DETERMINATION OF THE INFORMATIONAL CHARACTERISTICS OF SYSTEMS FOR REMOTE SENSING FROM SPACE

O.M. Pokrovskii

A.I. Voeikov Main Geophysical Observatory, Leningrad
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We have analyzed the main objects of iterest in ecological monitoring from space. A classification of user requirements for satellite information needed for the solution of various applied problems of the national economy is given. A comparison of these requirements with the characteristics of the available instrumentation intended for use onboard meteorological satellites and satellites employed in the exploration of natural resources is presented. Optimizing against the criterion of maximum information content has allowed us to select out the four sets of spectral sounding channels best suited for solving problems in the following four areas: oceanology, hydrology, geology, and forestry and agriculture. A mathematical economic model is also proposed that allows one to differentiate the spectral channels according to their degree of economic efficiency.

In recent years satellite instrumentation has continued to develop apace and has now been adequately checked over the course of numerous spaceborne experiments. Satellite data are now widely used to solve various applied problems. However, the question of the degree of correspondence of the satellite data with the user requirements has not yet been answered. In this paper we present an analysis of the basic characteristics of satellite instrumentation. We also discuss some methods for optimizing such information and economic significance of such instrumentation.

OBJECTS OF INVESTIGATIONS

The general structure of investigations based on the satellite data is shown in Fig. 1. Two main areas of research, i.e., global circulation problems and geophysical processes, are involved in most ecological problems. Among the global circulation processes most important are the energetic and hydrological cycles as well as the combination of biogeochemical cycles. The latter cycles involve, for example, the carbon and nitrogen cycles, and the cycles of other elements, which have not yet been adequately studied. An alternative trend in global ecological monitoring is to monitor the geophysical processes in the ocean, in the atmosphere, and over the continent. The above–mentioned scientific problems are closely related with a number of earth sciences (geology, oceanology, hydrology, and climatology) and with certain branches of the national economy (forestry and agriculture).

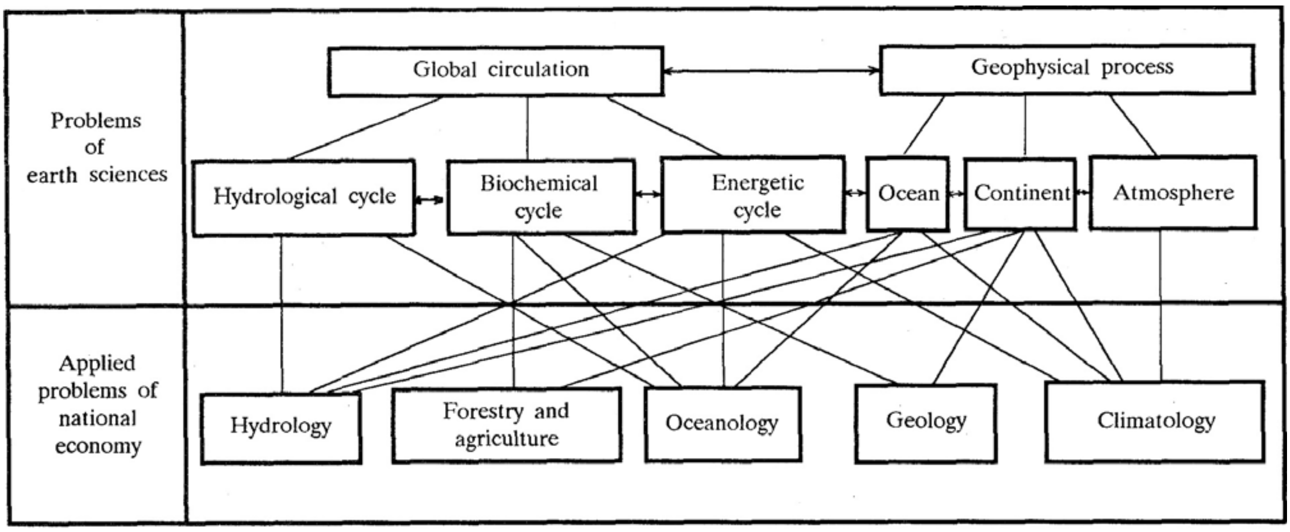

FIG. 1. Structure of the problems in ecological monitoring based on the satellite data.

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USER REQUIREMENTS FOR THE INFORMATION OBTAINED FROM SPACE

In the majority of cases the users of the satellite data can quite clearly formulate their own needs for the basic informational characteristics of the instrumentation (e.g., spectral channels, geometry of the experiment, spatial and temporal resolution, and so on). In the investigations discussed below we use the outline of such requirements given in Ref. 1, which covers the needs of the four groups of problems of the national economy: I – oceanology (102 requirements), II – hydrology (33), III – geology (36), and IV – forestry and agriculture (32). Table I shows requirements that are important for solving several applied problems from each of the four groups. The great variety of the requirements make it nesessary to select the optimal conditions of the experiments for solving the entire set of problems of the national economy.

TABLE I. Requirements for the optical remote sensing systems

Groups of problems related to the national economy	Spatial resolution (m)	Viewing angles	Viewing swath (km)	Spectral intervals, μm		
				Visual range	Near–IR range	IR range
1	2	3	4	5	6	7
I. OCEANOLOGY						
1. Charting coastal currents and mapping tides	60–90	45–60	200	0.41–0.44 0.45–0.47 0.51–0.53 0.55–0.57 0.57–0.64 0.64–0.69 0.68–0.70	0.77–0.80	10.9–12.6
2 Water turbidity	50–100	0–30	40–100	0.3–0.5 0.5 0.65	0.90	–
3. Charting the ocean surface (color, salinity, oxygen content, organic pollutants, and temperature)	30–60	0–20	100	0.37–0.40 0.40–0.43 0.43–0.45 0.45–0.48 0.48–0.51 0.51–0.53 0.53–0.55 0.55–0.57 0.57–0.61 0.61–0.66 0.66–0.70	0.70–0.82	10.9–12.6
4. Sea ice	100–200	0–30	100–200	0.45–0.53 0.50–0.58 0.53–0.57 0.57–0.64 0.64–0.69	0.73–0.82 0.8–1.1	10.9–12.6
5. Population and migration of pelagic organisms. Organic pollution	1000	0–10	50–100	0.45–0.53 0.53–0.57 0.57–0.64 0.64–0.69 0.50–0.58	0.73–0.82	8–14
6. Pollution of coastal waters	10–30	0–10	50–100	0.30–0.40 0.45–0.53 0.48–0.59 0.53–0.57 0.50–0.58 0.57–0.64 0.64–0.69	0.73–0.82 0.80–0.90	10.9–12.6

TABLE I. (continued)

1	2	3	4	5	6	7
II. HYDROLOGY 1. River basins	5–10	0.30	200	0.68–0.74	0.78–1.2	—
2. Floods	5–15	0–10	50	0.67–0.75	0.7–1.3	10–14
3. Marshes	3–5	0–10	50	0.51–0.57 0.53–0.57 0.57–0.64 0.64–0.67 0.64–0.69	0.7–1.3 0.73–0.82	10.9–12.6
4. Snow cover (density, melting)	10–50	0–20	200	0.38–0.51– 0.44–0.52 0.50–0.67 0.69–0.88	0.82–0.84 0.7–1.3 0.49–1.2	—
5. Glaciers and ice cover of rivers and lakes	5–15	0–30	50–100	0.44–0.50 0.50–0.55 0.46–0.52 0.52–0.58 0.50–0.58	0.79–0.84 0.8–1.3	8–14
6. Rains and moistering of the soil	5–30	0–10	50	0.49–1.2	0.78–0.84 0.8–1.3	8–14 10.9–12.6
7. Pollution of revervoirs	5–10	0–10	200	0.3–0.4 0.48–0.59	0.8–0.9	8–14 10–12
III. GEOLOGY: 1. Topographic mapping	10–20	0–30	100–200	0.51–0.63 0.63–0.70	0.70–0.89 0.89–1.0 0.8–1.3	8–14
2. Volcanic activity	10–20	0–20	100–200	0.4–0.7	—	10–12 8–14
3. Mapping of deposits	10–20	0–30	100–200	0.51–0.63 0.63–0.70 0.40–0.48 0.51–0.57 0.62–0.67	0.70–0.89 0.89–1.0	8–10 10–10.6 10.6–12.9 9.3–12.8
IV. FORESTRY AND AGRICULTURE: 1. Pedological charting	5–15	0–45	100–200	0.62–0.67	0.72–0.85 1.5–1.8 2.0–2.6	8–14
2. Soil erosion	5–10	0–45	40–50	0.40–0.48 0.51–0.57 0.62–0.67	0.73–0.78	—
3. Inventoty of forests	10–20	0–10	50–100	0.55–0.58 0.70–0.74	1.5–1.8 2.0–2.6	
4. Forest fires	10–20	0–70	500–1000	0.4–0.7	3.5–5.4	8–14
5. Assessment of the state of crops	5–10	0–10	50–100	0.55–0.58 0.51–0.57 0.59–0.68 0.66–0.70 0.70–0.74	0.76–0.83 0.5–1.8 2.0–2.6	8–14
6. Plant deseases	10–15	0–10	40–50	0.40–0.44 0.51–0.57 0.55–0.58 0.58–0.68 0.70–0.74	0.78–0.84 0.83–0.86	8–14

The requirements differ first of all in the selection of spectral sounding channels. The variety of positions and widths of the spectral intervals in the visible and IR ranges is shown in the upper part of Figs. 2 and 3. The wavelength scale is given in the upper part of the figures. The notation of the problems follows the outline given in Table I. The spectral characteristics of the multichannel remote sensing systems in use now are shown in the lower part of these figures. The results of comparing the lower and upper parts of Figs. 2 and 3 indicate that the instrumentation available is not optimal and, as a consequence, the problem of defining the optimal parameters of such remote sensing systems has arisen. Requirements for the active and passive superhigh–frequency measuring systems intended for the purpose of solving a number of problems of the national economy from the groups I–IV, are listed in Table II. The ends of spectral subranges are shown in Table III.

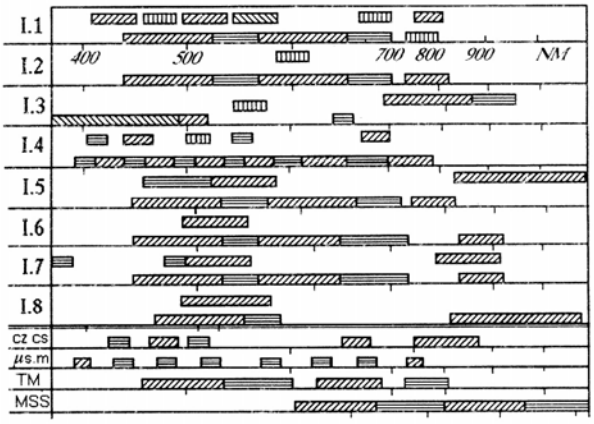

FIG. 2. Distribution of the users' requirements (group "oceanology") for the spectral sounding channels in the visible and IR ranges.

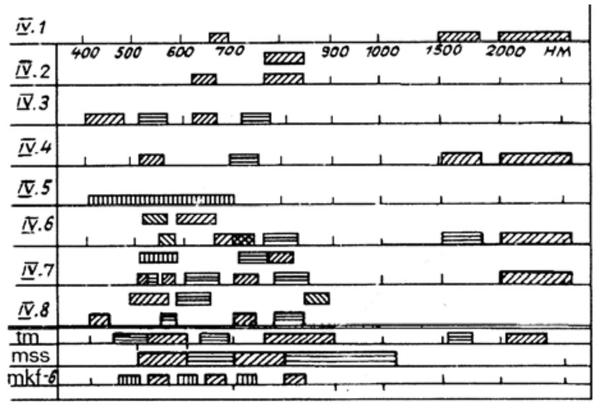

FIG. 3. Distribution of the users' requirements for the group of problems "forestry and agriculture" for the selection of the spectral sounding channels in the optical and near–IR ranges.

TABLE II. Requirements for the superhigh–frequency remote sensing systems.

Groups of problem of the national economy	Particular problems of the national economy	Employed spectral ranges	Type of the system (active or passive)	Instrumentation
I. Oceanology	1) Monitoring of sea ice drifts	*Ku, X, C, S, L*	pass.	Multichannel radiometer
	2) Monitoring of reverse drift of sea ice	*Ku, X*	pass.	Radiometer (measurements near nadir)
	3) Topographic mapping of the ocean	*Ku*	act./pass.	Laser range–finder operating in the nadir direction
	4) Temperature distribution in the atmosphere and near the ocean surface	*Ka, K, Ku, X*	pass.	Multichannel scanning radiometer
	5) Wind near the ocean surface	*Ku, C*	act./pass.	Dual–beam laser radar operating in two azimutal directions
	6) Charting the ocean salinity	*L*	pass.	Radiometer (measurements in the nadir direction)
II. Hydrology	1) Mapping of water surface	*C, L*	pass.	———
	2) Precipitations	*Q, Ka, K*	pass.	———
	3) Water vapor in the atmosphere	*Q, Ka*	pass.	———
III. Forestry and agriculture	1) Ground moistening	*L*	pass.	Scanning radiometer lidar with two detectors linked to antennas for reception of the vertically and horizontally polarized signals
	2) Assessment of the plant canopy state (index leaf surface, total biomass, bioproductivity)	*C*	act./pass.	
IV. Geology	1) Geological structure and morphological mapping	*L*	act./pass.	Laser range–finder radiometer (measurements in the nadir direction)
	2) Mapping of hidden topographic features	*L*	act./pass.	

TABLE III. Ends of the spectral intervals in the superhigh frequency range

Symbol of the interval	*W*	*Q*	*Ka*	*K*	*Ku*	*X*	*C*	*S*	*L*	*P*
Ends of the interval (cm)	0.13–0.33	0.33–0.63	0.72–1.0	1.0–1.9	1.9–2.5	2.5–3.5	3.5–7.1	7.1–15.8	15.8–63	63–100

ANALYSIS OF OPERATING OBSERVATIONAL SYSTEMS

The data presented in Tables I and II demonstrate the variety of requirements for the measuring instrumentation. Using methods of optimal experimental design, we succeed in optimally design[2] of various multipurpose systems. Below we consider only the degree of correspondence between the users' requirements and the characteristics of the remote sensing systems presently available.[3,4]

Optical range. Most suitable for solving oceanological problems is an MKSM multichannel apparatus. The channels of this biospectrometer centered at λ = 415, 449, 484, 534, 569, 621, and 676 nm ($\Delta\lambda$ = 10 nm) make it possible to solve many oceanological problems. The impossibility of measuring in the near–UV (0.3–0.4 μm) and near–IR (0.8–0.9 μm) should be mentioned among disadvantages of this apparatus. It is worth noting that the configuration of the MKSM instrument better meets the requirements of oceanological problems than an CZCS instrument used onboard NIMBUS–7. To solve the problems of hydrology, geology, forestry, and agriculture the following instruments were used: an MKF–6 apparatus, the type an MSU apparatus and a RSS–2 and RSS–3 apparatuses, and some others. Unfortunately, the scheme of measurements used in MKF–6 six–channel camera was not very good since the results of measurements at 660, 620, and 820 nm are affected by ozone and water vapor. The measurement channels of an MSU apparatus selected in analogy with an MSS apparatus (of American production) also do not completely meet the requirements for certain applied problems (see Table I). A better job is done of avoiding these problem in a TM apparatus (see Table IV). Therefore there exist two possibilities to meet the users' requirements. The first is to use an apparatus on a level with the TM. The second assumes the use of the RSS–3M spectrometer together with the MSU and MKF–6 apparatuses, since the RSS–3M apparatus makes it possible to make spectral measurements in the spectral interval from 0.4 to 0.7 μm with a spectral resolution[5] of 5 nm.

TABLE IV. Comparison of the spectral channels of an MSU and TM apparatuses.

MSU	TM
0.5–0.6	0.45–0.52
0.6–0.7	0.52–0.60
0.7–0.8	0.63–0.69
0.8–1.1	0.76–0.90
—	1.55–1.75
—	10.4–12.5
—	2.08–2.35

Near–IR region. In this region the MSU apparatus more or less meets the needs of hydrological and geological problems. The needs of forestry and agriculture can hardly be met with the MSU and MKF–6 apparatuses since in these devices there are no measurement channels in the spectral intervals 1.5–1.8 and 2.0–2.6 μm, nor in the atmospheric transparency window near 3.7 μm.

Thermal—IR range. For the solution of some problems, it is necessary to have at least two channels within the atmospheric transparency window from 8 to 12 μm.

Superhigh frequency radiometry. Table II presents an outline of requirements for an active–passive measuring system operating in the wavelength range from 0.1 to 100 cm. The best current instrumentation is the IKAR–1 superhigh frequency radiometric system produced by the Institute of Radio Electronics of the USSR Academy of Sciences. This system only partly meets the requirements listed in Table II. A combination of the base radiometers (with the wavelengths 0.3, 0.8, 1.35, 2.25, and 6.0 cm) operating in the nadir direction and of the Delta scanning radiometers solves the following problems:

1) measurements of the temperature and humidity distributions near the ocean surface and

2) measurements of the wind velocity near the ocean surface.

The use of the R–400 scanning radiometer makes it possible to solve two other problems: 1) assessment of the state of the plant canopy, and 2) charting of water surfaces.

The PRV radiometer is intended for topographic ocean mapping. Other problems are either very hard to solve or can be only solved in part.

OPTIMAL DESIGN OF THE OBSERVATIONAL SYSTEM

The importance of optimal design of satellite remote sensing systems is determined by a number of factors including the high expense of spaceborne experiments, weight and power limitations, limitations of information storage, and so on. In addition, it is nesessary to keep in mind certain aspects of the problem of the interpretation of satellite data: mathematically ill–posed inverse problems of reconstructing the parameters of a medium from the characteristics of the emitted, reflected, and absorbed radiation; uncontrolled fluctuations of the optical parameters of the atmosphere, etc.

In solving the problems of the design remote sensing experiments, two extreme cases must be eliminated, i.e., either an excess or an insufficiency of the extracted information, which can occur as a result of improper selection of the conditions of the experiments. In both cases the solution of the inverse problem may be depreciated to a considerable extent because of the ill–posed character of the problem.

We have developed two approaches to the solution of the problem of the design of multipurpose remote sensing systems: an informational approach and an economical one.[6] In both cases it is assumed that the users of the information, who represent the interests of various problems of the national economy, can accurately formulate their requirements for the basic characteristics of the systems (i.e., for spectral channels, geometry of an experiment, spatio—temporal resolution, and so on). Below we use the outline of such requirements presented in Ref. 1.

Informational approach. The main idea of this approach[2] consists of selecting the most important factors and determining the corresponding vectors of leading factors in the formalized specification space. A way of constructing the specification space and modifiing the factor analysis algorithm is presented in Refs. 2 and 6. The results of determining the optimal combinations of spectral intervals for the solution of problems of groups I–IV are presented in Table V. The calculated results for different applied problems of the national economy have been presented in Ref. 2. It should be emphasized that the data presented in the first line of Table V were obtained only from an analysis of user requirements on information, which ignore the selectivity of distortions caused by the atmosphere in different intervals of the electromagnetic spectrum as well as economic aspects of the spaceborne experiments. The second line of Table V presents the ends of the spectral sounding intervals, which have been refined taking into account the elimination of the absorption bands of H_2O, O_3 and NO_2 in the intervals 0.38–0.42, 0.57–0.62, 0.755–0.760, 0.785–0.790, 0.810–0.845, 0.910–0.960, and 1.10–1.16 μm. The strong contribution of molecular scattering in the interval 0.30–0.40 μm is responsible for the low information content of this spectral channel. Therefore, this spectral channel is not used in the remote sensing systems (see Table VI).

TABLE V. Selection of the spectral intervals (μm) *by the method of factor analysis.*

Groups of problems of the national economy	Factors						
	1	2	3	4	5	6	7
I. Oceanology	0.45–0.53	0.64–0.69	0.70–0.90	0.57–0.64	0.82–1.30	0.50–0.58	0.40–0.44
	045.–0.53	0.64–0.69	0.70–0.75	0.62–0.64	0.96–1.10	0.50–0.57	0.42–0.44
	0.70–1.30	0.51–0.59	0.44–0.52	0.67–0.74	0.57–0.67	0.30–0.40	0.38–0.49
II. Hydrology	0.96–1.10	0.51–0.57	0.44–0.52	0.67–0.74	0.62–0.67	0.70–0.75	0.42–0.49
	0.51–0.63	0.62–0.70	0.70–0.89	0.40–0.51	0.8–1.30	—	—
III. Geology	0.51–0.57	0.62–0.70	0.70–0.75	0.42–0.51	0.96–1.10	—	—
IV. Forestry and agriculture	0.51–0.57	0.59–0.70	0.75–0.78	0.70–0.74	0.40–0.51	0.55–0.58	0.88–1.30
	0.51–0.57	0.62–0.70	0.76–0.78	0.70–0.74	0.42–0.51	0.55–0.57	0.96–1.10

TABLE VI. Parameters of the space instrumentation in the visible and near–IR.

Apparatus	Spectral channels (μm)	Spatial resolution (in the nadir direction) (m)	Swath width (km)	Comments
MSS	0.50–0.60 0.60–0.70 0.70–0.80 0.80–1.10	80	185	Multispectral scanner
TM	0.45–0.52 0.52–0.60 0.63–0.69 0.70–0.90	30	185	LANDSAT – 4.5 thematic mapper
CZCS	0.43–0.45 0.51–0.53 0.54–0.56 0.66–0.68 0.70–0.80 1.05–1.25	825	1636	Coastal zone color scanner
HRV	0.50–0.59 0.61–0.68 0.79–0.89 0.51–0.73	20	60	Photography of the sea surface

An analysis of the potentialities of the available instrumentation from the standpoint of user requirements is presented below. Now if we arrange the selected spectral channels according to increasing wavelength, we shall be able to establish relationships among analogous channels associated with the problems of different groups (see Table VII). As can be seen, the short–wave channel 0.42–0.44 μm is used only for solving the oceanological problems. Analyzing the data in Table VI one can also see that the channel 0.43–0.45 μm is used only in an CZCS oceanographic instrument. The set of channels presented in Table V for oceanological problems has many features in common with the set of spectral channels of the CZCS instrument (see Table VI). Differences in the ends of the spectral intervals are due to an improper account of the users' requirements (see Table I) and the spectral optical characteristics of the atmosphere in the configuration of the CZCS instrument. Thus, for example, the CZCS instrument has no spectral channel in the interval 0.62–0.64 μm, which figures in the solution of all the listed oceanological problem.

TABLE VII. Optimal spectral sounding channels corresponding to the basic groups of problems.

Groups of problems of the national economy	Spectral sounding channels (μm)								
	1	2	3	4	5	6	7	8	9
I. Oceanology	0.42–0.44	0.45–0.53	0.50–0.57	—	0.62–0.64	0.64–0.69	0.70–0.75	—	0.96–1.10
II. Hydrology	—	0.44–0.52	0.51–0.57	—	0.62–0.67	0.67–0.74	0.70–0.75	—	0.96–1.10
III. Geology	—	0.42–0.51	0.51–0.57	—	0.62–0.70	—	0.70–0.75	—	0.96–1.10
IV. Forestry and agriculture	—	0.42–0.51	0.51–0.57	0.55–0.57	0.62–0.70	—	0.70–0.75	0.76–0.78	0.96–1.10

The data presented in Table VII also show that measurements in the two narrow spectral intervals 0.55–0.57 and 0.76–0.78 μm are necessary only for solving the problems of the group "forestry and agriculture." However, the information in these channels cannot be provided by any of the instruments available. The narrow spectral channel No. 6 is required only by users from the groups "oceanology" and "hydrology," while problems from the groups "geology" and "forestry and agriculture" require only information obtained over the wide spectral interval 0.62–0.70 μm, which joins channels 5 and 6 of groups I and II. This spectral interval is presented by a single channel in the available instrumentation.

This means that the current instrumentation does not meet the requirements of users from the groups "oceanology" and "hydrology" as far as obtaining data in channels 5 and 6 is concerned.

Comparing the data presented in Tables V and VII, one can see that the information provided by measurements with the TM cartographer best of all meets the requirements for the "geology" group of problems and to a less degree for the group "hydrology". The MSS multichannel spectral scanner meets the requirements much less. The matter is that it cannot provide the information for channel 2 (see Table VII), and channels 5 and 6 of the optimal set have been merged into one channel in its configuration. The information in channels 0.70–0.80 and 0.80–1.10 μm is significantly distorted as a result of the absorption of the reflected radiation by atmospheric gases.

So the above–presented data clearly show that the modern satellite instrumentation is, to a considerable degree, inadequate to the requirements of the users of information from different branches of the national economy.

Economical approach. Since the development of future satellite remote sensing systems should be sponsored by those branches of the national economy that make use of this information, the question arises of the economic profitability of the instrumentation intended for use onboard spaceborne platforms for long times. The multispectral and multipurpose character of satellite information allows one to analyze the problem of the optimal design of the corresponding observational systems from the standpoint of maximizing the integrated index of economic efficiency of a multipurpose system V, given that the particular efficiencies for each problem $v_i (i = 1, \ldots, N)$ are bounded on either side by given inequalities.

Let us now consider the formulation of the problem in more detail. First we denote by C_{ij} the economic efficiency of using the jth measurement channel ($j = 1,\ldots, M$) for solving the ith particular problem, by d_j the total expense of operatind the system and processing the information derived from the measurements made using a multipurpose system operating in the jth channel, and by b_i^+ and b_i^- the maximum and minimum values of the economic efficiency of using the obtained data for solving the ith problem. Then we may write the following expression for the economic efficiency K_j of the jth measurement channel:

$$k_j = \sum_i c_{ij} - d_j \quad (j = 1,\ldots, M).$$

By introducing the variable y_j, which is an indicator of activating the jth channel in the observational system, i.e., $y_j = \begin{cases} 0 \\ 1 \end{cases}$, the problem of optimal design can be reduced to the standard problem of Boolean integral programming[6]

$$\min_{(y = y_1,\ldots,y_M)} \left\{ -\sum_{j=1}^{M} K_j y_j \right\}, \tag{1}$$

$$y_j = \begin{cases} 0 \\ 1 \end{cases} \quad (j = 1,\ldots, M), \tag{2}$$

and

$$b_i^- \le \sum_{j=1}^{M} c_{ij} y_j \le b_i^+ \quad (i = 1,\ldots, N). \tag{3}$$

One of the most efficient numerical algorithms for solving problem (1)–(3) is the Balash method.[7] We used this method, implemented as a software package on an ES series computer, to design various versatile systems of remote detection of natural objects from space.[6] As has been already noted, the problems discussed in Ref. 1 are divided into four large groups: oceanology, geology, hydrology, and forestry and agriculture. Each of these groups is, in turn, divided into several subgroups. The number of specific problems involved in each of the main groups varies from 9 to 14. To illustrate the method, let us consider the results of selecting the optimal set of spectral sounding channels for versatile oceanological photography. Below, a list of the particular problems involved in the group "oceanology" is given.

1. State of the sea surface
2. Water turbidity
3. Sea ice
4. General purpose photography of the coastal zone
5. Charting coastal currents and tides
6. Global charting currents and the ocean surface
7. Charting of the coast line and shallow waters
8. Bathymetry and topography of ice
9. Population and migration of pelagic organisms
10. Pollution of coastal waters
11. Effect of pollution on the aquatic medium
12. Studies of bars and reefs

The total number of elementary spectral sounding channels for solving the 12 problems ($N = 12$) involved in the group "oceanology" is 37 ($M = 37$). In this case the number of elementary spectral intervals m_i required to solve the ith particular problem normally lies within the limits $18 \le m_i \le 33$. This means that any particular problem requires a large amount of information, which normally exceeds half the bulk of information required for the entire group of problems "oceanology." When developing multispectral instrumentation, one can assume that the total expenses will be inversely proportional to the width of the spectral interval and directly proportional to the spectral resolution. Let β be the expense of constructing one spectral channel with a spectral resolution of 1 nm. Then the expenses of constructing a channel with spectral resolution $\Delta\lambda$ (nm) will be $d_{\Delta\lambda} = \beta/\Delta\lambda$. Let b be the total efficiency of use of the information obtained from space in oceanology. We also denote by b_i the efficiency of use of the information for solving the ith oceanological problem. In this case $\sum_i b_i = b$. Let all of the b_i values be identical. Then $b_i = b/N$ is the average efficiency corresponding to the particular problem. Then introducing the threshold value a ($0 < \alpha < 1$) for the admissible deviations from the average efficiency, we can write the constraints as follows:

$$b_i^+ = (1 + \alpha)\, b_i, \quad b_i^- = (1 - \alpha)\, b_i, \text{ where } i = 1, \ldots, M .$$

Now we denote by J_i the numbers of the channels entering into the requirements for the observational system of the ith particular problem. Let χ_j be the indicator function of the jth measuring channel

$$\chi_j(J) = \begin{cases} 1, & \text{if } j \in I \\ 0, & \text{otherwise} . \end{cases}$$

Hence it follows that the coefficients c_{ij} which appear in the formulation of the optimization problem (1)–(3) are given by

$$c_{ij} = \frac{b_i}{m_i} \chi_j(J_i) \text{, where } i = 1, ..., M, \text{ and } j = 1, ..., N . \quad (4)$$

Using the specific values $\beta = 5$ and $b = 31$ we calculated all of the parameters which enter into Eqs. (1)–(3). Computer calculations of the economic efficiencies of the measuring channels $j = 1,..., N$ shows that some spectral intervals are unprofitable (negative values of k_j) from the standpoint of multipurpose use of the observational system. For oceanology such channels lie in the spectral ranges 0.40–0.45 and 0.69–0.73 μm.

Most profitable economically are measurements in the spectral channels 0.53–0.55, 0.66–0.68, 0.59–0.61, 0.61–0.64, and 0.55–0.57 μm. In these intervals the maximum values of k_j are reached. Thus, even quite simple calculations enable one to select the channels which are most efficient economically.

Thus, in the optimal configuration for oceanological studies channels 1 and 7 are less profitable in comparison with the rest of the channels presented in Table VII. However, it should be noted that this conclusion is valid only for the design of special–purpose oceanographic instrumentation. Other groups of problems have their own unprofitable spectral ranges. Thus, for example, for the group "forestry and agriculture" it would be more profitable to obtain information in the spectral channel 1.5–1.8 μm than in the channel 0.96–1.10 μm (channel 9). Analysis of the hydrological problems has shown that there are no unprofitable channels for this group.

In conclusion we summarize our main results as follows:

1. Basic objects of ecological monitoring have been analyzed.

2. A classification of user requirements for satellite information is given for the four main groups of applied problems of the national economy.

3. Comparison of these requirements with the characteristics of the instrumentation available for meteorological satellites and satellites employed for exploration of natural resources has revealed that the current instrumentation is not optimal.

4. Optimization against the criterion of maximum information content has allowed us to find the set of spectral sounding channels suitable for the above–mentioned four groups of problems: oceanology, hydrology, geology, and forestry and agriculture.

5. The use of the mathematical economic models allows one to distinguish between the spectral sounding channels for each group of problems according to their economic efficiency.

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