O_2 ($^1\Delta_g$) emission band, which has its center at $\lambda = 1.27\mu m$.

In all, there were more than 20 scannings of the field of noctilucent clouds above the earth's horizon. Depending on the clouds' structure and spectral density, their brightness varied within the limits of a single order of magnitude. The theoretical and experimental brightness values are quite close to each other. In addition to this, the hypothesis of an increase in hydroxyl (OH) emissions in the mesopause when noctilucent clouds appear has been confirmed.

The emissions of excited molecular oxygen are one of the strongest diurnal glows of the earth's atmosphere in the near infrared band. Despite this, this radiation was detected only relatively recently. Such a strong glow in the upper atmosphere could not be detected from the surface because it is almost completely absorbed by the molecular oxygen in the atmosphere's lower layers.

The first observations of the diurnal emissions of excited molecular oxygen in the earth's atmosphere near the wavelength $\lambda = 1.27\mu m$ were made in 1956, but were not identified. It was only with the appearance of airplane- and balloon-carried equipment, as well as the appearance of rocket technology, that we began to investigate the rules of O_2 ($^1\Delta_g$) emission and measure the altitudinal distribution of molecular oxygen in the $^1\Delta_g$ state.

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At the present time, the emissions of excited molecular oxygen are attracting special attention in connection with the fact that measurements of their altitudinal distribution (at altitudes above 70 km) make it possible to determine the ozone concentration in the upper atmosphere, where direct measurements of the ozone profile are extremely difficult to make. In addition, it can be assumed that in view of the presence of a high concentration of O_2 ($^1\Delta_g$) in the earth's upper atmosphere, the oxygen molecules can participate in the photochemical reactions taking place there.

Since the distribution of the layers of molecular oxygen is of a global nature and the layers are relatively stable under identical illumination conditions, there naturally arose the idea of using permanent orbital stations to organize experiments for the purpose of making a thorough study of the O_2 ($^1\Delta_g$) emission of the earth's atmosphere.

We will now present some results of the analysis of the measurements made on board "Salyut-4." They were made in January and May 1975 using the "Micron" teleradiometer, at an altitude of about 350 km. The scanning of the horizon was accomplished by the slow rotation of the "Salyut-4" station at a constant singular velocity of about 0.5° per second. Six informative profiles of the brightness of the earth's atmosphere were obtained under different illumination conditions within solar zenith angle limits of $\simeq 35\text{-}90^\circ$ in the area of the sighting line's perigee. From the data on the dependence of the glow's intensity on the altitude of the sighting line's perigee (and allowing for the sphericity of the atmosphere), the inverse problem of determining the altitudinal profile of the volumetric emission of molecular oxygen O_2 ($^1\Delta_g$) has been solved.

Figure 5 shows the daily pattern of the intensity of the O_2 ($^1\Delta_g$) emissions. An evaluation of the integral intensity of the O_2 ($^1\Delta_g$) glow of the entire layer of the earth's atmosphere in the vertical direction gives the value I = 36.5 MR, while on the basis of theoretical data, I = 20-44 MR.

Thus, the estimates of the integral intensity of the O_2 ($^1\Delta_g$) emissions and the vertical distribution of the volumetric emissions, as obtained from the results of measurements made from the "Salyut-4" orbital station, are in close agreement with the data from calculations and experiments with balloons and rockets.

During the flight of the "Salyut-4" station, a number of vertical brightness profiles of the atmosphere were obtained under different illumination conditions and in different geographical regions. In order to do this, the station was rotated, with a constant angular velocity, from its assigned initial position. The measurements were made on wavelengths of 1.35, 1.9, 2.2 and 2.7 μm with intake aperture resolution of about 7 km. When correlating the atmosphere's brightness profiles with the scale of the sighting lines' perigee altitudes, we used data on the sighting

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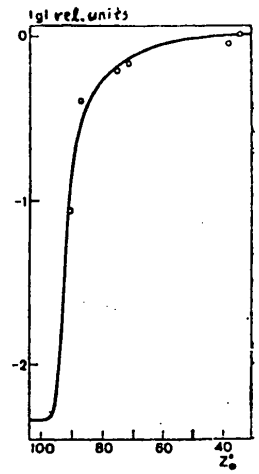

Figure 5. Daily pattern of intensity of molecular oxygen emissions. (Solid line -- data from balloon measurements; circles -- results of measurements made from the "Salyut-4"; $Z_\odot$ -- zenith angle of the Sun.)

lines' initial position and angular displacement rate and also analyzed the photographs taken with an on-board camera that was installed parallel to the "Micron" radiometer. The basic mass of measurements were made with large scattering angle values ($40^\circ < \gamma < 135^\circ$) and large solar zenith angles.

An analysis of the measurements showed that the shape of the atmosphere's brightness profile essentially depends on the state of the underlying surface -- its type, illumination conditions, cloudiness in the sighting lines' subperigee area. In principle each of the atmospheric brightness profiles that were obtained belongs, to a greater or lesser degree, to one of the following three types: profiles over sections of the earth's surface not directly illuminated by solar rays; over a diurnal, cloudless surface; over cloud cover illuminated by the sun.

The low absolute values of the b ightness of the earth's disk near the horizon are characteristic of the first type of profile. When scanning with a sighting line above the horizon, the brightness increases and reaches a maximum for a sighting line perigee altitude of 10-15 km. In profiles of the second type, from one to three maximums are observed in the 0-15 km altitude interval. One of them is usually found at altitudes of about 5 km (and in some cases directly on the horizon), while the other two are seen at altitudes of about 10 and 15 km, respectively. The latter two maximums sometimes merge into one, but this is apparently related to inadequate angular resolution on the part of the instrument. A characteristic of profiles of the third type is that

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the brightness of the diurnal atmosphere and the earth's disk below an altitude of 10-15 km remains on about the same level. Fluctuations in the brightness are caused by irregularities in the cloud cover's optical density.

At altitudes above 15-20 km, the differences in brightness profiles caused by the underlying surface become unnoticeable. (Young's) aerosol layer is manifested clearly in all brightness profiles. The supplementary brightness of Young's layer exceeds the brightness of pure atmosphere by an average factor of three, but in individual cases reaches a factor of five or six. The maximum brightness of Young's aerosol layer is reached at an altitude of 18-25 km.

An analysis of the data that have been obtained showed that as far as the accuracy of the spectral brightness measurements and correlation with the scale of the sighting lines' perigee altitudes are concerned, they can be used as initial data when solving the inverse problem of atmospheric optics -- calculating vertical profiles of the scattering coefficient and determining its aerosol component.

During the second expedition on board "Salyut-4," a series of measurements were made at the nadir for the purpose of defining more precisely the dependence of spectral brightness in the near infrared band of the spectrum on the sun's zenith angle $Z_\odot$ from such widely diversified natural formations as dense clouds and water surfaces. The effective diameter of the instrument's field of view at the level of the objects being measured corresponded to approximately 1 km.

Cloud brightness was measured on several orbits, with different $Z_\odot$ values, over the USSR and the Pacific and Atlantic Oceans. An analysis of the relationship $B_\lambda (Z_\odot)$ that was derived for dense cloud cover showed that it is almost cosinusoidal; that is, the deviations from it are not substantial. On this basis it is possible to conclude that in the solar zenith angle interval $10^\circ < Z_\odot < 80^\circ$, the rule $B_\lambda(Z_\odot)/\cos Z_\odot$ = constant is observed. The dispersion in the average brightness of individual cloud formations is apparently caused by variations in the structure and vertical thickness of the cloud fields. A thick vertical structure of the cloud cover causes the appearance of shaded sections that reduce the effective brightness in the instrument's field of view.

Such measurements were also made for the purpose of defining the $B (Z_\odot)$ more precisely for water surfaces. The spectral brightnesses of the Pacific and Atlantic Ocean water areas were measured, along with separate bodies of fresh water. As $Z_\odot$ decreases from 90° to 80°, on the average the brightness of water surfaces increases slowly, which is related to the decrease in extinction. In the zenith angle interval $40^\circ < Z_\odot < 80^\circ$, B_λ stays at almost the same level, but with a further reduction in $Z_\odot$ the brightness of water surfaces begins to increase abruptly. This phenomenon is related to the appearance of a mirror reflection from a water surface at the zenith.

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The results of measurements in the near infrared band of the spectrum that were made from the "Salyut-4" orbital station made it possible to define more precisely a number of optical atmospheric phenomena in the earth's twilight and diurnal atmosphere that were observed from space. We also obtained additional information on the energy-spectrum and spatial characteristics of several natural formations on the underlying surface.

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CONTEMPORARY PROBLEMS IN SATELLITE OCEANOLOGY

Moscow ISSLEDOVANIYE ZEMLI IZ KOSMOSA in Russian No 1, 1980 manuscript received 5 Sep 79 pp 55-63

[Article by B. A. Nelepo, The Marine Hydrophysical Institute of the Ukrainian Academy of Sciences, Sevastopol']

[Text] Studies of the ocean which have been made in the last decade have brought about a sharp change in concepts of the nature of hydrophysical processes which take place in its depths. The discovery of the synoptic variability of the ocean [1], related to the existence of eddy formations (with diameters of from tens to hundreds of kilometers) which travel at speeds of several kilometers per day is of particular importance in this field. The larger values of the orbital velocities (tens of cm/sec) and the considerable vertical dimensions which are commensurate with the depth of the ocean are the reason for the marked impact of these formations on large scale circulation systems. As is well known, the circulation of the ocean which arises as a result of the existence of temperature contrasts, nonuniform water density and the rotation of the earth, leads to a redistribution of the thermal and mechanical energy on a planetary scale. The turnaround in concepts of global circulation, related to the discovery of the synoptic variability of the ocean, has had an impact on all branches of fundamental and applied oceanology. The discovery of synoptic variability of the ocean became possible through the use of a qualitatively new procedure for studying the ocean: studies in hydrophysical test areas for which the combining of the efforts of all the leading oceanographic organizations of our nation and intense international cooperation was needed. Thus, modern oceanology needs the introduction of new procedures which provide for the continuous input of information on processes occurring in the ocean in a wide space-time range of the phenomena being studied.

As is well known [2], the major problems of contemporary oceanology are as follows:

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Fundamental	Applied
The creation of unified thermo-hydro-dynamic models of the ocean--atmosphere system for various space-time scales of the phenomena.	The prediction of wind waves, short term weather forecasting, the prediction of conditions of the ocean environment for the needs of marine navigation and the fishing industry, long range weather forecasting and the forecasting of tropical hurricanes.
The creation of ecosystem models.	The prediction of the biological productivity of individual regions and the entire world ocean for the efficient utilization of its food resources.
The creation of physical chemical models for the transport and accumulation of substances in the ocean.	The detection of regions which are of interest for the industrial extraction of mineral resources, monitoring the pollution of the ocean and the development of means to combat it.
Investigating the laws governing the spatial distribution of useful minerals at the bottom of the world ocean, primarily in shelf regions.	Detecting regions of interest for the industrial extraction of useful minerals from the sea bed.
Studying tectonic phenomena in the water areas of the world ocean.	Forecasting earthquakes and tidal waves.

An analysis of these problems shows that the primary research task is the design of the most diverse models of the ocean, the gradual refinement of which depends on the volume and nature of information accumulated or obtained over definite intervals of time. It is obvious that the development of models which adequately depict nature depends on the reliability of the theoretical concepts of the major hydrophysical processes in the ocean. Methodologically speaking, these problems can be solved at the present time by continuously monitoring either individual water areas of the ocean or the entire ocean as a whole, which is possible only on the basis of the functioning of a system of artifical earth satellites. When investigating these little studied processes, this monitoring can be assured by the operation of a comprehensive ship--buoy--satellite system.

Informational Hydrophysical Parameters. The experience with decoding the data received from earth satellites which has been acquired at the present time in various bands of the electromagnetic spectrum gives

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evidence of the promise for its utilization in studying the physical processes in the world ocean [3-5]. The surface of the ocean has been studied in the Soviet Union for a number of years from space by means of the "Salyut" orbital stations, as well as the "Kosmos" series of space vehicles. The transfer function of the atmosphere, which has an influence on the determination of ocean characteristics was studied [6] from the low orbiting "Kosmicheskaya Strela" satellites ("Kosmos-149" and "Kosmos-320").

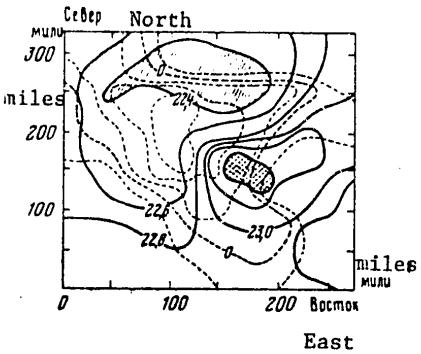

Figure 1.
Isotherm deformation at the surface of the ocean with the action of a synoptic eddy. The eddy boundaries are indicated by the dashed lines.

Studies of the emissions of the earth and ocean in the centimeter and infrared ranges were carried out with the "Kosmos-243" and "Kosmos-384" satellites. This information was supplemented with the data of the "Meteor" series meteorological satellites [7-9]. A procedure for relaying oceanological information from a buoy through a satellite has been developed [10].

The first specialized Soviet satellite for ocean research, the "Kosmos-1076", was successfully launched in February of 1979; this satellite provides for observation of the ocean in the visible, infrared and SHF bands. This satellite is also the main component of the existing satellite--buoy--ship system which substantially expands ocean research possibilities.

At the present time, it is now possible to formulate the minimum requirements which must be placed on the precision of the determination of hydrophysical parameters, working from the major problems of oceanology. Naturally, this precision is determined on the basis of the specific features of specific oceanological problems. The major requirements concern measurement precision, spatial resolution and the width of the ocean region under study which is taken in, time averaging and the read-out frequency. Apparently, the optimal solution consists in a compromise approach to satisfying each of these requirements.

We ahall consider the specific oceanographic parameters, the possibilities for the determination of which by direct and indirect methods are combined with the requisite level of information content: the temperature of the ocean surface: the depth of occurrence and intensity of a

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discontinuity layer, the velocity and direction of currents, salinity at the surface of the ocean, wave height and the direction of wave propagation, the temperature of the portion of the atmosphere near the water, air humidity, velocity and direction of the wind, cloud cover, radiative energy flux, the extent of ice coverage of the ocean surface and the degree of pollution of the sea surface.

The Ocean Surface Temperature. The temperature of the ocean surface is one of the most important and informative hydrophysical parameters. At the present time, the temperature field can be determined from the inherent radiation of the ocean in the infrared and SHF bands. As a result of this, the following problem can be solved: the study of the synoptic variability of the ocean, the singling out of frontal zones and zones of strong currents, and the investigation of the structure of the active layer of the ocean.

Mesoscale Variability. The results of shipboard observations show that the temperature field of the ocean surface is subordinate to a substantial extent to the nature of eddy motion in the main oceanic thermocline. In this case, the fundamental features of the distribution of the temperature are due to the advective eddy currents, which perturb the major regional temperature distribution. In contrast to the circulatory nature of eddy current motion in the main oceanic thermocline, the distribution of the ocean surface temperature is determined [11] by the intrusive nature of isotherm displacement (Figure 1). The characteristic formations in the upper layer of the ocean have a scale of 40--400 km. Their average rate of spatial travel is 5--8 km/day. The temperature gradients for the indicated scales amount to 0.2--2.0° C in the regions of influence of abyssal synoptic addies and 2--3° C in regions where there are intensive formations of the Gulf Stream ring type. The identification of synoptic eddy formation from their appearance in the temperature field of the ocean surface makes it possible to estimate both the kinematic characteristics of the eddy formations and the nature of the interaction of the upper boundary layer of the ocean with the oceanic thermocline layer.

Temperature Anomalies. Temperature anomalies are traced against the average climatic background as formations with typical spatial scales running from hundreds to thousands of kilometers, characteristic lifetimes from noths to tens of months and a depth capacity running to tens of meters. Their amplitudes (extreme deviations from the climatic norm) reached 2--3° C, and because of the considerable thermal inertia of the ocean as compared to the atmosphere, there anomalies exert a significant influence on the weather on a planetary scale. The primary requirements placed on the results of remote sounding, which make it possible to trace the evolution of these anomalies, consist in the width encompassed for the regions of the ocean and the data arrival rate. The derivation of amps of the surface temperature on scales of the entire ocean with a frequency of one to two times per week is the most optimal. Spatial resolution in this case should be 30--50 km, and the precision in the determination of the temperature should be no worse than 0.5° C.

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Frontal Zones and Zones of Strong Currents. These phenomena are rather well defined at the present time. For this reason, the major task is the study of such characteristics as the variability of the axes of the fronts and flows, meandering and stability. The main attribute of these formations is temperature drops at boundaries, running up to 10° C, something which makes it possible to detect them reliably in the infrared and SHF bands. In the case of such temperature contrasts, the measurement precision can amount to 0.5-1.0° C, however, the spatial resolution should fall in a range of 1--2 km. We will note that the information on the position of frontal region boundaries is likewise contained in data on the color index and many other characteristics.

The structure of the active layer of the ocean. The upper active ocean layer is the major link in the interaction processes between the ocean and the atmosphere. Its investigation should be based on data on surface temperature, the position of the lower boundary of the quasi-homogeneous layer, and the depth of occurrence of the density discontinuity layer. The temperature and thickness of the quasi-homogeneous layer determine the power of the temperature anomalies (the heat content and lifetime), which must be accounted for in weather forecasting problems, and additionally, the position of the discontinuity layer determines the lower boundary of the active photosynthesis region in the upper layer of the ocean.

Theoretical models exist which allow for the determination of these parameters based on the results of remote sounding. The input parameters of such models are the atmospheric temperature, the radiative energy flux, the wind velocity, humidity, pressure and cloud cover. In the case of calculations based on existing models, a precision of 0.1° C in the measurement of a temperature and 1 m in the position of a discontinuity layer are required. When such accuracy is achieved, it proves to be possible to calculate the heat plus at the boundary of the discontinuity layer and determine the heat input into the main oceanic thermocline.

In reviewing the considerations related to the determination of the ocean surface temperature, one can compile a list of requirements which are nec ssary when studying phenomena on different scales (see the Table).

The Requirements Placed on the Determination of the Ocean Surface Temperature

Scale of the Phenomenon, km	Precision, °C	Resolution km	Periodicity days
400 and more	1	30-50	0.2-0.1
400-500	0.2-0.5	10-15	0.5-0.3
50 and less	0.1-0.2	3-5	1.0
Gulf Stream rings (70-200)	0.5	5-10	0.5-0.3
Frontal regions	0.5-1.0	1.2	0.3-0.2

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The Radiation Balance of the Ocean--Atmosphere System. The successful functioning of meterological satellites has made it possible to obtain extensive data on the radiation balance of the earth--atmosphere system and its components. It has turned out that the satellite data on the conditions of the oceans show a lower albedo and greater levels of emitted long wave radiation [12]. Work to determine the radiation fluxes at the surface of the ocean based on satellite measurements [13] has been done, and the theoretical possibility of a unique solution has been demonstrated for problems of finding the normal values of the total solar radiation, albedo, effective long wave radiation and the radiation belance at the ocean's surface from satellite data.

The Temperature of the Atmospheric Layer Near the Water. The temperature of the atmospheric layer near the water is one of the most informative parameters of models of the ocean and atmosphere interaction. It determines primarily the rate of heat entry into the ocean as a result of contact heat exchange with the atmosphere.

Wind Velocity. In calculations of the local structure of the active ocean layer, an informative parameter is the absolute value of the wind velocity, which enters into formulas describing the heat balance at the ocean's surface, the rate of delivery of mechanical energy to the intermixed layer and the dissipation of mechanical energy in this layer.

Atmospheric Pressure. In the formulas for calculating the heat balance components at the surface of the ocean, the pressure level in the layer near the water is of no substantial importance. For example, in a range of pressure variation of 920--1,080 mbar, an error in the determination of the pressure ± 1 mbar introduces a 1 percent error in the determination of the corresponding components of the thermal balance.

Air Humidity. The humidity of the air in the ocean layer near the water is included in the formulas for calculating the heat losses due to evaporation and the outgoing long wave radiation, which in a temperature range of 12--32° C can be computed with a precision of down to 1 percent from the following formula: where e is the water vapor pressure, mbar; n is the amount of cloud cover [on a 12 point scale]. The specific humidity of the saturated vapor, which determines the evaporative heat losses in a temperature range of 18--26° C and a pressure of $\simeq$1,000 mbar with 1 percent precision, is a linear function of T_s. Considering the fact that the saturated vapor pressure under actual conditions will fluctuate in a range of 2--50 mbar, it can be assumed that the requisite precision in the calculations of the relative humidity amounts to $\pm$ 1 mbar.

The Velocity and Direction of Currents. The design of high precision radio altimeters, which make it possible to measure large scale slopes of the level of the oceanic surface, is becoming a feasible reality. The utilization of the dynamic method requires an especially precise measurement of the deviations of the oceanic surface from the equilibrium

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position from satellite altimetry. For example, with a current velocity of 10 cm/sec, the level drop transverse to the axis of flow on a 10 km scale should amount to 10 cm [5]. In this case, the precision in determining the altitude difference with an error of 20 percent should amount to about 2 cm. The results of the operation of such an altimeter as part of the on-board equipment of the U.S. "Seasat" oceanographic satellite gives evidence that the planned precision of this instrument of ± 2 cm has already been attained at the present time.

The Chromaticity of the Ocean. In the open ocean, at a sufficient distance from the shores, the primary factors which determine the optical properties of the waters are substances of biological origin: phytoplankton and zooplankton, detritus and dissolved products of their decomposition. In regions near the shore and in regions where continental waters are drained, terrigenous suspensions and dissolved substances of mineral and organic origin are added to them.

The presence of impurities in the water leads not only to scattering, but also to the absorption of radiation in visible range of the spectrum, something which in turn leads to sharp changes in the spectral characteristics of the radiation emitted from sea water. Thus, the cells of phytoplankton which contain chlorophyl, carotinoid and other pigments, the absorption coefficient of which take on high values in narrow portions of the spectrum, are the cause of the occurrence of narrow bands in the spectra of ascending radiation. A reduction in the radiation flux in regions around 550 nm is characteristic of areas with high concentrations of phytoplankton.

The Study of the Ocean Depths. The Skin Layer. At the present time, the use of remote sounding equipment is limited to studies of just the most upper layer of the ocean. Thus, with the use of infrared and SHF equipment, there arises the problem of interpreting the data on the ocean as regards the existence of a thin skin layer at its surface, within which the thermodynamic properties of the medium differ sharply the properties of the top homogeneous layer. Laboratory and full scale experiments have demonstrated that a temperature gradient of 0.4-2.0° C can take up a depth of 1 mm, and this cold film is preserved with winds of up to 10 m/sec, i.e., even under conditions of developed wave agitation. Despite several reasons which account for the destruction of the cold skin layer, its restoration takes place rather rapidly. According to experimental data [14], its restoration time amounts to about 12 seconds. Thus, it can be concluded that the existence of a cold surface film in the ocean is a ubiquitous phenomenon and on the average, is stable with time. Until we know the true temperature distribution in the skin layer, as well as the law governing its horizontal distribution at the surface, the lack of precision in the determination of the characteristic of the upper homogeneous skin layer using remote sounding methods will substantially reduce the information content of the data obtained. Thus, the problem of studying the skin layer of the ocean is one of the most important in satellite oceanology.

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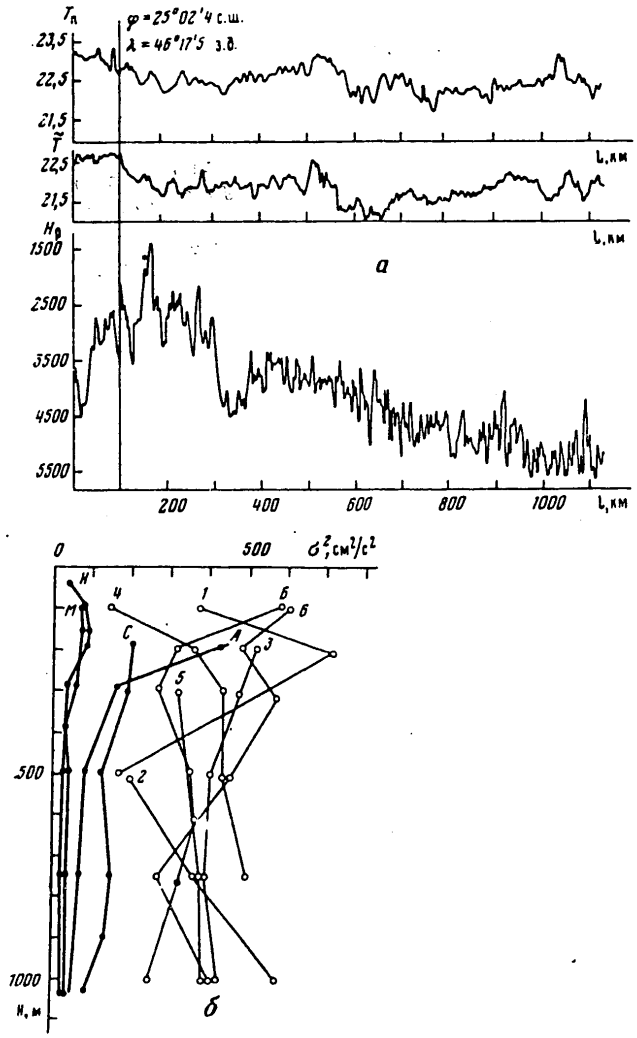

Figure 2. Experimental studies of internal waves.

Key: a. Synchronous recordings of the ocean surface temperature (T_s) and the integral temperature ($\tilde{T}$), plotted from echograms of the bottom relief of the ocean (H_p); b. The depth distribution (H) of the total dispersion of the current velocity fluctuations, ^{2}, in various regions of the world ocean.

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Internal Waves. Theoretical and experimental studies of internal waves in the ocean, as well as their interaction with wind waves have opened up remarkable prospects in recent years for studying not just the surface from space, but also the depths of the ocean. It has been shown in theoretical studies [15] how irregularities such as oceanic ridges, canyons, individual mountains, depressions and shoals generate internal waves, where the characteristics of these waves depend substantially on the properties of the obstacle. It has been found that synoptic eddies are likewise generators of internal waves. Experimental studies in the region of such formations has confirmed these calculations [16] and have made it possible to obtain additional characteristics of the generation of internal waves by the specific relief features of the bottom and the structure of the waters in the area of synoptic eddies (Figures 2a and b) [16].

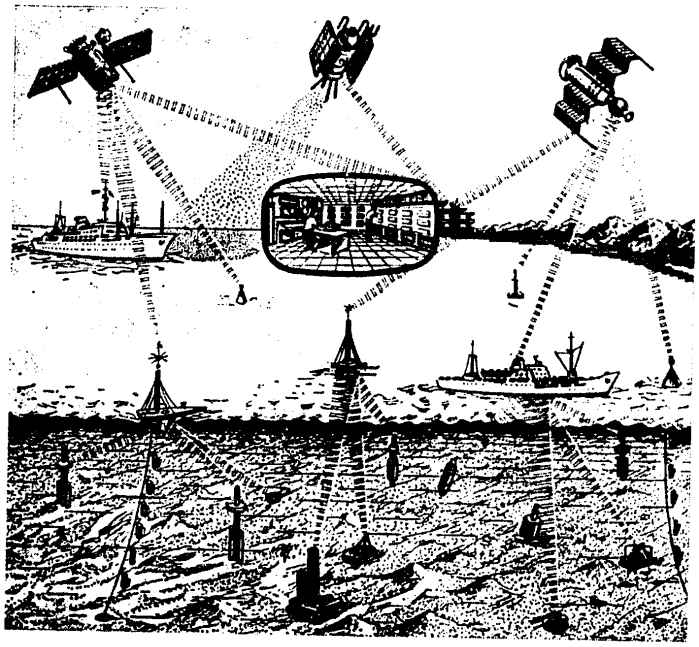

Figure 3. Space studies using earth satellites.

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Special experiments devoted to the study of the interaction of internal and surface waves have shown that this interaction leads to a distortion of the spectrum of surface capillary waves. This fact can be ascertained using methods of microwave scatterometry, as well as in the visible range of the spectrum as a result of the existence and transformation of slicks on the ocean's surface [1]. Although just the first steps are being taken in this new field of ocean study from space, such research is extremely promising.

Providing for Measurements Beneath Satellites. What has been said above shows that frequently the multiplicity of little studied phenomena leads to a distortion of the satellite information obtained. Moreover, the methods of remote sounding from satellites are a new tool in the hands of oceanologists and differ fundamentally from the traditional methods, primarily in the spatial averaging of the measured characteristics. This makes additional demands on the organization of the accompanying measurements in the network of test and calibration test areas, which are necessary for the correct interpretation of the data obtained. The dimensions test areas should be an order of magnitude greater than the resolution element of the measurement system, which is based on space vehicles. By combining the work in test areas using contact and remote equipment, one can provide for reliability in the interpretation of the results, especially in the initial stages of the work.

The Possibilities and Prospects for Satellite Oceanology. At the present time, the contribution of remote methods to ocean research using the tools of space technology is as yet inadequete. This is primarily related to the necessity of designing new equipment, as well as the methods of processing and interpreting the measurement results. Modern methods of remote sounding, in contrast to contest methods, yield only a two-dimensional depiction of the processes developing in the depth of the ocean. To interpret these data, it is necessary to develop completely new theoretical approaches to the resolution of the problem. For this reason, the practical value of satellite oceanology in the coming decade will depend in many respects on the intelligent combination of new and traditional procedures of ocean research. The methods of satellite oceanology are at their base methods of large scale studies which make it possible to realize the operationally timely surveying of extensive water areas, and to provide an overall idea of the dynamics of the processes taking place. The role of sp ce vehicles does not consist in replacing scientific research ships and buoy measurement tools. The most reasonable approach is to conduct the research in such a way that the satellites provide for globally encompassing the water areas of the world ocean. Stationary buoy systems will provide for the functioning of a reference network of measurement points, similar to the way meteorological satellites provide for observations of a ground network of meteorological stations. Scientific research vessels in this system will become a tool for studying processes which take place rapidly, as trigger processes, which will make it possible in the future to refine the operation of the system

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as a whole. A large part in such a plan also belongs to drifting independent measurement buoys, the servicing of which can be accomplished only from scientific research vessels (Figure 3). The experience in studying the oceon from orbital stations and space vehicles has demonstrated that great seccesses in this new field of research can be anticipated in the years just ahead.

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HOPES AND REALITIES OF OCEANOLOGY FROM SPACE

Moscow ISSLEDOVANIYL ZEMLI IZ KOSMOSA in Russian No 1, 1980 manuscript received 10 Aug 79 pp 64-78

[Article by K.N. Fedorov, Institute of Oceanology imeni P.P Shirshov of the USSR Academy of Sciences, Moscow]

[Text] Introduction. The rapid development of space technology over the last two decades has opened up new enticing possibilities for researchers of our planet earth, including oceanologists. It has turned out that near earth orbits can be a very convenient place to position observation and measurement equipment for gathering important scientific information on the world ocean. A new scientific field which consists in developing methods of gathering data on the ocean and its resources from space, and which is sometimes not entirely correctly called "space oceanology", has begun to develop rapidly. Right now, this field is in the stage of the gradual realization of existing possibilities and those being newly discovered, as well as the inevitable stage in science of gaining insight into the ratio of the real and imaginary values of the proposed methods. It is specifically for this reason in the given stage that it is very useful to analyze the successes and failures which have occurred in order to separate reality from allusion and direct the main efforts in this field towards achieving that which ocean researchers are primarily in need of and that which is now actually feasible within the framework of the existing technical resources. The major achievement in this area over the last few years (here in our country and abroad) can be considered the clear realization by professional groups of oceanologists of the fact that remote space tools and methods are not the bases for an entirely new science of the ocean, but are only an important addition to the already operating arsenal of modern "contact" tools and methods of oceanology. This understanding of the problem makes it possible to consider all the knowledge of the ocean which has already been acquired over the last entire century of scientific oceanology, and to apply new methods where they are the most efficient from the viewpoint of profitability and obtaining new knowledge. The real possibility of the intelligent setting of technical assignments for the

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design of measurement instruments and sets of scientific equipment for space vehicles follows from this same understanding. This in turn is a guarantee of obtaining not simply information, but rather useful information on questions of interest to researchers.

This history of oceanology as a science is rich in examples of the implementation of new tools and methods of research. The introduction of the capsizing deep water thermometer in the middle of the last century determined the procedure for hydrological soundings in the ocean for the entire next 100 years, but was also the reason for a number of enduring scientific errors concerning the turbulence and structure of the waters of the ocean. More than a decade (1965-1975) went to the mastery of modern hydrophysical probes and methods of working with them. The time which was spent, however, was rewarded with the discovery of the fine thermochaline structure and the fine layer nature of the motion of ocean waters. The introduction of space tools and methods in the practice of oceanology must be regarded in many respects as being completely similar. And if the absolutely necessary work in the field of procedures in combined with the pioneering efforts to apply the new data to the solution of oceanological problems which have been around for a long time, then the most interesting scientific results will not be slow in coming to life. It is specifically for this reason that it would be entirely incorrect to limit ourselves in the given stage to the solution of just some problems of a purely methodological nature.

Space oceanology as such actually begins only there where the data obtained using space tools is used directly to study the ocean. While the published works of the beginning of the 1970's [1-4] primarily cited various examples of the possible application of remote methods of oceanology, as well as the data obtained by these methods, over the last two to three years studies have appeared [5-8] which would have been impossible without relying satellite data. Thus, authentic space oceanology (if we are to use this unfortunate term) is already taking its first steps. These steps are all the more important since new generations of oceanologists will learn from them, for whom the data on the ocean obtained from space will become a natural part of their daily scientific work. In taking the steps, we are learning to find the combinations of remote methods of ocean research and traditional "contacts" methods which are the most advantageous from the viewpoint of the scientific result and material expenditures. We are convinced that this is the only true course.

This article is not a review. Those desiring to become acquainted in detail with the capabilities and prospects for ocean research using remote methods can refer to the existing review literature [9, 10]. The most important thing at this stage is to ascertain those most pressing tasks from which the transition from procedures to daily practice must be begun. The following sections of the article are devoted to just this.

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Urgent Problems of Contemporary Oceanology and the Adequacy of the New Method. The Temperature of the Ocean's Surface. Because of new measurement methods, the variability of the physical characteristics of the world ocean was completely realized for the first time over the past decade [11]. Along with this came the understanding that the study of this variability can cast light on the interaction of numerous physical processes which participate in the complex equilibrium which provides for the average natural state of the ocean. One of the most important physical characteristics of the ocean, the variability of which scientists would most of all like to study is the ocean surface temperature (TPO). Orbital equipment opens up the possibility of quasisynoptic (practically instantaneous on the scales of ocean variability) surveying of all the water areas of the planet and measurement of the radiation of radio brightness temperature of the water surface in the infrared or SHF bands. Oceanologists have never had this capability before. And just how reliable, precise and useful is the satellite information on the TPO being received at the present time, and what are the prospects for improving its quality?

Despite the promise and the all-weather capability of the SHF methods being developed, the most reliable and procedurally ironed out remote tool for TPO measurements for practical purposes is and apparently will be for a long time, infrared radiometry. This point of view was once again confirmed at the recent colloquium of the IUCRM on passive radiometry of the ocean (Canada, Patricia Bay, 14-21 June 1978). And in fact, all of the regularly operating satellites of the well-known NOAA series, the "Nimbus", GOES and "Meteor", have scanning IR radiometers in their set of scientific equipment to obtain images of the heat picture of the surface of the earth, including the ocean. Those as yet few fruitful studies of the thermal field of the ocean's surface, which were based on airborne and space data [5-8, 12, 13], were all without exception based on the use of the infrared band, frequently in conjunction with measurements in the visible band (to take the influence of cloud cover into account).

The spatial resolving power of the VHRR scanning IR radiometers with ultrahigh spatial resolution of the NOAA series satellites (about one kilometer) and the "spin-scan" radiometers of the GOES geostationary satellites (about 8 km when viewing an entire hemisphere) is completely satisfactory for oceanologists. A comparison of shipboard and satellite measurements of the TPO up to now reveals deviations in individual pairs of values from each other in a range of $\pm 5^{\circ}$ with an extremely stable mean square difference of about $\pm 1.5^{\circ}$ [14, 15]. This is evidence of the entirely adequate sensitivity of infrared measurement equipment, and at the same time indicates the considerable difficulties in establishing an absolute relationship between the values of the radiation temperature measured from satellites, as well as the lack of comparability of the spatial averagings, which are unavoidably related to the two different methods. The opinion has been put forward repeatedly that the problem

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of precision in the measurements of the TPO in the infrared band can be completely solved if we learn how to correctly account for the absorbing and distorting influence of the atmosphere, which nonetheless remains considerable even in specially selected transmittance windows.

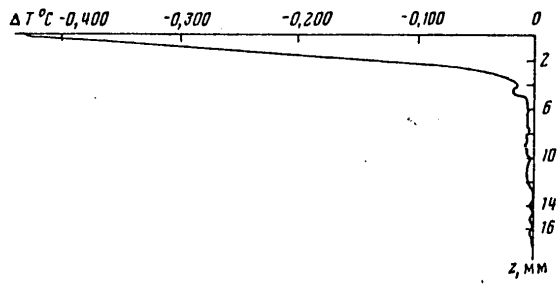

Figure 1. A cold heat exchange "film" about 5 mm thick close to the water--air separation surface in the water, which is cooled through the free surface. The values of ΔT are deviations in the water temperature from its values at the 18 mm level (°C).

However oceanologists have their doubts on this score, which are related to the fact that depending on the conditions for heat exahange between the ocean and the atmosphere, the difference between the ocean surface temperature and the water temperature in the lower lying surface layers can fall in a range of from -1 to +3° C [16-18], where individual authors believe [18] that even more significant deviations can occur at the lower limit (down to -3° C). Vertical temperature profiles in the upper thin layer of water are shown in Figures 1 and 2 for the case of a negative thermal balance of the free surface (the laboratory experiment of [16]) and a positive thermal balance of the upper layer of the ocean (the full scale measurements of the author and V.T. Paki). It can be seen quite well that in the first case (Figure 1), with entirely natural values of the overall thermal losses by the water surface (about -63 watts/m^2), the temperature drop in the upper layer which is 5-6 mm thick exceeds -0.4° [16]. In the second case (Figure 2), the daytime radiation heating in still weather brought about a temperature gradient of +3° C between the surface and the 8 m level. Such a large temperature gradient in the case of the freshening of the near surface layer of the ocean by rain, based on observations by the author of this paper, can be concentrated in a layer with a thickness of less than 1 m, as a result of which, the difference between the readings of a radiation thermometer and the thermodynamic temperature at the 1 m level on a clear sunny day can reach 1-3° C. On the other hand, the observations show that at the moment the rain falls, the radiation temperature of the ocean's surface can fall off by 1-2° C [19], as the thermodynamic temperature close to the surface usually drops by 0.2-0.3° C.

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All of these differences are of the same order of magnitude with the above indicated ambiguities in the estimation of the TPO based on the data of IR radiometers. They will undoubtedly remain in force after the most strict accounting for the influence of the atmosphere. And although a number of heat exchange effects yield to calculations [20], others nonetheless remain unpredictable in connection with the a priori lack of knowledge of the vertical salinity profiles within the bounds of the upper one to two meter layer of the ocean. In view of what has been said above, assertions are frequently encountered that the scientific utilization of infrared measurements of the TPO is impossible until a final solution of the problem of accounting for atmospheric influence; this position cannot be acknowledged as either substantiated or useful. The papers cited above serve as a proof of this [5-8]. Today's increase in interest among oceanologists in oceanic fronts, their formation (frontogenesis), evolution and travel [21] suggest ways to use utilizing the regularly obtained IR images of the ocean surface for the analysis (including statistical analysis) of the positions and motions of frontal interfaces in the ocean. For this purpose, it is not the absolute values of the radiation temperature which are important, but rather its local contrasts [22]. In this case, the identification and accounting for interference due to cloud cover takes on the greatest importance, rather than the corrections for absorption by water vapor or aerosols. Despite the fact that in the range of TPO measurements in the infrared band, the procedural and technical aspects do not fundamentally represent insupperable obstacles for oceanologists, nonetheless, we do not have here in our nation regular monitoring of the TPO of the desired quality because of a lack of scanning infrared radiometers of the requisite sensitivity and spacial resolution. As a result of this, research institutes and laboratories engaged in the study of the ocean do not receive valuable scientific information which would be obtained in the case of an efficiently thought out organization of the matter on a nationwide scale.

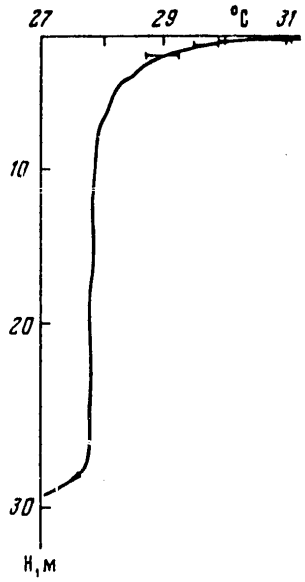

Figure 2. The daytime radiation heating of the near surface layer of the ocean. The horizontal line segments are the limits of short period fluctuations (the data of the 27 voyages of the scientific research ship "Akademik Kurchatov", 1978).

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Measurements of the Ocean Level. Over the course of a century, fluctuations in the levels of oceans and seas were measured only along the shores and on islands. Only in the last decade has measurement engineering made it possible to measure variations in the level on the open ocean by means of bottom tidal gauges, positioned at selected points on the bottom of the ocean. However, oceanologists have never had the tools to obtain an instantaneous picture of the surface topography of the ocean, which would make it possible to qualitatively and quantitatively assess tides, currents, eddies and wind surges. The possibilitite of obtaining such a picture were opened up for the first time by satellite radar altimetry. Those desiring to become familiar in more detail with the operational principles of an orbital radio altimeter can do this either from primary sources [23-25] or review papers [9, 10]. Here, we shall cite only the basic requirements based on the precision and resolving power of the measurements, which follow from the fact that oceanologists already know the shape of the relief of the free surface of the ocean.

The Geoid. The geoid is understood to be the equipotential surface in the gravitational field of the earth, which only under specified conditions can agree with the unperturbed mean sea level. The geoid is an irregular surface, which deviates substantially from an ellipsoid of rotation. These deviations of geoidal relief fall in a range of ± 100 m, while the deviations of oceanic relief do not exceed ± 10 m. One can become familiar with the problems of altimetric measurements of the geoid in paper [26].

Oceanic Currents. Strong surface currents cause marked variations in the level of the ocean surface. The greatest level variations have been registered in the region of the western boundary currents. Based on the data of [27], deviations in the level of the Gulf Stream amount to 3.5 m at 300 km. The eastern boundary currents, such as the California current, are characterized by significantly smaller anomalies in the level, which do not exceed 34 cm over 1,000 km [28].

Meanders and Eddies. The wavelength of meanders of large currents, as a rule, falls in a range of 100-300 km. Their travel velocity is such that a typical meander (for example, the Gulf Stream) covers a distance equal to the wavelength over a time on the order of two months [27]. Changes in the ocean's surface relief amounting to about 1 m over 100 km are characteristic of phenomena on this scale. Eddies which are formed in the process of the separation of the meanders from the main stream of a current ("rings" of a current), are characterized by relief variations of the same order of magnitude.

In the more general case, a typical eddy which is somewhat remote from the Gulf Stream, has a cross-section on the order of 100 km, in which case the velocities of the current in it can reach three knots, which at a latitude of 40° should lead to a contrast in the topographical relief of about 30-40 cm. As was noted in [28], eddies remote from the main

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boundary currents and which arise as the result of the action of other mechanisms, have a cross-section of 200 km and move at a velocity of about 5 cm/sec for a current speed in them of up to 20-25 cm/sec. Such eddies produce less marked variations in the topographic relief (on the order of 5-10 cm).

Inclines of the Water Surface Close to Shores. The ocean level close to the shore line of continents frequently deviates substantially from the mean value. Thus, for example, close to the shores of the North American continent, both on the eastern and the western side, the ocean level is 60 cm above the mean level, while the mean level of the Pacific Ocean close to the shores of the United States is 60 cm greater than the level on the Atlantic coastline [28].

Flood Tides, Wind Wates and Tsunamis. Flood tide and ebb tide phenomena on the average over the world ocean (with the exception of coastal regions) cause level fluctuations in a range of ± 1 m. Wind caves (capillary and gravitational) likewise change the relief of the ocean's surface. While the impact of capillary waves can be disregarded because of their small height (1 mm-1 cm), gravitational waves lead to considerable variations (on the order of several meters) in the surface relief.

Altimetric measurements can be of especially practical significance in the timely alerting of coastal regions of the occurrence of tsunami waves in the open ocean. However, it must be kept in mind that the surface rise in the open ocean with the propagation of a tsunami wave does not exceed 0.5 m and can be detected only with highly sensitive equipment.

Storm and Wind Surges, the Effect of Atmospheric Pressure, etc. Storm surges and drops, which occur close to shores can have an amplitude on the order of several meters. Level fluctuations caused by a change in atmospheric pressure are small on the whole, and as a rule, do not exceed 10 to 30 cm.

Fluctuations on the level likewise occur because of nonuniformities in the moisture circulation process (evaporation, precipitation, shore drainage). A dependence of the level on changes in water density is likewise known. In basing our arguments on the treatment of the specific topographical features of the oceanic surface considered above, the conclusion can be drawn that it is necessary to have a rather high level of resolving power for an orbital altimeter - on the order of 10 cm - for the purpose of obtaining information which is of interest to oceanology.

The mean square deviation of the readouts of the radio altimeter installed in the American GEOS-3 satellite, launched in 1975, is ± 70 cm [25], something which has already made it possible to solve a number of oceanological problems, for example, such as the determination of the boundaries of large currents based on sharp changes in the level. The data of the

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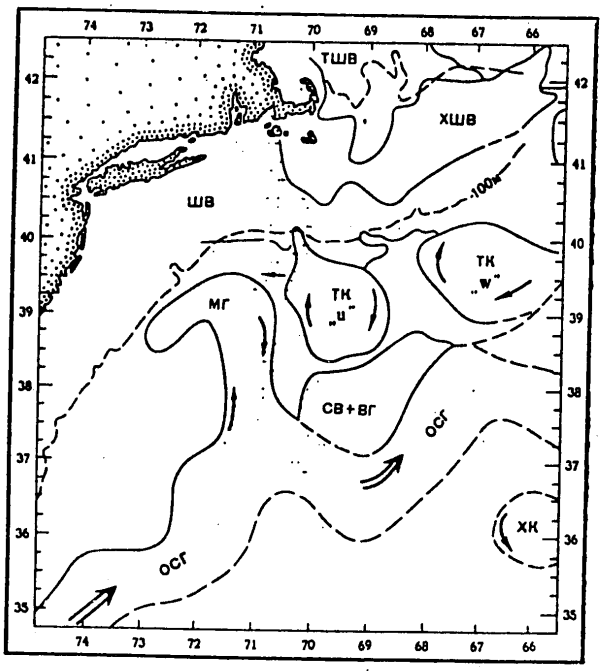

Figure 3. An example of a map of the experimental analysis of fronts for 23 August, 1978 (a copy from the American original):

Key: ШВ = Shelf waters;
ТШВ = Warm shelf waters;
ТК = A warm "ring";
ХК = A cold "ring";
ОСГ = The main stream of the Gulf Stream;
МГ = Gulf Stream meander;
СВ = Slope waters;
ВГ = Gulf Stream waters.

GEOS-3 satellite radio altimeter has already been used on a weekly basis for the experimental analysis of oceanic fronts (Figure 3) in the U.S. Even the first radio altimeter, which was installed in the "Skylab" orbital laboratory yielded extremely interesting information on the topography of the water surface above bottom depressions and elevations (9, 10, 29]. A map of the topography of the ocean's surface in the region of the Gulf Stream and the Sargasso Sea has also been successfully reproduced based on data from low trajectories of the GEOS-3 satellite [25, 30].

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The theoretical solvability of the engineering difficulties related to the use of radio altimeters from near-earth orbits, and the presence of clear cut requirements placed on measurement precision on the part of oceanologists are sufficient conditions for the development of the appropriate equipment here in our country.

The State of the Sea Surface (Wave Agitation), Drift Current and Wind (Velocity and Tangential Stress). Active sounding of the ocean surface using synthesized aperture radar (RLSA) will apparently be an extremely effective tool which allows for the study of the parameters indicated above from earth satellites. In principle, such a rader shuuld be included in a universal microwave complex, which incorporates all operational modes of an SHF radiometer, a radio altimeter, a scatterometer and a side-looking radar [10]. The data which can be obtained by means of such a complex could be used in forecasting navigation conditions on sea routes and in calculations of optimum ship navigation routes, taking weather conditions into account. For this reason, work with such a complex of equipment should be of the greatest interest for organizations which manage forecasting and sea navigation. The scientific research potential of such work is not altogether clear because of the high degree of variability of the parameters enumerated above. For work in physics and power engineering, the interactions of the ocean and the atmosphere at the present stage need precise contact measurements in the boundary layers of both media. Very precise tying of satellite to the corresponding systems of contact estimates of wave agitation intensity and wind, as well as the procedural and scientific research development of many intermediate stages are needed for systematic monitoring of the energy exchange between the ocean and the atmosphere on a global scale. Primarily required for this are airborne experiments with simultaneous contact (shipboard measurements of sea agitation and all the other numerous parameters which characterize the interaction of the ocean and atmosphere, as well as fundamental studies of the mechanisms of small scale and intermediate scale interaction of the ocean and atmosphere.

Measurement of the Salinity of the Surface Waters of the Ocean. The possibility of systematically mapping the salinity of the surface waters of the world ocean and following its variability in quasireal time would be extremely enticing to oceanologists. It would be all the more enticing since salinity measurements in oceanographic practice require more work than temperature measurements, and for this reason, they are practically never done with that spatial frequency and regularity which would make it possible to assess the entire spectrum of space-time variability. Specialists in passive SHF radiometry have repeatedly indicated the possibilities of remote measurements of salinity from aircraft and satellites [4, 31, 32]. We shall briefly assess the actual possibilities of the SHF method based on the information cited by them from the viewpoint of oceanologists. The most suitable band is apparently the 20-30 cm wavelength range, since at shorter wavelengths, the effect of the salinity

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is neglectibly small, and at longer wavelengths, space noise, reflected from the earth's surface, variable absorption in the ionosphere and interference of artificial origin have an influence. In order to estimate the possibility of salinity measurements using a microwave radiometer, one can make simple numerical estimates. If a wavelength of $\lambda = 20$ cm and an average ocean surface temperature of 15° C are chosen, then the estimates show that for this wavelength, a salinity change of 1 $^{0}/_{00}$ causes a change in the radio brightness temperature on the order of 0.3° K. We will note that at the present time, the measurement precision of radio brightness contrasts of the subjacent surface from a satellite amounts to about 1° K, while the salinity in the ocean changes by no more than 3-4 $^{0}/_{00}$ when making a transition from the equator to higher latitudes. Considering the fact that in the majority of open ocean fronts, the salinity gradients rarely exceed 0.5 $^{0}/_{00}$, we must unfortunately recognize that remote measurements of salinity changes in the frontal zones of the world ocean are as yet impossible, no matter how desirable and important they are to us.

The conclusion can be drawn that in the near future, one should actually count on only the indication of the separation boundaries of fresh and salt waters, as well as sharp anomalies in a salinity field (in the fresh water regions of the ocean, at the mouths of the large rivers).

The First Important Successes. The first important successes in the area of the application of remote data directly to the study of the ocean and its resources, as frequently happens, did not at all come where they were anticipated most of all. The profile of the surface temperature of the Pacific Ocean along the meridian, which was obtained from microwave data from the "Kosmos-243" satellite [1, 10] and which made the rounds of several journals, although also being evidence of considerable technical accomplishments, cannot be considered a success in an oceanographic sense, since this profile did not add anything to what we already had known for some time about the ocean. In our view, those examples of the use of aerospace data, which could substantially expand our knowledge of the ocean, are to be considered scientific successes. It is not difficult to enumerate and briefly consider these successes.

1. Observations of Oceanic Eddies. The first extremely interesting observations and measurements using an airborne IR radiometer made it possible to describe the formation and evolution of an anticyclonic (warm) Gulf Stream ring [33]. The development of satellite methods has brought about a combining of the efforts of the scientists of academic institutions and departmental services of the U.S. The results of 14 months of satellite and ship observations of cyclonic eddies in the western portion of the Sargasso Sea were presented by the authors of paper [12] in 1973, where these observations showed that: the eddies are formed in the region of Cape Hatteras and move in a southwest direction at an average velocity of about one mile per day; the absorption of the

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eddies by the Gulf Stream in the region of the Florida peninsula is quite probable; the possible lifetime of the eddies is on the order of two years. Later R. Legeckis [34] succeeded in making a film demonstrating the motion of eddies along the western border of the Gulf Stream at the Florida peninsula based on sequential infrared images, which were obtained by the SMS-1 geosynchronous meterological satellite. R. Pingree [8], in analyzing the IR images of the shelf waters around the British Isles and Europe, discovered the systematic formation of cyclonic eddies at fronts, the origin of which is related to tidal intermixing in shallow water. These are just a few of the brilliant examples of the useful information obtained from aerospace data over recent years.

2. The Statistical Analysis of Eddies and Fronts. The systematic work of numerous interpreters using IR images from NOAA series satellites for the region of the Gulf Stream current has made it possible to combine useful thermal data with the data from the radio altimeter of the GEOS-3 satellite, as a result of which, the special service of the U.S. Navy has been producing weekly maps of an experimental analysis in the Northwest Atlantic over a period of three years now (Figure 3). These maps have opened up new possibilities for oceanologists, which have been realized right away.

In 1979, G. Halliwell and C. Mooers [5] provided an example of the use of a two-year series of maps of an experimental analysis of fronts in the Northwest Atlantic to obtain statistical data on the number of cyclonic and anticyclonic Gulf Stream rings arising annually, their trajectories and velocities, the movements of the main front of the Gulf Stream as well as data on fluctuations in the position of the front between shelf and slope waters along the east coast of North America.

Infrared pictures from the American GOES (SMS-1) satellite, the "spin-scan" radiometer which has a spatial resolution of 8 m, can be used to systematically track the position of the frontal boundary of the Gulf Stream. G. Maul [35] established the fact that the relationships for the temperature gradients (contrasts), ΔT_0 and ΔT_s, measured from a satellite and a ship, can be expressed for the 11.6 m wavelength as $\Delta T_0/\Delta T_s = 0.941 - 0.221W + 0.19W^2$, where W is the precipitable moisture content of the atmosphere in $g \cdot cm^{-3}$. It follows from an analysis of this expression that the minimum temperature contrast which can be registered from the SMS-1 satellite is 0.7° C in the winter and 0.9° C in the summer. Our data (Figure 4) show that the actual temperature gradient across the main front of the Gulf Stream reaches 2-3° C in the summer, which exceeds the minimum which can be registered by a factor of three.

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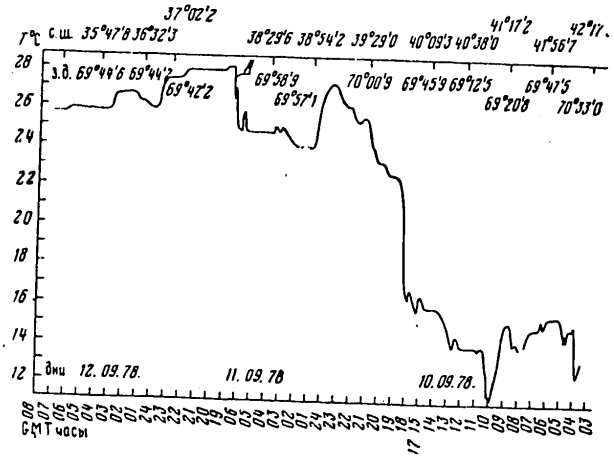

Figure 4. The variation in the surface temperature of the ocean during a crossing of the Gulf Stream from north to September of 1978. The major front of the Gulf Stream is designated by the letter A (data from the 27th voyage of the scientific research ship "Akademik Kurchatov", 1978).

3. The Detection of Traces of Internal Waves at the Surface of the Ocean. The detection of traces of internal waves on satellite heat maps and photographs of the ocean's surface in the visible range of the spectrum [36,37] was something unexpected for oceanologists, although individual observations of "banded" structures of ripples at the surface from ships, especially in regions close to shore [38,39], had already been interpreted as manifestations of internal waves. The physical nature of the mainfestations of internal waves at the ocean's surface is related in the majority of cases to the interaction of orbital motions in internal waves with the drift currents close to the water surface and the ripple. A strict theory of this interaction does not exist as yet. Other possibilities for detecting internal waves from space are related to the optical effects when a fresh water surface and turbid layer are present in the ocean [40]. In the work by the author cited here, an example is given of the use of an image obtained under such conditions for the calculation of the parameters of the internal waves (the periods, wavelengths and phase velocities). However, it should be noted that in this field, oceanologists are indebted to specialists who are responsible for obtaining satellite images of traces of internal waves at the ocean's surface. Despite the existence of an atlas of pictures of internal waves in the Northwest Atlantic, published by NOAA [41], detailed studies have not yet been made of the phenomenon itself based on this data.

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4. The Utilization of Satellites in Systems Incorporating Oceanographic Buoys. The most successful and widely disseminated approach was the use of transponder buoys in conjunction with various satellites to study the specific features of the circulation of ocean waters. The Woods Hole Oceanographic Institute in the U.S. used this method to study the motion of the Gulf Stream rings [13]. Australian scientists, using the American "Nimbus-6" satellite, detected the presence of eddy formations in the ocean on the western shore of Australia using this method [43]. French scientists recently carried out a successful research program on the currents at the shores of the Antarctic from the "Nimbus" and "Eole" satellites, placing the transponder buoys on icebergs. A broad program of study of the currents in Southern latitudes using numerous drifting buoys is a component of the international research of the First Global Experiment of PIGAP. The system of buoys, drifting at the surface or buoyant at a specified depth, and used to transmit information to a satellite, would permit a substantial expansion of the capabilities of contact measurements in the ocean. Data can also be gathered from buoys which are anchored in the ocean regions under study. Equipment will be housed in such buoys [44] for the measurement of a number of characteristics in the atmosphere near the water and in the ocean from the surface down to considerable depths, as well as the requisite data gathering and transmitting devices. The following can be included in the equipment compliment of a buoy: transducers for the temperature, humidity, and pressure in the atmosphere, wind direction and velocity, temperature, electrical conductivity and pressure in the water, the velocity components of currents, trnasparency and radio activity, the velocity of sound, dissolved oxygen, etc. The data collected from the buoys can be transmitted from satellites to ships or to ground based data centers.

Up to the present day, extremely few experiments using satellites to gather information from buoys have been performed. Only the successful French-Australian experiment of 1972 is to be noted [45].

Closely related problems are the gathering of information by satellites on the position of ships, as well as increasing navigation precision based on the reception of signals from a special navigation satellite or satellites. Modern systems make it possible to fix the position of a ship with an accuracy of down to tens of meters, something which is at least an order of magnitude above the usually employed methods of radio navigation and astronomical position determination. At the present time, several Soviet scientific research vessels have already been equipped with satellite navigation equipment, something which has made it possible to improve the scientific value of numerous measurements which have been performed to a significant extent [46].

5. The Utilization of Data from Satellites and Orbital Laboratories for Ship Guidance to Objects of Study. The Woods Hole Oceanographic Institute and the Research Triangle Institute (U.S.) were pioneers in

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the application of this method, where satellite IR data was utilized to correct the program of full scale studies of a front, separating shelf and slope waters on the northeast coast of America, as well as for the guidance of scientific research ships to Gulf Stream rings for the study of the latter [47, 48]. This method was successfully used in the 27th voyage of the scientific research ship "Akademik Kurchatov" in the Soviet-American Polymode program. The satellite data, and especially the American weekly maps of the experimental frontal analysis and information on the Gulf Stream front and position of the rings which were transmitted by the American group via radio were successfully used in the operational planning of expedition work in studying the Gulf Stream rings and the fronts related to them.

Orbital laboratories with crews of cosmonauts on board have proved to be useful in organizing commercial space reconnaissance in guiding fishing ships to potentially rich commercial regions in the open ocean related to fronts and eddies. Although this activity in and of itself does not provide us with new knowledge on the ocean, it can be developed only on a scientific basis. The cosmonaut crews should receive definite oceanographic training for this purpose and be trained in the visual detection of interesting regions in a commercial sense based on a number of criteria established in practice. This program has already been implemented by the Ministry of the Fishing Industry over recent years in close cooperation with the cosmonauts Vladimir Kovalenko, Aleksandr Ivanchenkov, Vladimir Lyakhov and Valeriy Ryumin. In our opinion, this program should be expanded, making it a truly scientific one so as to extract from it not only commercial advantages, but also new knowledge of the ocean. For this purpose, definite procedural refinements directed towards a greater systematicity of the visual observations of eddies and fronts in the ocean from orbit should be introduced into the program.

The Possibilities for the Solution of Some New Problems. Space engineering is the engineering of the future. For this reason, it is natural to anticipate that the scientific tasks which confront the designers of space equipment and cosmonauts should be directed towards the future - they should be tasks targeted for the long term.

At the present time, many scientists link hopes for systematic monitoring of changes in the climate of our planet to space engineering. Since the Pacific Ocean determines the variability of the climate of continents in many respects and is itself an important indicator of climatic trends, the possibilities of such monitoring seem to be more urgent as applied to certain characteristics of the Pacific Ocean.

Another long range task is working out the scientific bases for commercial fish farming in the ocean, which is to replace present day fishing, which despite all of the efforts to make it efficient, has not come far in terms of its philosophy from primitive wild game hunting. The development

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of aquaculture in the ocean requires systematic detailed studies of the variability of the fundamental physical fields. Extensive biological and hydrochemical knowledge will be needed. It is necessary to not only identify regions of increased productivity, but also to know the stability of their geographical position, their seasonal variability as well as their variability over the years. Statistical data are needed on the chlorophyll content, the currents, fronts and the interaction between the ocean and the atmosphere. Studies of frontal divisions in the open ocean and in coastal regions can prove to be especially important, since fronts, as natural boundaries in the ocean, can theoretically be skillfully utilized in commercial fish management of the future. An extremely wide field is opening up here for systematic observations and measurements from space. Interested organizations would act correctly if they would begin to think through such a program even now, calling on scientific collectives for assistance which are engaged in fundamental research of the ocean and which have already accumulated important factual information on these problems.

Problems of this kind are as yet in the discussion stage. An attempt will be made below to introduce certain useful considerations based on contemporary knowledge of the variability of the world ocean into the discussion of the climate monitoring problem.

If mankind could learn to predict the changes in the climate of our planet, and moreover, change the climate in the requisite direction, many important economic problems would be solved for future generations once and for all. We shall consider the question of the possibility of the systematic ascertaining of a stable climatic trend from the naturel variability of physical (weather) conditions observed on the earth on scales of 1 to 10 years; we are to speak a priori of only those physical characteristics which include some cumulative, averaging interesting effect of the variability of many other parameters. One of these characteristics, because of the large thermal inertia of the ocean as compared to the atmosphere, is the temperature of the ocean waters. Even in this case, however, the variability of the ocean temperature cannot be representative either at any point or at any depth. Other characteristics of the same kind can apparently be the areas of the polar ice caps of the planet or individual well studied glaciers, as well as the areas of the winter snow cover of the continents after the interannual variability has been filtered out of the series of observations.

We shall consider the possibilities for climate monitoring in more detail, for these are related to the temperature of the ocean waters. It can be said intuitively that it is not the temperature of the waters close to the surface at some point and not the abyssal water temperature which are the most representative in the sense of interest to us. The inertia of the former is too small (the synoptic period, i.e., 7 to 10 days), while the inertia of the latter is too great (1,000 years) for our

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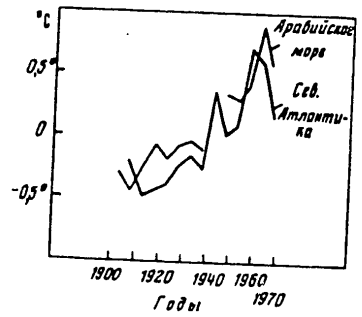

Figure 5. The trend in the variation of the temperature in the northwest Atlantic and in the Arabian Sea over many years.

Key: 1. Arabian Sea;
2. Northwest Atlantic.

purposes, so that the correspnnding amplitudes of the variability are too great in the first case and too small in the second to obtain the desired result. The thermocline waters below the level of seasonal variability could be more indicative in terms of their temperature, but in this case, it is quite difficult to fix a stable measurement point, and making measurements from satellites in this case would be altogether impossible. Therefore, considering the actual possibilities of the method and the actually observable variability of the temperature of the waters of the ocean's surface, it is necessary to select a certain "key" region with small seasonal and interannual variability of the temperature ot the surface, with good depth penetration of the intermixing, and with a predominant advective contribution to the thermal balance of the upper active layer of the water. Besides everything else, this region should not be covered too frequently by clouds, if one has the use of infrared radiometry in mind. Measurements of the radiation temperature of the ocean's surface should be integrated or averaged over the selected region. Without indicating any examples right now, it can be said that the choice of such a region is a difficult one, but quite resolvable problem for oceanologists. The second question which is to be resolved is what is the length needed for a series of observations in order to reliably ascertain a climatic trend, given the attainable precision of the method at the present time? It has already been indicated above that the mean square error of IR measurements of the TPO based on all the existing data falls in a range of $\pm 1.5^{\circ}$ C. On the other hand, it is known from the analysis of almost a 70 year series of observations [49, 50], that the climatic trend of the TPO for the northern portion of the Indian Ocean and the north Atlantic amounted to about 1° C (Figure 5) from 1900 to 1970 (a warming trend). This means that at least a hundred years of observations are needed in order to reliably distinguish such a trend using the data of IR radiometry of the TPO. If this is true, then realistically considering the optimal duration (2 to 3 years) of uninterrupted functioning of the necessary equipment in orbit, it will be necessary to give some thought to doing a good job of relating and tying the series of measurements of instruments sequentially launched into orbit to a unified standard. The three problems posed above are: the choice of the requisite parameter and the averaging and measurement range, the definition of the minimum significant duration

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of a series of measurements, and assuring the comparability of the data over the entire length of the series, all of which are necessary elements in the preparation of programs for any measurements directed towards the ascertaining of a climatic trend. Because of the knowledge accumulated by oceanologists concerning the nature of TPO variability, definite departure points already exist for the solution of these problems. If a more careful analysis demonstrates the impracticability of climatic monitoring of the ocean surface temperature from a satellite in selected "key" regions of the world ocean, then it will be necessary to turn to other geophysical parameters.

Conclusion. The use of aerospace methods to solve scientific and economic problems similar to those which were mentioned in this article requires the implementation of a series of serious organizational measures. A fundamental improvement in long term planning and in the design and production of the requisite instrumentation is to be pursued in the most serious manner. Apparently, this is now the most important question which must be solved without delay. Oceanologists in turn are ready to carry out all of the requisite procedural developmental work and formulate requirements for such equipment. Another important question is the organization of an actually operative dissemination of the scientific information obtained by aerospace means among interested institutions. We shall hope that in the years just ahead serious progress will be planned in the field of study of the world ocean from space.

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REMOTE METHODS OF STUDYING THE EARTH'S SURFACE AND THE ATMOSPHERE OF THE EARTH IN THE MICROWAVE BAND

Moscow ISSLEDOVANIYE ZEMLI IZ KOSMOSA in Russian No 1, 1980 pp 95-105

[Article by N.A. Armand, Institute of Radio Engineering and Electronics of the USSR Academy of Sciences, Moscow]

[Text] Introduction. Radiophysical studies of the surface of the earth and its atmosphere are attracting increasing attention at the present time in the development of space methods of earth observation. Just as other methods of remote sounding, they are based on the study of the effects of the interaction of radio waves and a medium. This interaction leads to a change in the amplitude of the radio waves, their frequency, phase, polarization, etc. The nature of these changes is related both to the geometric properties of the objects being studied (for example, sea waves) and their physical-chemical properties. For this reason, measurements of the parameters of radio waves which pass through the medium being irradiated or which are reflected and scattered by a medium make it possible in principle to obtain information on the properties of the medium.

The use of superhigh frequency radio waves for the observation of the earth from space substantially supplements optical and infrared observation methods, and in a number of cases, has its own advantages. These advantages are based on the specific properties of the interaction of microwaves with the natural environment. Radio waves in the centimeter, and especially, the decimeter band are practically not absorbed at all and are not scattered by clouds, something which makes it possible to consider radio observations of the earth all-weather possibilities. This is of no small importance considering the fact that a significant percentage of the time various portions of the earth's surface are covered by clouds. Moreover, because of the comparatively low absorption (as compared to optical and IR waves) in the soil of the earth, in snow, ice, etc., radio observations make it possible to look inside earth covers, with a prospect of going to a depth of several tens (and perhaps even hundreds) of meters. Also related to this same circumstance is the fact that observations in the radio range make it possible to avoid the shielding effect of vegetative covers.

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A sophisticated coherent processing technology for radio signals yields definite advantages both in studying, for example, the spectrum of sea wave agitation and other inhomogeneities in the form of ground covers. On the other hand, the comparatively long wavelengths of the frequencies use make it possible to avoid effects due to small roughnesses of the surface, and when analyzing the experimental data, to base the work on simple concepts of the reflection of plane waves from plane separation boundaries.

As compared to optical observation methods, radio methods are inferior in the attainable spatial resolutions. However, the existing capabilities here are really not that bad. The use of synthesized apertures makes it possible to attain a resolution on the order of 10 m.

Radiophysical methods are broken down into active and passive. Active methods are based on studying the change in the amplitude, frequency, phase polarization or spectrum of the radio waves radiated by a special transmitter and absorbed, reflected or scattered by the medium being studied. It is possible here to make wide use of coherent signal processing equipment, generate probe signals of a specified waveform, spectral width, polarization, etc.

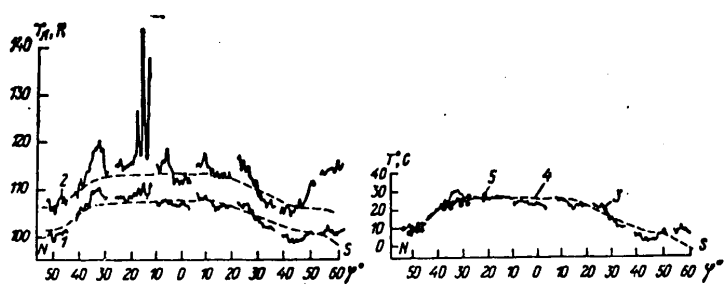

Figure 1. A latitude cross-section of radio brightness temperatures (T_b, °K) and the surface temperature of the Pacific Ocean (T, °C) based on measurement data from the "Kosmos-243" satellite.

1. Measurements at a wavelength of 8.5 cm;
2. Measurements at a wavelength of 3.4 cm;
3. The restored temperature;
4. The mean climatic temperature;
5. Measurements from ships.

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Passive (or radiothermal) methods are based on a study of the intensity (in some cases, the predominant polarization) of the inherent radio emission of ground covers. The intensity of this radiation depends on the temperature of the medium, its structure and the physical-chemical properties. For this reason, radiothermal observation methods make it possible to come to conclusions not only, for example, concerning the physical-chemical properties of ground covers, but also their temperature.

Remote radio sounding methods have been in use for a comparatively long time by geophysicists, meteorologists and astrophysicists. All of our knowledge of the earth's ionosphere prior to the appearance of high altitude geophysical rockets and earth satellites were based solely on the results of remote (radar) sounding. These methods are continually being improved and are widely used in studying the ionosphere to this day. Radar methods are used rather widely to study the structure and dynamics of clouds. It is natural that remote radio sensing is widely used in astrophysics (radio astronomy).

The appearance of earth satellites and the possibility of a global survey of the earth related to this have brought about new developments in radiophysical methods of remote observation. These studies were started more than 10 years ago in the Soviet Union. In 1968, the "Kosmos-243" satellite was launched, in which microwave radiometers were installed. In 1970, the "Kosmos-384" was launched with similar equipment. Subsequently, radiometers were installed in several satellites of the "Meteor" series, and at the present time have been installed in the "Kosmos-1076" satellite. Similar experiments were started in the U.S. with the launching of the "Nimbus-5" satellite in 1972.

The properties of the earth's atmosphere place specific limitations on the range of frequencies suitable for radio sensing of the earth from space. Thus, because of the opacity of the earth's ionosphere, the use of wavelengths longer than 10 m is practically excluded. The absorption of radio waves by atmospheric gases and absorption and scattering in clouds make it difficult to use, and in a number of cases, completely preclude the use of the short wave portion of the millimeter and submillimeter bands for radio observation of the earth's surface. This same circumstance, on the other hand, makes it possible to study the atmosphere and hydrometeors based on absorption and scattering effects. For this reason, when designing satellite systems for radio observation of the earth, one is to figure on a range of wavelengths from a few millimeters to several meters, depending on the problems being solved - a band which is conventionally called superhigh frequency.

Fundamental Physical Principles. We shall cite a few extremely simplified relationships which illustrate the possibilities of utilizing ratiophysical methods in remote sensing.

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Imagine that a radar is directed at the nadir. Then the signal power W received by the radar will be proportional to the product

$$W \simeq P|R|^2 \tag{1}$$

where P is the transmitted power while R is the Fresnel reflection factor. For homogeneous media with a complex dielectric permittivity:

$$\hat{\varepsilon}=\varepsilon+i\delta \tag{2}$$

and the quantity:

$$|R|^2=\frac{|\hat{\varepsilon}|-2\sqrt{|\hat{\varepsilon}|}\cos\frac{\Delta}{2}+1}{|\hat{\varepsilon}|+2\sqrt{|\hat{\varepsilon}|}\cos\frac{\Delta}{2}+1}. \tag{3}$$

Here:

$$\Delta=\operatorname{arc\,tg}\frac{\delta}{\varepsilon} \tag{4}$$

is the loss angle which characterizes radio wave absorption in the ground. In the case of dry soils (or rock), the loss angle is small, and for this reason:

$$|R|^2\simeq\left(\frac{\sqrt{\varepsilon}-1}{\sqrt{\varepsilon}+1}\right)^2. \tag{5}$$

Measurements of the received signal power make it possible to determine the dielectric permittivity of the ground. The latter is related to the density of the ground ρ by the empirical formula of [1]:

$$g/cm^3 \tag{6}$$

which immediately leads to the possibility of estimating its density.

In the case where the ground is made damp, because of the large value of the dielectric permittivity of water ($\varepsilon \simeq 80$), the size of the reflection factor will be determined practically only by the bulk concentration of water in the ground. The possibility of determining the moisture of soils, the extent to which they are bogs, etc., using remote radiophysical methods can be seen from this.

Imagine that some layer of material lies on the surface of the earth (ice, any kind of soil) with homogeneous properties and poor absorption, or, for example, there is some kind of rather extensive inclusion at a certain depth, the electrophysical properties of which differ from those of the surrounding medium. Then the reflection of radar signals will be observed from the upper and lower boundaries. If sufficiently short pulses (or sufficiently ideband signals) are used in the radar, then the signals reflected from the upper and lower boundaries can be separated with respect to their time of passage. This time difference, τ, is equal to:

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$$\tau = \frac{2l\sqrt{\varepsilon}}{c}, \tag{7}$$

where l is the thickness of the layer (or the depth of the inclusion), c is the speed of light in a vacuum. Since we already "know how" to determine ε, then the time measurement makes it possible to estimate the thickness of the layer being probed (for example, ice) or to determine the depth of the inclusions. The power of the pulse reflected from the lower boundary depends on the jump in the dielectric permittivity between the ambient medium and the inclusion being sounded. Thus, a certain possibility is opened up (and it must be said, one which is not easy to realize) for the determination of the electrophysical properties of various kinds of inclusions at shallow depths.

When irradiating the surface of the earth at some angle, back scattering of the radio wave occurs because of nonuniformities, where the intensity and spectrum of the back scattering are determined by the scales of the surface nonuniformities. Processing signals scattered in this fasion makes it possible for example, to study the intensity and spectrum of sea wave agitation, and to make a judgement based on it concerning the nature of the wind over the ocean, etc. Moreover, the use of so-called side-looking radars (RBO) makes it possible to do radio mapping of the earth's surface. The use of synthesized aperture methods and short pulses makes it possible to obtain good spatial resolution in this case. Since the properties of the scattered signal depend on the characteristics of the relief and the electrophysical parameters of the ground, definite possibilities are opened up here for the geological interpretation of the radar images, which to a certain extent can supplement and make more precise the optical images of the earth's surface.

Passive radar methods offer no few promising features for radio observations of the earth from space. The intensity of radio emissions is conveniently characterized by the so-called brightness temperature, T_b, which is related to the thermodynamic temperature, T, by the simple expression:

$$T_b(\omega) = \tag{8}$$

Here, $\kappa(\omega)$ is the emissivity, which depends on the electrophysical and geometric properties of the medium, the frequency ω at which the radiothermal radiation is registered, and usually to a slight extent, on the temperature (since the electrophysical parameters of the medium being studied depend on the latter). For a semi-infinite medium:

$$\varkappa(\omega) = 1 - |R(\omega)|^2, \tag{9}$$

where R, just as before, is the reflection factor. If the electrophysical properties of the medium are well-known (for example, water), then the recording of the radiothermal emission make it possible to determine

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the temperature of the ground covers. The idea of measuring the temperature of the world ocean (without discussing details here which complicate the matter) is also based on this.

If, on the other hand, we know the temperature, then definite conclusions can be drawn concerning the emissivity, and subsequently, concerning the electrophysical and other properties of the medium being studied, based on the intensity of the radiothermal emission.

Let us now imagine that the irradiating medium is a layer of the atmosphere or cloud cover. In a first approximation, disregarding the altitude dependence of the properties of these layers, their inherent radiation will be characterized by the brightness temperature:

$$T_b = T_a = T(1-e^{-q}), \tag{10}$$

where the optical thickness q is determined by the attenuation factor γ and is equal to:

$$q = \gamma l \tag{11}$$

where l is the thickness of the layer. If the issue involved concerns the troposphere of the earth, then the attenuation here is due to radio wave absorption at specific frequencies by water vapors and oxygen. Absorption by water vapor is proportional to their concentrations, and for this reason, by knowing, for example, the intensity of the radio emission at a wavelength of $\lambda = 1.35$ cm (the water vapor absorption line), one can estimate the values of the optical thickness, q, and from this, draw definite conclusions concerning the water vapor content in a vertical column of air. A similar scheme of reasoning leads to the notion of the possibility of determining the water reserves of clouds.

We shall once again emphasize the fact that the arguments cited here are extremely rough and have neglected numerous extremely important details. In particular, for the realization of the measurements described here, it is necessary to turn to the analysis of the radiation in different portions of the radio spectrum, in order, for example, to eliminate the effect of the natural radiation of ground covers, against the background of which the observations are made, take into account the inhomogeneity of atmospheric properties with respect to altitude, etc.

The Results of Certain Experiments. Experimental studies in the field of remote radio sensing of the earth from space are not very numerous and the majority of them are of a methodological nature with the goal of working out the scientific principles of various sensing methods, ascertaining their practical capabilities, and establishing a relationship between the data on ground covers and the atmosphere obtained by both radiophysical methods and optical, infrared and other methods

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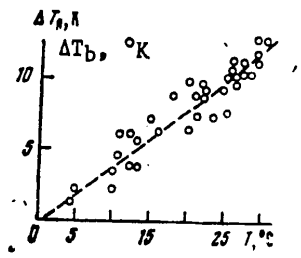

Figure 2. The relationship between the increment in the radio brightness temperature at a wavelength of 8.5 cm and the thermodynamic temperature (an experiment with the "Kosmos-243" satellite).

(for example, contact methods), as well for the purpose of setting more justified technical requirements for equipment, which is proposed for subsequent use in service satellites (for example, meteorological ones). Besides the space vehicles for the solution of methodological problems, aircraft are also widely used, in which case, extensive scientific and procedural material has been accumulated in these kinds of experiments.

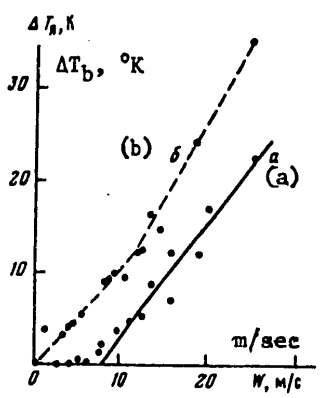

Figure 3.

The increase in the radiobrightness temperature as a function of the wind velocity based on experimental data (the points).

Key: a. Vertical observations;

b. Observations at an angle of 55° to the vertical.

It does not prove to be possible in this paper to describe the existing material in all its completeness. The details on and references to the corresponding literature can be found, for example, in monograph [2] or in the reviews [3-5].

The first experiments on space radion sensing of earth covers, as has already been noted, were carried out with the Soviet "Kosmos-243" and "Kosmos-384" satellites, in which radiometers with working wavelengths

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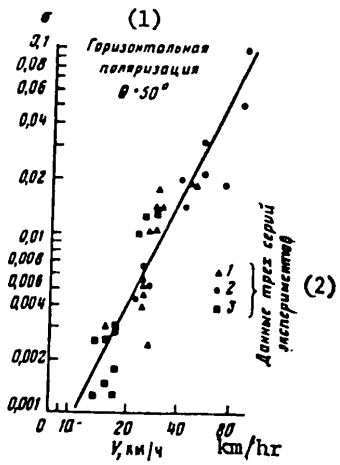

Figure 4. The scattering coefficient at a frequency of 13.9 GHz as a function of the wind velocity (measurement data from the "Skylab" satellite.

Key: 1. Horizontal polarization, = 50°;
2. The data of three series of experiments.

of 0.8, 1.35, 3.4 and 8.5 cm were installed. This choice of frequencies of the recorded radio emissions was not accidental. Radio wave propagation in the 8.5 cm band is subject to a small degree to the influence of precipitation and clouds, because of which, the inherent radiation of the ground covers is registered in this range. Heavy precipitation begins to have an effect on the radiation of 3 cm waves. The 1.35 cm wavelength was intended for measurements of the moisture content in the atmosphere, and the 0.8 cm wavelength is convenient for registering the radiation of clouds to determine the water content in them. Such a breakdown

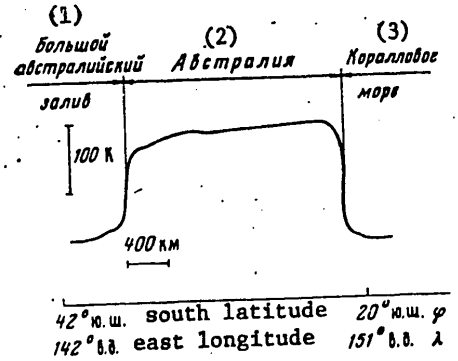

Figure 5. The radio brightness temperature profile of Australia based on measurements at a wavelength of 8.5 cm, 24 Sept., 1968.

Key: 1. Great Australian Bight; 2. Australia; 3. Coral Sea.

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of the roles of the various bands is extremely sketchy. In fact, only the combined analysis of the intensity (and polarization) of the natural radiation at various wavelengths makes it possible to identify with sufficient reliability the variations in the temperature of the ocean, areas of precipitation and sea wave agitation, types of ice covers, regions of increased soil humidity, etc.

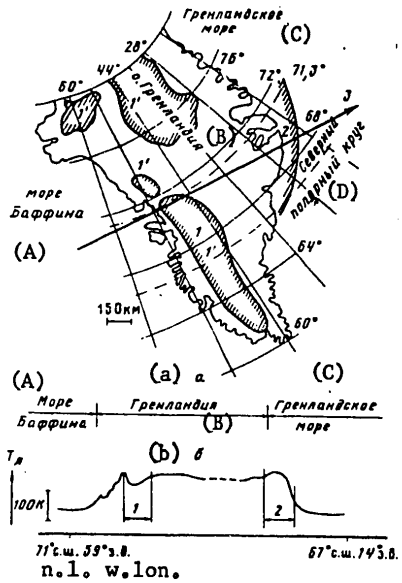

Figure 6. The radio emission field of Greenland ice covers.
a. Schematic map showing the regions (1; 1') having a low value of the radio brightness temperature:

1. Measurement data from the "Kosmos-243" satellite, wavelength 3.4 cm, Sept. 1968;
1'. Measurement data from the "Nimbus-5" satellite, wavelength 1.55 cm, Sept. 1973;
2. Sea ice (the "Kosmos-243" satellite;

b. An example of the realization of the radiometric measurements along trajectory 3 in map a.

Key: (A) Baffin Bay;
(B) Greenland;
(C) Greenland Sea;
(D) North Polar Circle.

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A latitude (along the satellite trajectory) section of the brightness temperature (i.e., the radiation intensity) at wavelengths of 3.4 and 8.5 cm is shown in Figure 1. For example, it can be seen that the emission at the 3.4 cm wavelength reacts substantially more actively to the presence of areas of precipitation in a region of 15° north latitude (something which is detected from the peak in the brightness temperature). The combined analysis, about which we were just speaking, makes it possible to "clean" out the interfering influence of precipitation and obtain data on the thermodynamic temperature of the ocean, which is shown in the lower portion of the figure. Also shown there with the points are the results of ship measurements, which illustrate the precision attained in the described experiments measuring the surface temperature of the ocean. The accuracy of the measurements is comparatively low (see Figure 2), but as it turns out, it can be improved to a quantity on the order of 1° C.

The brightness temperature of the ocean also depends on the wave agitation intensity. This dependence arises both because of the change in the shape of the radiating surface and foam formation. The corresponding experimental data which were obtained in different wavelength bands using satellite and airborne instrumentation are generalized in the graph of Figure 3. The latter illustrates the possibility of registering the intensity of sea wave agitation based on the radiothermal emission, and then using the sea agitation to make a jusgement concerning the wind above the ocean's surface.

Similar measurements can also be performed using a radar, since the intensity of the back scattered signal is determined by the height of the waves. Corresponding measurement data from measurements made in the American "Skylab" satellite are shown in Figure 4.

Figure 5 illustrates the radio contrast between the sea and dry land. It is easy to see that it is rather high and can be explained primarily by the difference in the emissivities of the water and dry land surfaces, since the temperature differences are naturally not so great. Similar radiative contrasts are observed at an ice--water boundary. This is illustrated in Figure 6 where the regions of ice cover are depicted which were investigated using microwave radiometric equipment installed in Soviet and American Satellites. It was established during the studies that the emissivity is determined by its type and age. The greatest emissivity is observed for sea ice as compared to continental ice, and especially, shelf ice. Besides the type of ice, the structure of the snow cover also has a strong influence on the emissivity.

If sections of ice and open water simultaneously come in as a "radio spot", the emissivity of such a system will occupy an intermediate value between the emissivities of water and ice, and its magnitude will depend on the solidarity of the ice, something which also makes it possible to determine the latter based on the results of microwave sensing from space. An example of these kind of measurements is shown in Figure 7.

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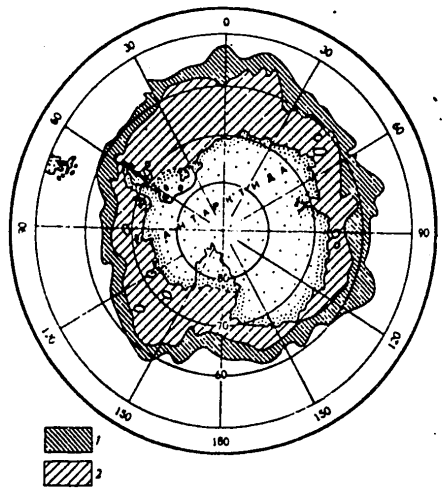

Figure 7. A schematic map showing the solidarity of the Antarctic ice based on measurements from the "Kosmos-243" satellite.

1. Ice cover solidarity greater than 5 points on a 12 point scale;
2. Ice cover solidarity less than 5 points.

Radiometric measurements, carried out from Soviet and American space vehicles have made it possible under conditions of cloud cover and when vegetative cover is present to register extensive regions with increased moisture content in different parts of the globe. A comparison of data obtained over a period of several years has made it possible to trace the change in the hydrological conditions in these regions. An example of such a comparison can be seen in Figure 8.

Measurements performed using radio altimeters installed in the American "Skylab" and "GEOS-3" satellites have made it possible to establish the variations in the position of the ocean level which are related to its surface state and the influence of currents. Absolute measurements of the propagation time of radio signals reflected by the sea surface, where precise data are available on the orbit of the satellite in a geocentric system of coordinates, open the prospect of determining the shape of the geoid and specifying more precisely the amplitudes of the spatial harmonics of the gravitational field of the earth. In particular, the influence of gravitational anomalies was registered in the region of the Puerto Rico trough during measurements of the ocean level height made with the altimeter installed in the American "Skylab" satellite. A schematic of the corresponding experiment and the results of the measurements are shown in Figure 9.

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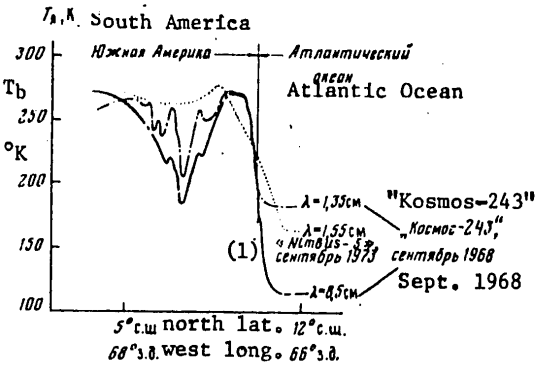

Figure 8. The brightness temperatures in the Orinoco River basin (South America).

Key: 1. λ = 1.55 cm, "Nimbus-5", Sept. 1973.

It should be noted that there has as yet been little experience with the radar study of ground covers from space. Besides the indicated measurements, we will note a small number of experiments on radio mapping of the ocean using a side-looking radar, installed in the American "Seasat-A" satellite [6].

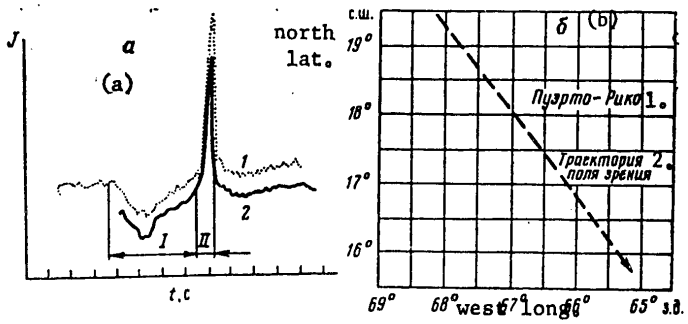

Figure 9. The readings of the 2 cm band radioaltimeter of the "Skylab" satellite.

a. Readings of the radio altimeter (J) in conditional units as a function of polar time;
b. Flight plan;

I. The gravitational anomaly region;
II. Dry land area;
1, 2. Measurements on different orbits;

1. Puerto Rico
2. Trajectory of the field of view.

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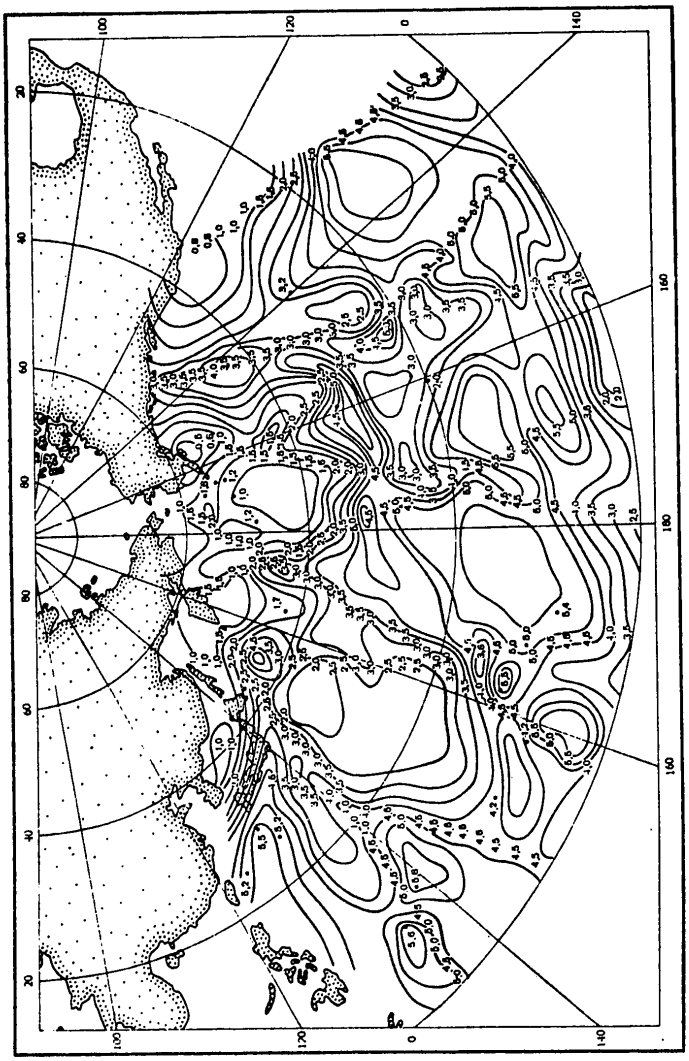

Figure 10. A schematic map of the isolines of moisture content of the atmosphere above the polar region of the Pacific Ocean based on radiothermal measurements from the "Kosmos-243" satellite.

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Along with the study of the state of ground covers, remote microwave sensing methods, as already noted, make it possible to obtain data on the atmosphere and hydrometeors. Measurements made with a radiometer at a wavelength of 1.35 cm (in conjunction with measurements at other wavelengths) have made it possible to obtain data on the moisture content of the atmosphere. An example of these data is shown in Figure 10, where a map is given for the isolines of moisture content, W (g/cm^2), in the northern protion of the Pacific Ocean. Since the measurements were made along a route, such a map can be drawn only by using the data of a number of satellite revolutions, assuming slow variation of the moisture content in the atmosphere.

Figure 11 demonstrates another example of the capability or remote radio methods. Shown here is an averaged latitude section of the water reserve of clouds, Q (kg/m^2), over the ocean, based on measurements made during September of 1968. It is possible to make such measurements, apparently, only in the radio frequency range.

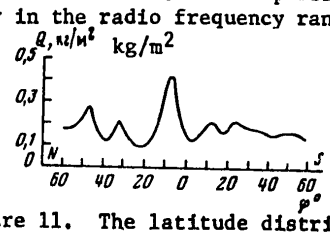

Figure 11. The latitude distribution of the water reserve of clouds above the oceans based on measurements from the "Kosmos-243" satellite in September of 1968.

Conclusion. The results of theoretical and experimental studies carried out in different countries demonstrate the broad possibilities for radiophysical methods of remote sensing of the earth. Along with the data obtained by other methods, data from radio observations can find (and is finding) applications in meteorology, oceanography, in studying ice and snow covers, in geology, agriculture, forestry, land reclamation and water management and in other fields. It is probable in this case that the corresponding equipment will be installed both in earth satellites and in aircraft. The question of which problems are to be studied using space equipment, and which are to based on aircraft, requires further discussion and studies in a number of cases. One of the considerations, of a purely radio engineering nature, is of no small importance here. We are talking about the spatial resolving power of radio equipment. In the majority of cases, the size of a resolution element is determined by the size of the radio spot which is "illuminated" by the antenna of the radio system. In the majority of cases, the spatial resolution which is attainable in the radio frequency range proves to be extremely poor. To increase the latter, in the case of space radio observations, it is necessary to either substantially increase the dimensions of the antenna - up to quantities on the order of several tens of meters, or to use special methods of signal generation and processing (for example, apperture synthesis), something which is not possible in all cases (for example, in cases of radio thermal observations).

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In connection with what has been presented above, it can be assumed that space methods of radio sounding will find application in the immediate future in the observation of portions of the earth with large scales of spatial (including statistical) homogeneity, for example, such as the surface of the ocean, ice and snow covers, large forest areas, desert and steppe regions, etc.

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ON THE FURTHER DEVELOPMENT OF METHODS OF STUDYING THE EARTH FROM SPACE

Moscow ISSLEDOVANIYE ZEMLI IZ KOSMOSA in Russian No 1, 1980 manuscript received 23 Aug 79 pp 125-133

[Article by Ya.L. Ziman, Institute of Space Research of the USSR Academy of Sciences, Moscow]

[Text] The study of the earth from space, its natural resources and environment has gone beyond the bounds of experiments at the present time and occupied its rightful place among the other applications of space engineering to the solution of urgent economic problems. For this reason, where previously the main task of scientific research was the development of methods and principles of constructing the technical means of assuring the design and placing in service of the appropriate industrial space complexes, this task has now been somewhat transformed. The work of scientists today in the field of remote sounding (DZ) should be more of a search character. The tasks of the next studies should follow from the results of the practical utilization of the existing hardware and pursue the goals of further developing and increasing the efficiency of methods of earth study from space.

An analysis of the materials from the experimental and practical utilization of space hardware for the study of the earth's natural resources makes it possible to come to the following basic conclusions:

1. The effectiveness of remote sensing is unequal from the viewpoint of the solution of problems posed by the developing needs of modern society. The greatest impact from the use of DZ, which can be due to the specific features of the method and the value of the positive results which can be obtained, is manifest in the study of the geosphere, from the viewpoint of its bioproductivity, and in particular, in ascertaining regions of the oceans rich in fish and sea animals, in forecasting the harvests of agricultural crops and in detecting damage to sown crops (up to the present, up to 20% of grain crops are lost because of diseases and other unfavorable effects), etc.

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The orientation of DZ systems towards questions of studying, forecasting, monitoring and protecting the bioproductivity of the geosphere requires periodic examination of the areas being monitored, as well as the operationally timely obtaining, processing and topical interpretation of the data obtained.

2. The problem of topical interpretation of the data of space photographs cannot be solved in the majority of cases with one-time or episodic local examinations of the individual formations, or when photographs are made on a single scale, which, as a rule, provides for only the detection of the objects and phenomena being investigated.

When taking photographs of the earth from pace, it is necessary on one hand to take into account the dynamics of seasonal and vegetative changes in the formations under study, and on the other hand, the interrelationship and mutual conditioning of the natural macro-, meso- and microprocesses and phenomena taking place at the surface of continents, in the ocean, in the atmosphere and in the depths of the earth.

3. The requirements of globality and high periodicity of earth observations and the striving to increase the topical information content of the data received lead to a rapid increase in the break between the rise in the flow of video information received from space and the actual capabilities of its processing and topical interpretation (of the data received from the "Landsat" satellites, less than 5% undergoes a complete cycle of processing and interpretation).

Consequently, it is necessary to seek out ways of curtailing the flows of information incoming from space without marked detriment to the basic goals of DZ or a way of radically solving the problem of data processing.

4. Interpretation, including topical interpretation, based on only one analysis of DZ data with respect to a spectral criterion does not assure automation of the solution of the majority of problems because of the nonuniqueness of the spectral attribute and the lack of a priori information on the spectral-structural phenomena of the ground formation properties generating it.

Consequently, it is necessary to expand the criteria space of formalized interpretation simultaneously with increasing the precision of spectral criterion selection, and to begin a systematized cataloging of ground formations.

5. DZ equipment which has been designed and is being developed has been oriented, as a rule, towards the solution of some abstract universal problem, without having the capability of spatial and spectral retuning when photographying various natural regions and solving topically different groups of problems. This leads in some cases to excess redundancy of the data received from space, and in other cases, to their clear inadequacy.

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Thus, there exists the need to develop and further refine the principles of DZ hardware design, as well as for measurement processing equipment directly on board a space vehicle, for the purpose of singling out only the requisite data and transmitting it to earth.

In working from what has been presented above, a comprehensive program for further research and experiments has been developed in the Institute of Space Research of the USSR Academy of Sciences, the major original procedural postulates of which reduce to the following: it is proposed that a dynamic approach be taken as the basis of the technological scheme for earth research from space; along with large scale photographs, taken in the interest of examining local regions, it is proposed that regular measurements and a study of the spectral brightness field of the earth and its individual regions be started for the purpose of finding the interrelationships between the parameters and the variations in this field with geophysical and geographic processes and phenomena which take place on the surface, in the atmosphere, and maybe also in the depths of the earth; the photographing of various ground formation is to be carried out in different spectral ranges with spectral and spatial resolutions which are optimal for the solution of the given specific problems; the spectral analysis of ground formations, performed on the basis of remote sounding data, should be combined with structural analysis.

We shall deal briefly with the procedural principles enumerated above and the ways of realizing them. The proposals concerning the principles of the dynamic approach and the technological scheme for the conduct of the investigations of the earth's natural resources from space were set forth in [1]. The automation of the proposed solution requires an in-depth study of the interrelationships between the spatial and energy characteristics of the inherent and reflected solar radiation of earth formations and their kinds and states. The basic result of such a study should be catalogs of the radiation characteristics of specific kinds of ground objects and mathematical models of the change in these characteristics with the influence of various external conditions and possible internal transformations.

The dynamic approach and the proposed technological scheme require high precision in the spectral measurements and the comparison of materials from examinations at different times, something which in turn makes it necessary to provide for coordinate and radiometric standardization of the data received from space.

Automated coordinate standardization is the transformation of the raw images into a specified cartographic projection and a definite scale; it is realized most precisely based on a correlation analysis of these images and calibration images of reference areas. The mathematical studies of this problem which were made at the IKI [2] have demonstrated the expediency of utilizing integral transforms, known by the name of Mellin and

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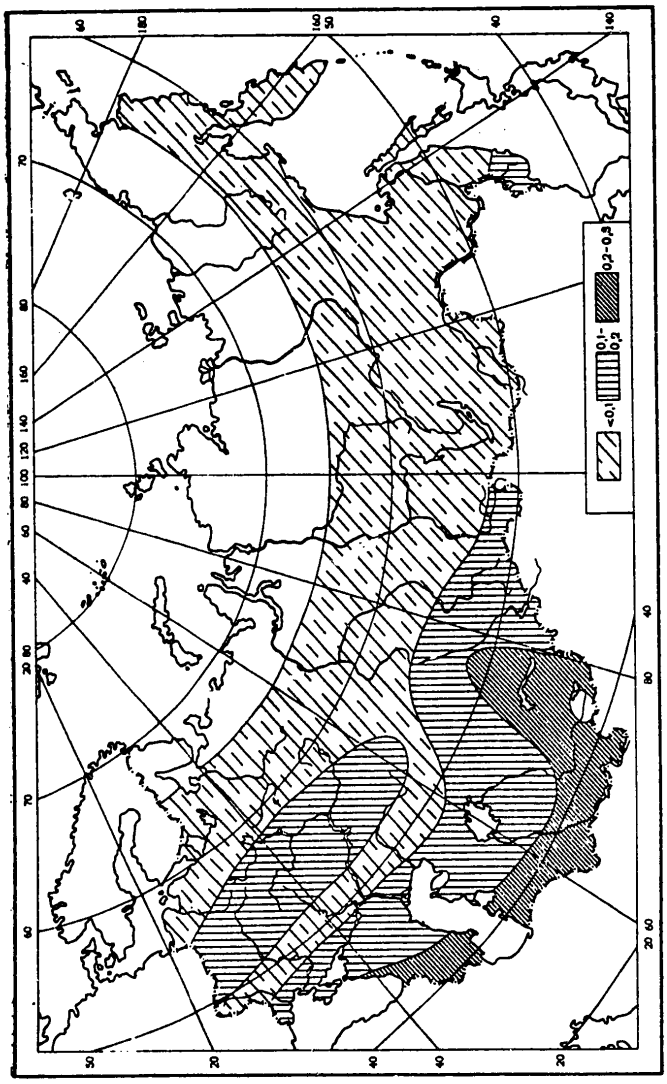

Figure 1.

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Fourier-Bessel transforms, for its solution. The proposed approach would make it possible to substantially reduce the machine time and can be realized on computers of the unified series.

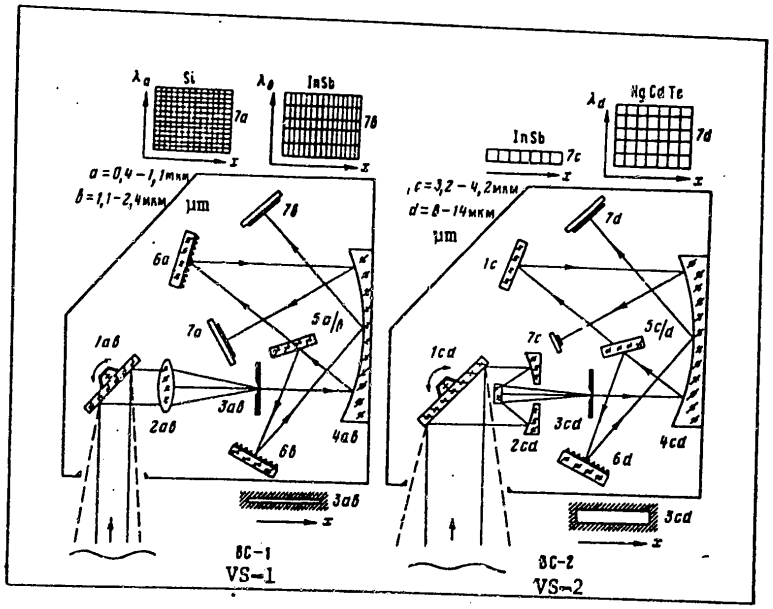

Figure 2.

In the radiometric standardization, the solution of the problem of taking into account the influence of the atmosphere on the results of measurements of the emission of ground formations from space is problematical. The equation for the transport of solar radiation in the atmosphere [3] makes it possible to separate the effects of the atmospheric haze, the scattering of light along the observation beam and re-reflection effects. All of the requisite light transmittance functions of the atmosphere are computed by the Monte Carlo method, and in that region where the statistical accuracy of the calculations is inadequate, derived analytical expressions are employed. The optimal filter for the elimination of atmospheric interference is determined on the basis of the computed transmittance functions. The final filtration stage - the reproduction of the video information undistorted by the atmosphere - is performed by means of fast Fourier transform algorithms. Calculations have shown that the effects of light scattering are substantial in the case of real spatial resolutions, and re-reflection effects have a radius of 1-10 km.

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Knowledge of the state of the atmosphere at the moment of taking the picture and absolute radiometric precision of the video information being processed are necessary conditions for its optimum filtration. For each electromagnetic wavelength at which photography is carried out, the state of the atmosphere should be specified by the scattering and capture cross-section as a function of altitude and the indicatrix of molecular and aerosol scattering. The selection of the filter parameters can also be made on the basis of a comparison of the spectral brightness of calibrated areas measured from space and under near-earth conditions. The appropriate correction algorithm for the images was realized on the YeS 1040 computer [4]. The solution of the problem in real time using coherent optical systems is being studied.

One of the efforts in the field of studying the spectral brightness field of the earth was carried out in the IKI during the processing of pictures received by the MKF-6 equipment from the "Soyuz-22" spacecraft and was reported in April of 1978 at the Budapest conference of the "Interkosmos" working group on remote sensing [5]. Collation maps of the territory of the Soviet Union, depicting the distribution of brightness and optical contrast in six spectral bands were compiled on the basis of photometry of the received multiband photographs. An analysis of these collation maps showed that optical contrast is a sufficiently informative characteristic; the geographic distribution of contrasts in different spectral bands correlates with definite natural characteristics. Shown in Figure 1 as an example is one of the collation maps obtained in the indicated experiment, which depicts the optical contrasts in the 460-500 nm band. The distribution of the contrasts in this band is in good agreement with the distribution of the mean monthly transmittance of the atmosphere, obtained from meteorological observation data. To study the global characteristics of the brightness field of the earth, it is proposed that data from both solar synchronous and geostationary satellites be used.

When taking pictures of the earth from space, the expediency of a flexible variation of the number of spectral channels, and the magnitudes of the spatial and spectral resolutions is obvious. One of the probable approaches to solving this problem is designing remote sounding equipment in which such variation can be accomplished upon instructions from the earth based on previously specified programs or by means of a self-adaptive system.

Such equipment could be, in particular, a standardized video spectrometric complex for aircraft and satellites, encompassing a range of electromagnetic wavelengths from 0.4 to 15 micrometers. In structural terms, the complex could include two main videospectrometers operating synchronously and in phase, the VS-1 and VS-2: the first in the visible and near infrared region of the spectrum, the second in its thermal infrared bands. Possible simplified VS-1 and VS-2 schematics are shown in Figure 2: 1-- are the reflectors; 2 -- are the objectives; 3 -- are the slot diaphragms; 4 -- are collimators; 5 -- are dichroic mirrors; 6 -- are diffraction

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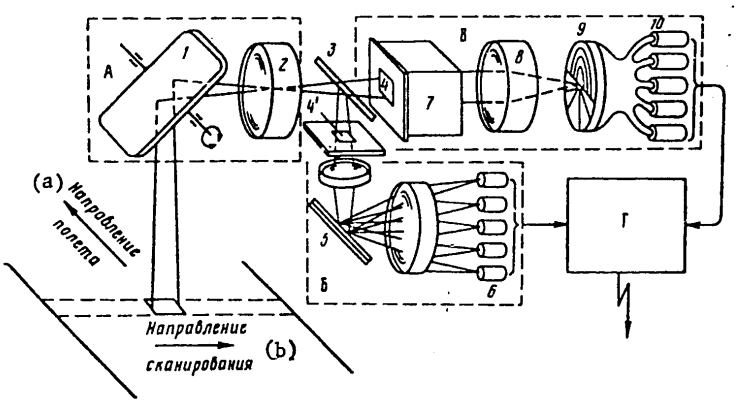

Figure 3.

Key: a. Direction of flight;
b. Direction of scanning.

gratings; and 7 are matrix radiation receivers. For the case of stationary input mirrors, a band of the earth's surface is photographed which is taken in by the long side of the slot diaphragms oriented perpendicular to the line of flight. In this case, there is the capability of shifting the viewing band by changing the setting of the reflectors, taking in the necessary portions of the earth's surface. The reflectors can operate in scanning modes also (when taking photographs from high altitudes). In this case, during each scan, a strip will be recorded corresponding to the long side of the slot diaphragms, now oriented along the line of flight.

In the configurations of the various video spectrometers, the light going from the earth's surface passes through the input objective and the slot diaphragm to the dispersion system, which breaks the slot image down into the spectrum. The orientation of the slot and its spectral decomposition are mutually perpendicular. The image which is cut out by the slot diaphragm and scanned by the dispersion system in a frame is read out by a matrix photodetector. In this case, each line of the frame being read out corresponds to the image of the same narrow strip of the earth's surface in a definite region of the spectrum; in such a configuration, the number of spectral bands can be equal to the number of lines in the matrix.*

*The appropriate structural design was proposed by the following staff members of the Space Research Institute of the USSR Academy of Sciences: G.A.Avanesov, A.G.Sychev, Ye.G. Lykashova, Yu.K. Terent'yev and S.N. Sosin.

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The operational cycle of the matrix photodetectors consists of the storage of the light energy in the light sensitive section, the transfer of the information to the memory and reading it out through a buffer register. The possibility of combining several lines in one during the readout, selecting particular lines or groups of them, as well as the capability of summing signals with respect to several elements of each line makes it possible when photographing various objects of the earth's surface to provide for flexible variation in changing the spectral and spatial resolutions, and combinations of spectral bands.

Both spectrometers generate a single flow of video information intended for simultaneous automated processing by means of computers. The question of the possibility of utilizing such instruments or the necessity of including yet another special spectrometer in the complex to study the parameters of the atmosphere, the knowledge of which would make it possible to carry out corresponding radometeric correction of the measurements of the spectral brightness of ground formation is being studied. The expediency of combining sensors for the optical band with microwave systems in a single information and measurement complex is obvious.

The first model of an aircraft spectrometer designed in the configuration described above is in the testing stage. The charge coupled device matrix used in this instrument provides for photographing the earth's surface in a wavelength range of 0.35-1.1 micrometers with various operationally variable resolutions and numbers of spectral channels. The matrix contains 250 elements per line and 140 lines.

Automated methods of classification based on the data of remote sounding of the kinds and states of ground formations are based primarily on the spectral differentiation of the latter. It has become obvious that one spectral criterion in a whole series of cases is inadequate for a unique interpretation of remote measurements. Because of this, many researchers are taking the approach of expanding the criteria space, which are easily subjected to formalization, and are primarily attempting to utilize structural characteristics of the ground objects being studied from space as such a criterion. For this, orthogonal image transforms are effected (Fourier, Hadamar, Karunen-Loev, etc), which make it possible to automate the singling out of extended objects of a definite structure, determine their predominant azimuthal orientation and spatial structural homogeneity. Research in the indicated field is likewise underway at the IKI, and in this case, two approaches have been planned to the problem of combining the analysis of the radiation characteristics of ground formations in different ranges of the electromagnetic spectrum and the characteristics of the spatial distribution of the brightnesses of these formations. It is provided in both approaches that the area being analyzed (we shall call it the operational unit) exceeds the size of the resolution element of the raw video data by several times.

APPROVED FOR RELEASE: 2007/02/08: CIA-RDP82-00850R000200080012-8

APPROVED FOR RELEASE: 2007/02/08: CIA-RDP82-00850R000200080012-8

In the first case, structurally homogeneous operational units are initially selected, and the ratios of the measured brightnesses in different electromagnetic spectral bands are analyzed only for them. In the second approach, the spatial frequency spectrum is obtained for each operational unit and its characteristic is used as an additional classificational criterion for the ground formations being studied. If in this case numerical values of the energies in several specified spatial frequency spectral bands are obtained, then one can make complete and full use of the procedures, hardware and algorithms for the structural analysis of the images which are used everywhere in processing multispectral video data. The question of performing the structural analysis directly on board a space vehicle is also being studied, where this analysis provides for obtaining and transmitting to earth the video information depicting the distribution of energy at the ground surface in different spatial frequency spectral bands. The indicated problem requires the production of images with a spatial resolution, as well as their structural analysis, which can be performed by means of on-board computers or by optical means.

One of the possible optical configurations for the design of the on-board complex for the execution of multiband photography of the earth's surface simultaneously in several electromagnetic spectral bands (~~as is being~~ done now) and in several spatial frequency spectrum bands is shown in Figure 3. The complex includes four functionally different systems: A is the optical scanning of the ground surface; B is for the measurement of the intensity of the radiation in different electromagnetic wave spectral bands; C is for the measurement of the energy in different spatial frequency spectral bands; D is for the coding, packaging and transmission of the video information.

In the optical scanning system, mirror 1 provides for element by element inspection of the terrain transverse to the flight path of the vehicle. Objective 2, which is distinguished by a high resolution, generates an instantaneous image of a portion of the object being photographed, which is fed through semitransparent mirror 3 simultaneously to both measurement systems B and C. Two identical field diaphragms, 4 and 4', register the same instantaneous field of view in the complex in both measurement systems, where this field of view determines the spatial resolution of the video information transmitted by it to the earth (this resolution is substantially below the resolution of the intermediate image generated by objective 2 in the plane of field diaphragm 4).

System B includes the dispersion optics (for example, diffraction grating 5) and can be designed in various well-known configurations of existing optoelectronic instruments for multispectrum photography, at the output of which there are photodetectors 6, which produce the video signals of the images in different electromagnetic spectral bands.

APPROVED FOR RELEASE: 2007/02/08: CIA-RDP82-00850R000200080012-8

APPROVED FOR RELEASE: 2007/02/08: CIA-RDP82-00850R000200080012-8

In system C for the measurement of the energy in different spatial frequency spectral bands, block 7 transforms the derived image to a coherent one. Space-time light modulators of the "Fototitus" type or an intermediate photographic image vehicle (preferably for repeat use, for example, on a thermal photographic plate), which is thereafter illuminated by coherent laser light, can be employed as such a unit. Positioned after the unit for the conversion of the image to a coherent one is the optical system (lens) 8, in the focal plane of which a Fourier spectrum of spatial frequencies of the image of the portion of the ground surface is formed, where this image is produced in the plane of field diaphragm 4. This spectrum is split into bands by optical splitter 9. The energy in each of the bands is fed to one of the photodetectors, 10, which generate the video signals of the images depicting the characteristics of the structure of the recorded terrain in different spatial frequency spectral bands.

The number, arrangement and configuration of the spatial frequency spectral bands should be chosen depending on the photographic assignments. If the spatial frequency spectrum is constructed by an optical system such as shown in the Figure, then when it is broken down into bands, it is expedient to use ring and radial filters, since the distance from the center of spectrum is proportional to the spatial frequency, while the distribution energy over the different radial directions of the spectrum maps the azimuthal directionality of the elements of the structure of the recorded terrain. It is important to know the latter, for example, when analyzing sea waves and ascertaining the changes in their spatial structure.

The derivation and visual analysis of so-called spatial-spectral band images can be of interest, where each element of them corresponds to an operational unit and encodes the quantity of energy in a definite spatial frequency spectral band. An example of such images is shown in Figure 4. The original fragment, a, was broken down in a computer into operational units having a size of 8 x 8 resolved elements, and a two-dimensional Hadamar spectrum was obtained for each of them. The two other fragments were constructed from the results of a structural analysis of the original. Here, the optical density of each element corresponds to the sum of the energies in the Hadamar spectral band shown in the schematic; fragment b maps the zero harmonic of this spectrum. In examining the photographs shown in Figure 4, attention is drawn to the fact that elements of definite dimensions smaller than an operational unit, i.e. the resolution at the ground surface of spatial-spectral band images, are mapped into these spatial-spectral band images (see fragment c). In other words, by transmitting the spatial-spectral band video information with a resolution at the ground surface of, for example, 50 to 80 m, one can obtain data on ground formations of substantially smaller dimensions, for example, 2 to 5 m*.

*The proposals for the method and the design principle for the equipment to photograph the ground surface in different spatial frequency spectral bands were worked out by the author of this article in conjunction with V.A. Kottsov and Yu.M. Chesnokov.

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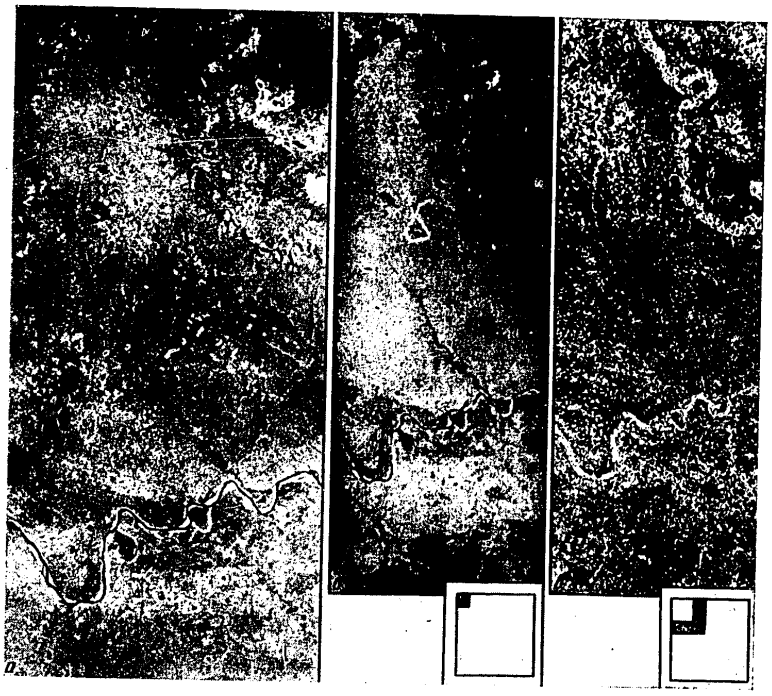

Figure 4.

Many of the questions touched on in this paper are absolutely just by way of discussion and require further theoretical analysis and experimental checking. Despite this, the level of the work done on the indicated problems even today makes it possible to start the realization of a series of specific proposals for further research in the field of remote sending.

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