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16 November 1979

USSR Report

GEOPHYSICS, ASTRONOMY AND SPACE

(FOUO 7/79)

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UPPER ATMOSPHERE AND SPACE RESEARCH

Translation

EXCERPTS FROM MONOGRAPH ON SPACE VEHICLE CONTROL

Moscow UPRAVLENIYE KOSMICHESKIMI APPARATAMI (Space Vehicle Control) in Russian 1978 signed to press 14 Nov 78 pp 33-99, 145-185

[Excerpts from book by G. D. Smirnov, Izdatel'stvo "Nauka," 17,500 copies, 192 pages]

General Description of Space Vehicle Control System

Description of System, Purposes and Problems

The control system in a general case is the totality of objects, considered as an integrated whole. It includes the controlled object, the controlling facility and the communication channels which ensure interaction among them.

In the implementation of a space flight a control system is used which consists of a space vehicle or controlled object, a ground flight support complex or controlling facility, and communication radio channels intended for the reception and transmission of different kinds of information. The totality of the means created for this purpose forms an extremely complex land-space control system of the remote type, involving one or more space vehicles with their spatial-temporal and functional characteristics, and elements of spaceflight ground support, situated at different geographic points on the continents and ocean areas over the earth.

The basis for control is the process of adoption of decisions which are formulated as instructions, orders and commands and which are sent to the controlled object for execution. In order to finalize a decision it is necessary to process and analyze a definite quantity of information reflecting the principal characteristics of the controlled object.

The ground-space system, consisting of an individual space vehicle and the ground support complex for its flight, forms a closed control circuit. The number of such circuits corresponds to the number of vehicles serviced by the ground support complex, and characterizes its handling capacity. The combination of some number of space vehicles serviced by a stipulated ground support complex can be called a multicontour control system.

Examining the functioning of an individual circuit, it is possible to obtain some idea concerning the operation of the entire ground-space control system. This simplifies description of the system and with some error reflects the quantitative and qualitative aspects of the processes transpiring in it.

The elements of the ground-space control system are situated in space and on earth. The system is characterized by great distances separating the space vehicle from the ground flight support facilities. A graphic idea concerning the magnitude of the system, for example, when carrying out interplanetary flights, is given by the extent of the communication channels, estimated using the distance and time of radio signal propagation. These data are given in Table 7.

Table 7

Time of Radio Signal Propagation as Function of Distance of Planets

Parameter	Moon	Venus	Mars	Jupiter	Saturn
Distance from earth, km	$4.05 \cdot 10^5$	$5 \cdot 10^7$	$8 \cdot 10^7$	$6.27 \cdot 10^8$	$1.3 \cdot 10^9$
Time of signal propagation to object and back in sec	2.7	$3.3 \cdot 10^2$	$5.3 \cdot 10^2$	$4.2 \cdot 10^3$	$8.6 \cdot 10^3$

The distribution of ground support elements has a global character. For example, the flight control facilities for the "Molniya-1" communication satellites are located in Moscow and Vladivostok, that is, at a distance of about 7500 km. The elements of the support complex for the manned spaceship "Soyuz-19," a mission carried out in 1975 under the "Apollo"-"Soyuz" program, were located in the territories of both the USSR and United States, as well as in the Atlantic Ocean area.

The totality of ground support facilities for space flights includes a number of data-measurement, radiocommunication and radiocommand subsystems. Working in these subsystems are various computers and groups of specialists ensuring normal functioning of individual elements and subsystems as a whole.

The Space Vehicle Control System, the highest control facility in the system, accomplishes the overall planning, coordination and finalization of control decisions in the "earth-space vehicle" system both for the space vehicles and for different ground support subsystems (the "ground").

A brief characterization of the "earth-space vehicle" control system makes it possible to assign it to the class of multicontour, multiphase, nonlinear and nonstationary complex systems similar to control systems of a national type.

The need for high speed and high accuracy of the system is caused by the requirements for a high reliability of control of a space vehicle, moving in space at an enormous velocity, and a great number of controlled and monitorable rapidly transpiring processes aboard vehicles and in their neighborhood.

The "earth-space vehicle" control system in full measure has all the criteria for complex systems, which include:
-- the possibility of a breakdown of the system into a number of isolated subsystems;
-- great dimensions of the system (the concept "dimension" includes a considerable number of individual subsystems, units, their spatial distribution and the time intervals of system functioning);
-- retention of the general purposefulness of functioning;
-- presence in the system and its individual subsystems of some number of inputs and outputs, which makes it possible to assign it to systems of the open type;
-- a hierarchy of the system (its multilevel structure), making it possible to adhere to the principles of subordination of the lower levels to the higher levels;
-- circulation of great flows of information of the stochastic (probabilistic) type with clearly expressed random characteristics;
-- the presence of a multipurpose aspect of functioning of individual subsystems, ensuring solution of the general problem assigned to the system.

A description and analysis of the "earth - space vehicle" system, like many other complex control systems, is accomplished using the theory of observability and controllability.

By the term "system observability" is meant the problem of determining its state on the basis of measurement (observation) data. System controllability is evaluated by the possibility of a purposeful change in its state during a definite time interval. The realization of controlling functions in the system assumes the presence of a close correlation between observability and controllability.

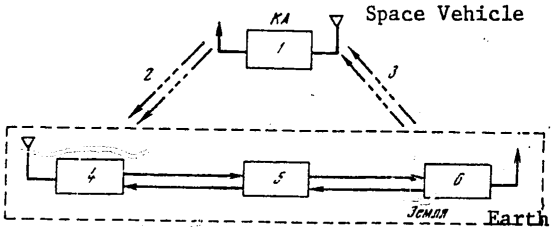

Fig. 10. Enlargement of block diagram of "earth-space vehicle" control system. 1) space vehicle; 2) reverse channels; 3) direct channels; 4) information-measurement subsystems; 5) information-computation subsystems; 6) command subsystems

The technical means for solving the observability problem for a spacecraft are the information-measurement subsystems, which in their input sections interact with the space vehicle, and in their output sections -- with the information-computation subsystems. The problem of space vehicle controllability is solved by autonomous, nonautonomous and mixed control means, the basis for which is radio command and programming subsystems. Figure 10 shows a block diagram of the "earth - space vehicle" system.

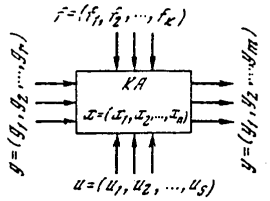

Fig. 11. Diagram of states of a space vehicle and "environmental" effect on vehicle.

The state of the space vehicle is determined by a number of parameters characterizing both the effect of the external medium and the controlling apparatus on it and the transpiring of processes within the vehicle. The parameters measured in flight are called monitorable, whereas those which are not measured are called nonmonitorable. The parameters expressing the external influences on the space vehicle are called "effects." However, the effects produced by the control system are called "controlling effects." The effects on a space vehicle not dependent on the control system are called perturbations; they can be broken down into two types: load and interference. The load, changing with time, is determined by the functioning of the space vehicle and the vehicle in essence cannot be protected against it. However, interference is associated with different undesirable phenomena and its decrease is desirable in any way possible.

The parameters characterizing the state of the space vehicle and on the basis of which control is accomplished are called controllable or operational. Their number can be extremely significant: for example, on spaceships of the "Soyuz" type this number attains 300. Usually, the more complex the vehicle, the greater is the number of different instruments and systems with which it is supplied and the greater is the number of controllable parameters necessary for control.

The parameters characterizing the effects on the space vehicle and its state are schematically shown in Fig. 11. Here the totality of the monitorable perturbations is denoted by the vector $g = (g_1, g_2, \ldots, g_n)$, the unmonitorable parameters are designated by the vector $f = (f_1, f_2, \ldots f_k)$, the controlling effects -- by the vector $u = (u_1, u_2, \ldots us)$, the controllable parameters -- by the vector $y = (y_1, y_2, \ldots, y_m)$. The totality of the monitorable and nonmonitorable parameters, characterizing the state of the space vehicle, is designated by the vector $x = g + f = (x_1, x_2, \ldots, x_n)$; in this case $n \geqslant m$.

The systems of equations, being a mathematical description of the space vehicle, relate the controllable (operational) parameters to all the external and internal effect on it. The mathematical description of the vehicle can be represented in the form of systems of differential equations (for continuous processes), difference equations (for discrete processes) or their combination for complex processes.

With known initial conditions the system of equations makes it possible, on the basis of the external effects g, f, u to find the vector of state x and the output controllable parameters y of the space vehicle.

Since a space vehicle is a dynamic system, it is necessary to investigate the functional dependence of u, g, f with stipulated functional changes of the external effects g(t), f(t), u(t) or their statistical characteristics. Then the control algorithm reads as follows:

$$y = \lambda \{u, g, f\},$$

where λ is a nonlinear, vector operator, making it possible, with known functions of time u(t), g(t), f(t) to determine y(t). By means of introducing the concept of an auxiliary vector, characterizing the state of the space vehicle, the mathematical description of space vehicle dynamics is represented by the Cauchy equations in normal form:

$$\dot{x} = \Psi_{\dot{x}} \{u, g, f, x\}; \; y = \Psi_{y} \{y, g, f, x\},$$

where x = dx/dt, and $\Psi_{\dot{x}}$ and Ψ_y are some (in a general case) nonlinear vector operators, transforming the time-dependent variables u, g, f, x. For solving these equations it is necessary to know the initial conditions, that is, the vector x(0).

If the controllable parameters gi and y_k are sufficient in order to determine the state of the space vehicle (vector x) in accordance with the Cauchy equation unambiguously, the vehicle is called completely observable. If using the controlling effects u_i it is possible to stipulate unambiguously the state of the space vehicle, the vehicle is called completely controllable. Such cases are ideal; in actual practice the observability and controllability of a space vehicle are realized with a series of limitations and assumptions.

A space vehicle, having the properties of observability and controllability, has a possibility for controlled transition from one state to another. In this case the subsequent state may differ from the preceding spatial-temporal parameters (range, velocity, direction) or functional parameters (temperature, pressure, current voltage), which characterize each subsystem (instrument) aboard the space vehicle.

The first group of parameters is extracted from the information on navigation measurements; the second is the telemetric parameters. The measured values of the parameters in both groups and the time t_i reflect the behavior of the vehicle at this same moment.

The total number of parameters determines the multidimensional space of states of the space vehicle and the limiting values of each parameter characterize the region of the state space in which the point representing the space vehicle may be situated. Any state of the vehicle is represented by a set of numerical values of the parameters and can be designated in state space by some point which can arbitrarily be called the "representative point." Its movement in state space corresponds to a change in the state of the space vehicle and the limits of movement determine the region of its admissible states.

For example, the vehicle's performance of a maneuver in space involves a change in the value and direction of its velocity vector, which is a reason for its transition from one state into another.

The totality of the controlling effects, considered in the form of the function u(t), is formed by the space vehicle control system and is one of its principal tasks. The controlling effects to which the space vehicle is subjected can be divided into two types. The first includes effects changing motion of the center of mass and rotation of the space vehicle relative to the center of mass. Since these effects exert an influence on the dynamics of the vehicle, they can be called dynamic. Among the controlling effects of the second type are those which exert an influence on the transpiring of processes in different instruments and systems of the spacecraft and exert no direct influence on its dynamic characteristics. Effects of this type can be called functional (for example, operation of scientific instruments, communications equipment, means for observing the earth from space).

In addition, an equally important task of the control system is the output of the written and oral orders and commands which are realized by the ground organizational-technical facilities of the system. The execution of this task is assigned to the Control Center, carrying out direction of the system as a whole.

The perturbations to which a space vehicle is subjected and which are not dependent on the control system are formed by the external medium surrounding the vehicle. The system "medium," in a general case, is the totality of the elements not entering into the makeup of the system, but exerting an influence on its state and behavior (that is, on controllability). Since the "earth - space vehicle" system is open, in this system there is a definite interaction with the external medium. The medium exerts an influence on the control system, and the latter, in turn, exerts an effect on the medium.

A space flight transpires in a different external medium whose properties exert different influences on the vehicle. In the first phase of the flight the space vehicle is situated in a medium with terrestrial characteristics; then for a long time it is present in space and in the final stage

[redacted]

is subjected to the influence of a Venusian medium with a temperature up to +400°C, a pressure of 100 atm and a gas composition of the atmosphere different than on the earth. And despite such diverse media, the spacecraft must have complete controllability, because only in this case will it accomplish the assigned mission.

The quality of control or the possibility of solving the assigned task are usually evaluated using the criterion of effectiveness of the system, by which is understood the degree to which the goal is attained. With this state space it is assumed that there is choice of some region within which the target point is situated. In many cases the target is not stipulated by a point, but by a target function, using which the control system "guides" the object in the optimum way.

Since a space vehicle is a complex apparatus with a great many assemblies, a number of controllable processes can transpire in it, some of which must be lessened, whereas others must be strengthened. For each process it is possible to formulate its particular target function and their totality determines the principal target function of the space vehicle. Problems in finding the target functions are solved using a special mathematical method, linear programming, and their solution makes it possible, by theoretical procedures, to determine the possibility of attaining a stipulated target in the optimum way.

Control Methods

As already mentioned, the principal elements of the control system are the controlled object, the controlling system and communication channels, ensuring the exchange of information. The controlling system forms and transmits control signals (commands) for the object to be controlled, from which, in turn, signals are transmitted to the controlling system, carrying information on its state. The communication channel used for the transmission of information on the state of the controlled object is called the feedback channel.

The presence or absence of a feedback channel makes it possible in a classification of control systems to designate them as closed or open. The principal difference between them is in the different methods for producing the controlling effects.

In open systems the controlling effects are not influenced by the actual course of development of the controlled process and the state of the surrounding medium. In such systems the control process is realized on the basis of rigorous programming methods, elimination of the effect of perturbations on the controlled object or compensation of this effect.

Control under a rigorous program assumes that the law of change of the controlled parameter is known and it can be introduced into the control system in advance. The method of control under a rigorous program is used in systems where the influence of perturbing effects is insignificant.

In order to increase the effectiveness of control in open systems use is also made of the method of compensation of the effect of perturbations on the controlled object. In this case the controlling system registers the magnitude of the perturbation and forms a controlling effect on the controlled object, the result of which should be a compensation of the influence of the perturbing effect. In addition to such systems, there are systems in which it is not the influence of the perturbing effects which is compensated, but the effects themselves.

In closed systems the controlling effects are produced on the basis of allowance for changes in the state of the controlled object. Such systems function in the following way. Given effects (commands) are fed to the controlling system; these are determined by the state of the controlled object. Information concerning this is fed through the feedback channel. A special device compares both states and in the case of their noncoincidence controlling effects are produced in the control system; these eliminate the mismatch which arises.

Depending on the type of commands, closed control systems can be classified as stabilization systems, systems with programmed control and "tracking" systems. In stabilization systems the controlled parameters are kept constant with the necessary accuracy. Programmed control is based on the representation of a command in the form of a function of some parameters, which determine the state of the controlled object. "Tracking" systems are closed systems intended for changing the state of the controlled object in conformity to a law unknown in advance, determined by some external medium.

In "earth-space vehicle" control systems it is systems with a feedback which are predominantly used. They ensure a higher effectiveness under conditions when the elements of such a system are spaced at great distances and are subject to a great number of perturbing effects arising during changes in the characteristics of the surrounding medium.

The overwhelming majority of space vehicles are multifunctional controllable objects, the makeup of which includes a number of subsystems, individual instruments and apparatuses. Their "matched" operation is directed to the performance of the goal assigned to a space vehicle. The control of such an object requires the presence of several controlling systems, each of which is intended for the realization of a definite function. If it is assumed that each subsystem of the vehicle consists of a controlled object and a controlling system, in this case it can be represented as a multicircuit control system. Since there is an interrelationship between these "circuits" in the performance of control processes, such systems can be classified as multiply connected control systems.

The control problem, involving the producing of controlling effects, is more difficult to solve the more complex is the space vehicle. In the simplest on-board subsystems for regulation or stabilization on the basis of a limited number of parameters (pressure, temperature, current strength or voltage) a relationship is established between the changes in these parameters and the controlling effect. In complex space vehicle subsystems there is an increase in the number of controlled parameters and accordingly the relationships between them are more complex. The relationships become less definite and frequently have a random, stochastic character.

In such cases the choice of an unambiguous solution may be difficult.

A multicircuit and multiply connected system for the control of elements and apparatuses, concentrated aboard a space vehicle, is the lower level of the general system for "earth - space vehicle" control constructed on the hierarchical principle.

The next, higher level is control of a vehicle by means of ground command radio links.

The scheme for control of a space vehicle on the basis of use of these radio links also provides for the presence of feedback communication channels through which there is transmission of less detailed information on the state of individual space vehicle subsystems and on the results of realization of the controlling process, that is, information on the reaction of the controlled subsystems to the controlling effects. The reception of information on the state of a space vehicle, including data on its spatial-temporal and functional characteristics, is accomplished by the information-measurement subsystems: radar and radiotelemetric stations, communication and television systems entering into the closed "earth - space vehicle" control circuit.

The controlling effects transmitted through the "command radio link - space vehicle" channel have a more general content than the effects formed in space vehicle subsystems. They include commands for the switching of some subsystem on or off, the imparting of a constant (rigid) or correctable (flexible) form to work programs in which in discrete form there is representation of a successive set of commands and the time of their execution. In addition, using command radio links it is possible to transmit to the vehicle some extraordinary commands, duplicating the operation of control systems by individual subsystems of the space vehicle in different unforeseen situations.

Allowance for the functional relationships arising in the process of interaction between a space vehicle and ground radio control facilities makes it possible to define three possible methods for control which can be realized in the "command radiolink - space vehicle" system. Now we will consider them in greater detail.

The modern level of cybernetics, and in particular, on-board digital computers, used in space technology, makes it possible to ensure autonomous control of space vehicles (without use of ground facilities). In this case the space vehicle has an automatic system incorporating the controlling system and the controlled systems in a single technical complex. Such a method assumes a preliminary development of the controlling program, including in this some number of different commands and initial data required for the realization of a given control process.

The controlling program in coded form (for example, in binary codes) is registered in the memory block of the control system and in a stipulated time interval $t = t_1 = t_0$, whose initial moment t_0 is determined by a specially fed command or an on-board controlling system, brings about the necessary process in the controlled system. The complexity of the controlling program is evaluated by the total time of its operation and also the number and frequency of execution of individual commands contained within the program. The simplest programs have two alternative commands, for example, "switch on - switch off" for some device on the vehicle.

More complex programs consist of two or three dozen individual commands produced by the space vehicle control system in dependence on the current state of some particular controlling process. An example of a complex control program is ensuring the soft landing of a space vehicle on the lunar surface.

The controlling program can be introduced into the control system in advance, prior to the launching of the space vehicle, when the control process has been sufficiently well studied and there is a virtual absence of a mismatch between its computed and actual course. In all other cases the computed controlling program is subjected to correction, taking into account the difference between the flight trajectory of the space vehicle and the stipulated trajectory, changes in the state of the on-board instrumentation or requirements on changes in the control process.

The logical possibilities of an on-board computer as a tool of programmed control for a space vehicle make it possible to formulate rigid and flexible programs. By "rigid" is meant those programs in which the sequence in the issuance of commands, their meaningful content and the time intervals between commands remain constant. Flexible programs are used for the control of processes not known in advance. In such programs the sequence of issuance of commands, the time intervals and their meaningful content can vary. In this case the controlled parameter of some control process must with a stipulated accuracy reproduce this measured parameter or its time function.

In addition to an on-board electronic computer, for the programmed control of space vehicles it is possible to use time-programming or command-timing units. These automatic components also constitute computers, but of a type somewhat simplified in comparison with an on-board computer.

The method of programmed control of space vehicles, being completely independent of ground facilities, has many merits. In its realization it is not necessary to take into account the time and conditions for the propagation of radio waves, the state of the ionosphere and the presence of noise; there is no need for allocating special frequency ranges for the control channels. There is a considerable decrease of the load on the ground flight support facilities. However, this method also has some shortcomings: absence of ongoing monitoring of the state of the space vehicle on the earth, difficulty in operational intervention in the controlling program executed aboard the vehicle.

The complete opposite of the space vehicle programmed control method is the command method, in which it is provided that each controlling operation, such as preparation of the on-board subsystems for operation, their switching on and off, restructuring and change in operational regimes, tasks for implementation of the flight program, are accomplished exclusively by commands from the earth.

The practical realization of this method under the condition of control of extremely complex systems requires a high efficiency of the direct and reverse communication channels. During brief time intervals, determined by the duration of the communication sessions with the space vehicle, it is necessary to rework and analyze a great volume of different information transmitted from the space vehicle, adopt a decision and transmit to the vehicle a considerable number of different commands. Such a control method is extremely time-consuming in implementation, overloads the ground facilities of the system and is inadequately reliable because from the moment of the vehicle's departure from the effective zone of ground command radio links no controlling operations can be executed aboard it. This reduces the effectiveness of the command control method and its use in "earth-space vehicle" systems is limited.

The third method for control of a space vehicle is based on the combined use of the two considered methods, as a result of which it is called a command-programmed control method. With its application in the control system, for the forming of controlling effects use is made of elements of both the on-board automatic systems and the ground radio command facilities. The command-programmed method, due to the possibilities for control flexibility, the possibility of duplicating individual control tasks, and as a result of this, having an increased reliability, has come into the broadest use in space control systems.

The essence of the method is as follows: a control program for some space vehicle subsystem is introduced into the memory units, on-board command-timing and time-programming devices or on-board computer before the launching or in the course of the flight by means of command radio links or other methods; then, at the computed time, a command is transmitted for activation of the control program. In the course of its execution commands can be issued for correction of the program or its discarding, which is influenced by the course of the controlled process in the space vehicle subsystem. The possibility of such intervention in the programmed control process makes it possible to take into account unforeseen situations arising in the medium surrounding the space vehicle, to eliminate the consequences of abnormal operation of a subsystem, and also to compensate for the accumulating errors in the regulable parameters. It also must be noted that in the case of abnormal or unintended operation of the control program the latter, by command from the earth, can be "scrubbed" or erased and again be put into the memory unit of the corresponding on-board control system.

The use of command-timing or time-programmed devices ensures the solution of problems in the programmed control of individual space vehicle subsystems. For example, their activation and deactivation in accordance with a definite time schedule, maintenance of some parameters within stipulated limits, etc. by on-board computers, which are usually universal, small and highly productive, make it possible to solve a broader range of problems relating to the control of a space vehicle. Using them, for example, it is possible to process the results of navigation measurements and compute the parameters of a maneuver of a vehicle in orbit. They can also process telemetric information on the functional state of a space vehicle and on the basis of the results form controlling effects for the controlled subsystems. Moreover, using on-board computers it is possible to carry out modeling of some emergency situations arising during the spaceflight process. The result contains data on the reasons for the malfunction and also gives recommendations on the adoption of subsequent solutions for safe outcome from the emergency situation which has arisen.

The command-programmed control method favors a substantial decrease in the volumes of information transmitted through the communication channels of the "earth - space vehicle" system, to a considerable degree makes the control process easier, lightens the load on the command and information-measurement subsystems of the ground complex, and finally, makes it possible to control the vehicle and its individual subsystems outside the effective zone of ground control facilities.

When in the system for control of a specific vehicle one of the considered control methods has been determined, the responsibility for its rational use is imposed on the space vehicle control center -- the highest level in the hierarchy of the control system. In this case the control center is given the right to solve strategic control problems determining the implementation of the spaceflight program as a whole. Taking into account the special position and significance of the control center in the overall control system, it is desirable to examine its principal peculiarities, the means and methods for solving the problems assigned to it.

The space vehicle control center is the central directing facility of the system, outfitted with the necessary resources. This, in essence, is the "brain," an operational-technical center which constantly holds in its hands all the control lines for the space vehicle from the moment that it is put into orbit to the end of its active functioning.

Among the main groups at the center which exert a direct influence on the control processes are the following:
-- the main control group, responsible for the development of the session and daily programs, the monitoring of their implementation and correction during the course of space vehicle flight; it heads and unites the activity of all the other groups participating in control of the space vehicle;
-- the flight ballistics support group, whose task is determination of the orbital parameters, evolutions of the orbit and other ballistic computations;
-- the telemetric support group, solving problems in the diagnosis and telemetric control of the state of on-board systems and assemblies;
-- group for analysis, modeling and simulation of different situations which may arise aboard a space vehicle;
-- group for computing, issuance and monitoring the implementation of programs and commands.

The result of joint operation of all the enumerated groups is the finalization of a decision on control of the space vehicle in a stipulated time interval, which is considered and approved by the flight director.

The launching of each space vehicle and the direct functioning of the groups entering into the space vehicle control center is preceded by the working up of a number of fundamental documents, instructions and procedures (flight documentation) determining the load placed on ground facilities, control methodology and some specific peculiarities of space vehicle control (for example, in the control of manned spaceships when procedures for manual control of individual on-board subsystems and instruments are allowable). The requirement that these be worked out ahead of time is dictated by the necessity for special servicing of each newly launched space vehicle, taking into account the space conditions prevailing at the moment of its launching. The launched vehicle must be entered into the schedule of motion of all active space vehicles and must normally "coexist" with them under the condition of optimum distribution of all the ground facilities for the support of space flights. In addition, a factor of extremely great importance in the processes of space vehicle control is the great velocity of their motion (for space vehicles in low orbits) relative to the ground control facilities. The duration of presence of such space vehicles in the zones of radio visibility of each point is 5-10 minutes. It is obvious that with such small time intervals preprepared documentation will considerably ease the control problem.

The flight documentation, in addition to documents determining the sequence and interaction of the information-measurement and information-computation subsystems, includes documents regulating the processes of space vehicle control. These documents include:
-- the flight mission, determining the purposes and objectives of the space vehicle and also containing a summary of the ballistic, mass, size, energy and other data concerning the vehicle;

-- initial data on the masses of the working media in the space vehicle subsystems, temperature, pressure, energy possibilities of the power units, measured directly prior to the launching of a space vehicle and being the initial points for reading between successive measurements;
-- the flight plan, containing orbital, session or daily work programs, with a description of the makeup of problems to be solved by the space vehicle in each stipulated time interval, with the enumerated involved ground support facilities, and also with the variety and time of the issued commands or special programs for space vehicle control;
-- a method (sometimes a model) making possible the operational adoption of an optimum solution on control of a space vehicle under normal or nonstandard conditions.

A space flight is usually carried out in accordance with the formulated program. The space vehicle Control Center carries out monitoring of implementation of all operations associated with the process of its control, ascertains the quality of operation of each on-board subsystem or instrument, stability of their working characteristics, current expenditure of the working medium and the needs for electric power.

Sometimes nonstandard situations can arise aboard a space vehicle, that is, those not provided for in the flight program. Their reasons are a determination of the characteristics, a partial malfunctioning of individual space vehicle subsystems or a change in its flight program. The appearance of such situations usually has a random or forced character and it is virtually impossible to predict them. The space vehicle flight program is supplemented for such cases by a specially developed method in which the most probable unplanned variants of on-board subsystems operation are considered. An appropriate recommendation is prepared for each variant; its main purpose is retention of the operability of the space vehicle in such a way that the flight mission will be implemented.

Particularly important space experiments, such as launchings of manned space vehicles, assume the preparation of special physical and mathematical models formalizing the processes of functioning of individual subsystems and the vehicle as a whole. Using a mathematical model introduced into an electronic computer it is possible to carry out a "play through" of the unplanned situations arising aboard the space vehicle and the results obtained in this case contain the most advantageous solution. The use of a model and an electronic computer makes it possible to determine the reasons for abnormal operation of the space vehicle and quite routinely formulate a plan for further actions for its control. A shortcoming of such a method is the great volume of preparatory work in formulating mathematical models and their computer debugging in the programming stage.

In individual communication sessions the control of a space vehicle is accomplished without preformulated solutions, when there are no developed mathematical models. In these cases the controlling process is carried out on the basis of finalizing and adopting operational decisions. The structural diagram of such control is characterized by increased requirements on the routineness of solution of all special problems to be solved in the system. It includes the reception, processing and analysis of the measurement data arriving in the course of the communication session and the operational adoption of a decision with the output of corresponding commands in this same communication session. Most of the problems to be solved by the information-measurement, information-computation and command elements of the system are dealt with on a real time scale (that is, at the rate of data reception) or at a quasireal scale (that is, with time lags making it possible to carry out space vehicle control in the current communication contact).

Such a control scheme is the most complex to design because during the short time interval of the communication session it is necessary to process and analyze a great amount of information and select the best from several control variants. Usually such a process is realized on the basis of the intensive operation of technical means and teams of persons capable of routinely evaluating the state of a vehicle in a particular communication session.

Functional and Structural Diagrams

For a more graphic representation of the "earth - space vehicle" control system use is made of functional and structural diagrams corresponding to the functional and structural representation principles.

A functional diagram is a diagram in which each functional element of the system is expressed by a definite link or apparatus. The structural diagram of a system is a diagram in which each mathematical operation for signal conversion corresponds to its particular link or apparatus.

Since the "earth - space vehicle" control system can be classified as a complex system, it can be divided into a series of isolated subsystems, each of which performs its special tasks with well-expressed properties of their general purposefulness. Such an approach simplifies the construction of functional and structural control diagrams and makes their investigation easier. In this case each subsystem can be examined autonomously with respect to the limits of its input and output sections.

On the basis of an analysis of existing control systems it is possible to define the following basic subsystems.

1. The space vehicle subsystem. It includes the entire diversity of actively operating space vehicles, which characterize space conditions at a given moment in time. (We will assume that passive space vehicles are not serviced in the system.)

2. The subsystem of command-measurement points (CMP), consisting of a network of interconnected stationary and nonstationary (floating, aircraft, helicopter) complexes, supplied with radiotechnical and radio communication facilities, subordinate to a single control facility.

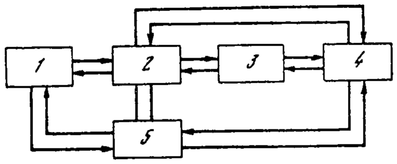

Fig. 12. Functional diagram of "earth - space vehicle" control system. Subsystems: 1) space vehicles; 2) command-measurement points; 3) computers; 4) flight control centers; 5) command radio systems

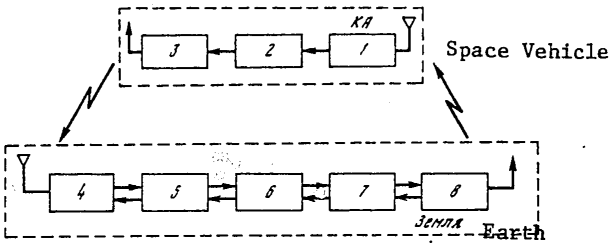

Fig. 13. Structural diagram of sequence of main operations in "earth - space vehicle" system. 1) reception of commands by space vehicle; 2) implementation of commands; 3) output of data concerning state of vehicle; 4) reception of information; 5) processing; 6) analysis of results; 7) formulation of decisions; 8) issuance of commands

3. The subsystem of computers ensuring mathematical processing and collection of the information used in the monitoring of a space vehicle and its control. The subsystems include regional and central single- and multiprocessor computers, apparatus for connection with communication channels and elements of representation of the results obtained.

4. The subsystem of central facilities for control of the system, consisting of means for automated control, communication units, means for the display of space conditions, state and behavior of the space vehicle, and also groups of specialists responsible for functioning of the "earth - space vehicle" control system.

5. The subsystem of command radio facilities, functionally combined with the central control facility, directly or through the command elements of the measurement points. The subsystem includes some number of command

radio stations of the autonomous or "matched" types.

The functional diagram of the control system has the form shown in Fig. 12. All the subsystems are interrelated. The relationship is ensured by means of direct and reverse channels of different types. For example, the interaction between the space vehicle and the CMP subsystem is accomplished only on the basis of radio communication channels. The other subsystems are related to one another both by radio and through wire communication channels. The group of direct channels in the system is usually used for the transmission of controlling effects regulating the sequence and order of operation of space vehicles or ground flight support subsystems. Measurement, time and radio communication information (radio exchange) is fed through the group of reverse channels, as are confirmations of the reception of control commands. With passage through individual subsystems the information in the reverse channels can be converted or subjected to different types of processing. These processes must transpire with mandatory satisfaction of the requirements on the maximum possible retention of the initially determined information characteristics constant in the entire length of the channel through which the signals pass.

The presence of reverse communication channels is characteristic for "earth - space vehicle" control systems. By their use it is considerably easier to carry out the control functions by such a complex technical apparatus as a modern space vehicle. In addition, the carrying out of experiments in space is accompanied by an influence on the vehicle from a number of random factors, which are extremely difficult to make allowance for. Space and the surfaces of the studied planets, despite intensive investigations, nevertheless "hide" individual inadequately understood effects and phenomena. The space vehicle control system must always be ready for their effects, which are difficult to predict.

A space vehicle, as a controlled object, consists of individual elements and subsystems, whose matched and controlled operation ensures the implementation of a given space experiment. During the course of the flight the controlling effects can be formed directly on the space vehicle in the corresponding apparatuses or be fed from earth. It must be emphasized that different space vehicle subsystems can be controlled differently. The use of the corresponding control methods for different space vehicle subsystems is determined by the nature of the processes transpiring in them.

For example, the control of a jet engine in the maneuvering of a spacecraft (docking, correction, landing) should be accomplished using control systems placed on the vehicle. Slowly transpiring processes can be controlled by means of commands fed from the earth.

The control process in the "earth - space vehicle" system is based on a number of successively or successively-parallelely executed operations whose meaningful description is shown in the structural diagram (Fig. 13). It reflects the meaningful character of implementation of the principal operations and helps to clarify their purpose without a tie-in to specific technical elements. In actuality, however, the diagram of the system is considerably more complex because the control operations can be performed in a number of technical apparatuses in the system simultaneously and then be synthesized into a single whole.

Thus, the operation of "information reception" includes data obtained on the state and behavior of the space vehicle transmitted by means of active radar, telemetry and television communication. All the information obtained using these information-measurement facilities undergo separate processing and analysis and in some cases are subjected to combined processing (for example, joint processing of radar and telemetric information). Later such information becomes the initial data for making a decision on space vehicle control.

Each technical means in the system functions in accordance with a complex algorithm which characterizes the presence of a considerable number of information-measurement conversions in them. In this connection we will cite a description of the algorithm for operation of the radiotelemetric system, which contains the following special operations:
-- primary perception of information concerning problems and results of space vehicle control;
-- collection, transformation and tie-in of information to the scale of telemeasurements;
-- formation of group signal and transformation of information to earth;
-- reception, discrimination and registry of information for long-term storage;
-- mathematical processing of operational volumes of information;
-- operational analysis of results of processing and issuance of recommendations on control of space vehicles;
-- forming of a decision and its embodiment in the command information.

The processing of navigation information is accomplished using an algorithm somewhat differing from that described. However, its main meaningful value remains approximately the same.

The cycle of space vehicle control in any time interval is considered completed when all the necessary controlling effects (radio commands) regulating the further implementation of the flight program have been transmitted to the vehicle.

The command-actuating process of space vehicle control, realized on the basis of the cited algorithm, includes the following operations:
-- selection of the makeup of command information;
-- formation of command information in accordance with principles of operation of the command radio link;
-- automatic or manual transmission of command information to space vehicle;
-- its reception and decoding in accordance with code criteria;
-- processing of decoded commands by the actuating parts of the space vehicle and sending acknowledgments to the earth.

The sequence of operations carried out by the command subsystem is the same as the algorithm of its operation. Thus, in the realization of these two algorithms a controlling process is carried out in the "space vehicle - earth - space vehicle" system.

The meaningful form of the algorithms can be transformed into systems of different equations, as is necessary when using computers of the analog or digital types in the system. The systems of equations in this case by means of different algorithmic languages are transformed into a computer code and are introduced into a digital computer for solutions of the corresponding control problems.

The totality of the algorithms, represented in a meaningful or formalized form (in the language of mathematical formulas and dependences), characterizes the mathematical description of the system and the processes transpiring in it. The problem of developing a mathematical description is extremely complex and requires a knowledge of the physical laws on the basis of which some particular process transpires.

The requirements of operational and reliable control of a space vehicle are to a great extent dependent on the perfection and flexibility of the organizational structural diagram. By this we will mean the organization of work of control personnel and groups of specialists servicing the technical apparatus of the control system. The basic problems arising in the development of such diagrams are a determination of the proper interrelationships among individual subdivisions of the control system, which is associated with the determination of their purposes and missions, working and stimulation conditions, distribution of responsibility among directors of all ranks. Here it is also necessary to include the rational choice of specific control schemes, the sequence of procedures preceding the adoption of a decision, the organization of information flows and the choice of the corresponding technical apparatus.

In developing the structural diagram for organization of the "earth - space vehicle" control system there could be an unambiguous solution of the problems of interaction between its individual elements and groups of control and servicing personnel, that is, their tasks, subordination, determination of working conditions and rest. All the goals and tasks are formalized in the most specific form possible, precluding their incorrect interpretation. It is entirely obvious that the points cited here are reflected in special documents, manuals and instructions, a knowledge of which and whose adherence to is mandatory for every specialist participating in the process of space vehicle control.

A number of specific requirements are imposed on personnel which participate in the system of space vehicle control. Some of them can be formulated in the following form:

-- a high degree of organization and a clear understanding of the importance of the problems to be solved;
-- the presence of a definite volume of knowledge and practical skills;
-- the ability for routine evaluation of the developing situation and to find the optimum solution;
-- the possession of good physical and psychological preparation;
-- assurance of a correct microclimate in the interrelationships in teams, good will, mutual understanding and the striving to assist a comrade.

In these requirements there is nothing exceptional, since to a certain degree they correspond to every normal man. The acquisition of experience and the accumulation of knowledge in working in the system forms a specialist meeting all the enumerated requirements.

The structural diagrams of organization of control of space vehicles can be constructed on the basis of the centralized or decentralized criterion. A centralized scheme provides for the adoption of all decisions exerting a significant influence on a space vehicle at the central control facility; a decentralized scheme allows the adoption of individual decisions independently of the central control facility.

As a rule, structural diagrams of the organization of control are centralized, that is, decisions exerting a direct influence on the implementation of a space experiment are made and issued by the Control Center. An exception to this rule can arise only when there are unforeseen situations of a random character.

The space vehicle control center, directing all subordinate elements of the system and having definite reserves of different apparatus, in the necessary cases ensures their flexible maneuvering with respect to the time and territorial criteria. The considered capabilities and authority determine the strategic character of the planned work and the decisions adopted by the Control Center within the framework of a specific space experiment. The significance and the scales of the work and decisions transformed into reality by the control center commands play a decisive role in the execution of the assigned missions by space vehicles with a stipulated effectiveness.

The work of the space vehicle Control Center as a facility for strategic planning and the adoption of decisions is based on application of the following basic principles:

1. There must be a model of the system, that is, a description of the structure of the system or the processes transpiring in it.

2. The final goal of the control system must be formulated.

3. Direct and indirect limitations must be formulated for the choice of the corresponding decisions.

4. It is necessary to determine the optimality criterion, making it possible to select the one, most effective solution from among some set of possible solutions and limitations.

These points make it possible to develop three approaches to the problem of adoption of a decision: satisfactory, optimum and adaptation approaches. The first approach takes into account points 1-3 and makes it possible to form one decision from a set of decisions. However, we cannot assert whether it is the best because point 4 is not taken into account. The making of a decision on the basis of the second approach makes it possible to eliminate the shortcoming inherent in the second approach. The difficulty is in the choice of the optimality criterion and the admissible limitations. The third approach has the assumption that the adopted decision must be corrected as new information is received, which usually requires the formulation of a great number of a priori decisions.

The enumerated approaches to the forming of decisions finds use in the control of a space vehicle in dependence on the developing situation, the completeness of modeling of the control system and the time interval allocated for preparations for a specific space experiment.

The considerable complexity and intricacy of the space experiments carried out, the great volume of diverse technical apparatuses in the control system, and also the great volume of pertinent information which is provided by them and the great many specific peculiarities in functioning of the technical apparatus create difinite difficulties in realizing the process of control of space vehicles.

In order to overcome these difficulties and in every way possible to increase the effectiveness, the structural diagrams of organization of control are now constructed on a multilevel or hierarchical criterion. In this case there is a separation of controlling functions among the elements of a system of different levels or ranks. A higher-level element controls elements of a lower level in the hierarchy and itself is controlled by an element of a still higher level.

A considerable advantage of the hierarchical system is the possibility of a distribution of the partial (auxiliary or tactical) problems in control by levels in the system with a corresponding forming of partial decisions relating for the most part to a particular or lower-lying level. This makes it possible to concentrate the solution of problems in strategic planning and the forming of controlling decisions at a higher level.

It should be noted that in hierarchical systems for the control of space vehicles there is a definite degree of autonomy of the intermediate and lower levels at which there is solution of tactical control problems. For example, ensuring reception of information from the space vehicle, mathematical processing and collection of the results obtained, supply of all system elements with uniform time signals, etc. In this case the totality of the results of solution of tactical problems characterizes the purpose of the system at a common scale.

In accordance with the definition of a hierarchical control system, all the levels successively arranged from upper to lower form a vertical, whereas all the elements at the same level are called the horizontal of the system. Accordingly, in this case communication systems are called "vertical" and "horizontal."

The following organizational schemes of hierarchical control structures have been developed and are used: linear, functional, linear-"staff" and matrix. In cosmonautics the most commonly used are the linear structures of organization of control, characterized by the principle of management under direction of a single person and personal responsibility for the space experiment carried out. Figure 14 is an organizational diagram of the linear structure of control of the hierarchical type, in accordance with which the "Soyuz-19" was controlled in the joint Soviet-American space experiment "Soyuz-Apollo." Such a scheme for the organization of control increases the overall effectiveness of the controlling processes and corresponds to increased requirements on the operability and reliability, in particular applicable to manned space experiments.

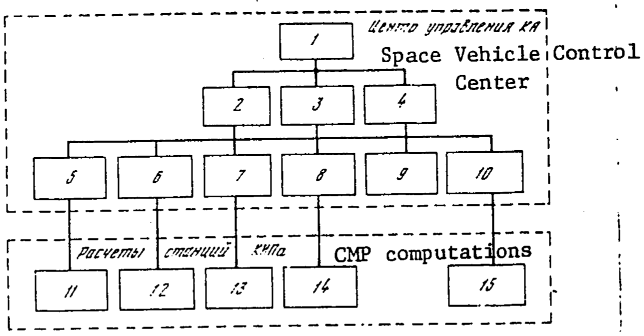

Fig. 14. Linear structural diagram of organization of control for "Soyuz-19" spacecraft. 1) flight director; 2-4) alternate flight directors; 5-10) specialized flight support groups: radio communication, navigational measurements, telemetric support, processing and analysis of results, forming of decisions, issuance of commands; 11-15) station computations: communication with space vehicle, radar and radiotelemetric systems, command radio link.

Here it should be noted that the space flight directors must have a wide range of knowledge and have well-developed psychological and will characteristics. The cosmonauts have all these to a considerable degree. Therefore, it is not without reason that specialists having experience either with space flights or in the development and designing of space vehicles, who know the peculiarities and dynamics of space flight and the work program, are drawn upon to direct complex space experiments.

The effectiveness of the space vehicle control system is dependent on the optimum construction of the control organization, that is, the most advantageous number of levels ensuring realization of the controlling process. It is evident that a number of levels more or less than the optimum number of levels in the structural diagram should complicate the control. The solution of the problem of optimizing the structural diagram of organization, in which groups of people are present, is a complex matter because the control process is influenced to a considerable extent by subjective characteristics which are difficult to formalize and take into account.

In systems for the control of space vehicles the optimization of the organizational structural diagram is most frequently carried out on the basis of the maximum possible reduction of the time on transmission of the results of processing of measurement information from its recipients at the Control Center. Here a series of limitations is introduced, for the most part relating to the minimum necessary volume of results, their accuracy and reliability. Usually the variety of technical apparatus and the interaction of groups of people in the control process are stipulated and the minimizing of the entire controlling process is dependent on the organizational-technical characteristics, routineness and smoothness in functioning of each level in the structural diagram. An improvement in the quantitative and qualitative indices of each technical apparatus and working groups of specialists in the control system is influenced by them having practical experience and the corresponding knowledge.

PROBLEMS TO BE SOLVED BY SPACE VEHICLES. DESIGN PECULIARITIES OF VEHICLES

Classification and Use of Space Vehicles

The broad range of problems involved in the exploration and conquest of space dictates the development of different types of space vehicles. There are a great number of different types of vehicles which can be classified on the basis of a number of distinguishing characteristics. The possibility and necessity of assigning them to individual groups facilitates the formulation of the technical requirements on the vehicles, their design, outfitting with on-board devices and assemblies and subsequent servicing by ground support facilities. The separation of space vehicles into individual classifiable groups also simplifies their description and study.

The basis for the classification can be criteria characterizing the purpose, design peculiarities, control methods, mass and size characteristics of the vehicles, presence or absence of a crew aboard them, etc.

In a broad picture the entire diversity of space vehicles can be divided into AES without a crew, spaceships with a crew and interplanetary manned or automatic ships and stations. In addition, there is a more detailed classification in the following form.

1. With respect to purpose: scientific research vehicles used for study of physical conditions in the upper layers of the atmosphere, for extraterrestrial space, for interplanetary space, on different planets of the solar system; vehicles for practical purposes, employed for solving practical problems in the interests of economic activity.

2. With respect to the type of communication with ground support facilities: without communication, with unidirectional communication (the "earth-space vehicle" channel operates), with unidirectional communication from the space vehicle (the "space vehicle-earth" channel operates) and with two-directional communication ("earth-space vehicle-earth").

3. With respect to the presence of a crew: manned, unmanned and ships with crews which are replaced from time to time.

4. With respect to mass: light (up to 300 kg), medium (up to 2,000 kg), heavy (up to 6,000-7,000 kg), superheavy (more than 7,000 kg).

5. With respect to the possibility for return to earth: nonreturnable, returnable and partially returnable (capsules).

6. With respect to presence of orientation systems: unoriented, oriented.

The purpose of the space vehicles being developed is of extremely great importance. The purpose function, which determines the effectiveness of use of space vehicles, can exert an influence on problems of economic or social policy. In other words, the determination of the purpose which a vehicle must serve and the practical use of the results obtained in its operation are closely intertwined with those economic expenditures which are necessary in the course of development, launching and flight of space vehicles. Accordingly, the active work of many types of vehicles in space is now preceded by corresponding economic computations making it possible to determine in advance their practical feasibility.

We note that at the present stage the use of space technology, including the solution of both purely scientific and applied problems, according to the evaluations of specialists, gives a considerable economic effect. For example, the methods for investigating the earth from space are considered the most perfect. According to the calculations of foreign scientists, merely in the field of meteorology with more precise weather predictions there can be an annual economy up to 2.6 billion dollars. According to an estimate of American specialists, an operative system of AES for study of the earth's natural resources will give an annual economic effect, in the fields of geology and agriculture alone, up to 1.2 billion dollars. Satellite communication systems ensuring commercial radiotelegraphic and radiotelephonic conversations have proven to be extremely advantageous. Their profitability is attributable to the long lifetime of communication satellites, the possibilities of organization of multichannel communication, improvement and cheapening of receiving and transmitting apparatus.

The sphere of practical use of space vehicles is extremely broad. We will examine the most characteristic space systems.

"Meteor" meteorological space system. This is intended for the reception of meteorological information from space. It includes data on the earth's radiation balance, characterizing heat exchange between the atmosphere and the earth's surface and the spectral distribution of solar and terrestrial radiation, information on the spatial distribution of the cloud cover, exerting a direct influence on weather-forming processes in the atmosphere, information on composition of the atmosphere, temperature distribution, determination of the upper boundary of the cloud cover.

For the reception and registry of this information in the "Meteor" system use is made of:

-- television equipment using small frames, ensuring the registry of cloud cover, ice and snow covers on the earth's illuminated side. The two cameras of the apparatus make a frame-by-frame survey of the underlying surface from the left and right side of a scanning band with a width of about 1000 km, with a small overlap;
-- IR radiometric apparatus, measuring thermal radiation (and temperature) of clouds and the underlying surface on the illuminated and unilluminated sides of the earth in the range 8-12 μm;
-- actinometric system, consisting of several radiometers, each of which registers reflected solar radiation, total radiation of the earth and atmosphere, which will make it possible to monitor the radiation balance of the "earth-atmosphere."

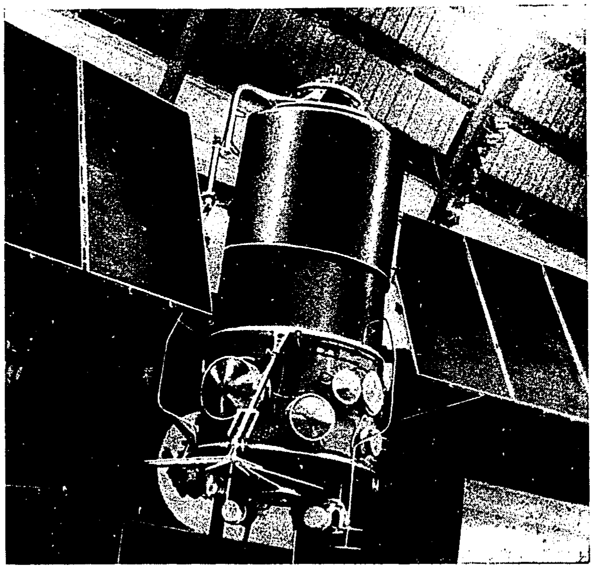

Fig. 15. Satellite of the "Meteor" meteorological system.

The first two types of apparatus ensure obtaining video information, that is, images of the clouds and surface, registered on photographic film and magnetic tape; the third, after processing on a computer, gives specific maps of radiation temperatures. An overall and separate analysis of the recorded information makes it possible to characterize and predict the development of weather conditions in stipulated regions of the earth.

In addition to satellites of the "Meteor" type (Figures 15 and 16), the system includes ground points for the reception and preliminary processing of space meteorological information, a control service and a center for the comprehensive processing of meteorological data. The planning of operation of the system is carried out in accordance with the instructions of the USSR Hydrometeorological Center, which take into account the current and future requirements of the weather service in the general system of its prediction and hydrometeorological support. On the basis of these requirements a program is formulated for the operation of the on-board meteorological apparatus for each day and for all working revolutions; the regions of investigations, time and operating regimes of the complex are determined.

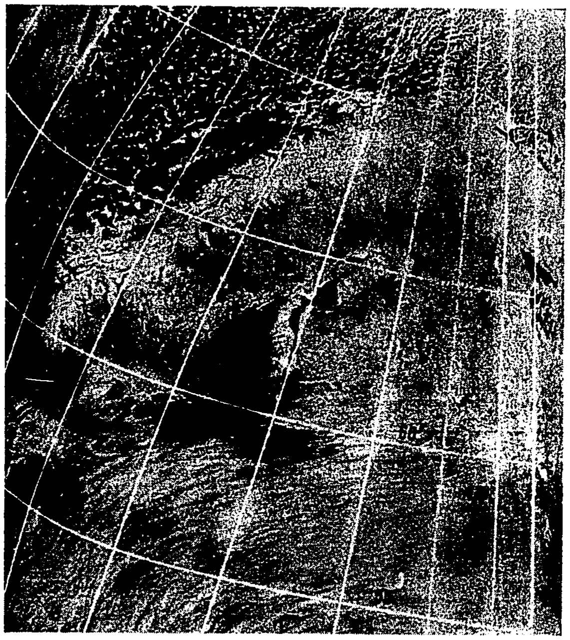

Fig. 16. Image of clouds and surface obtained using the "Meteor" system (well-developed cloud formations over the European USSR, ice in the northern part of the Baltic can be seen and Scandinavia is clearly defined).

It should be noted that some part of the information arrives for meteorological analysis at a real time scale, without its preliminary registry on on-board magnetic recorders. In the course of preliminary processing and routine analysis of these data, received at a ground station, data are received which have a periodic nature. These include information on the movement of cyclones, typhoons and other formations leading to weather calamities. Such information is immediately relayed to the corresponding agencies for the taking of precautionary measures.

The stations for the reception and preliminary processing of space meteorological information of the "Meteor" system were located in different regions of the USSR. They were equipped with antenna systems, apparatus for the reception, registry and processing of data. Here also there is apparatus for the transmission of videoinformation, high-speed electronic computers, special telephonic and telegraphic communication facilities. The problem of control of "Meteor" satellites is solved using a system of ground command-measurement (general purpose) stations.

In accordance with international agreements, routine information is transmitted to the countries belonging to the World Weather Service system. Weather maps are transmitted to Washington, Budapest, Warsaw, Paris and other regional centers.

A meteorological space system also exists in the United States where its basis is meteorological series of the TIROS satellites and their later modifications. Investigations of operation of meteorological satellites have been made and this has enabled the United States to proceed to the creation of a satellite meteorological system which supplies information to world meteorological centers and other services for the preparation of current weather forecasts in a form convenient for computer processing.

The future possibilities of satellite meteorology are tied in to the international program for global atmospheric research (GARP), which is directed to the creation and evaluation of a number of theoretical atmospheric models. The systems of meteorological satellites developed under this program will later become part of the global system of observations of the World Weather Service.

Soviet systems for satellite communication are being developed on the basis of high elliptical satellites of the "Molniya" type and "Raduga" geostationary satellites. Their task includes ensuring distant and superdistant radiotelegraphic and radiotelephonic communications, the transmission of programs of Central Television in black-and-white and color images.

The most extensively used variant of construction of a satellite communication system includes two receiving and transmitting radio centers, separated from one another by a distance required for maintaining communications, and a system of active relay satellites (Fig. 17).

The active relaying of radio signals assumes their reception aboard a satellite, amplification, frequency conversion and subsequent transmission. In this case telephonic communication can be organized in the following way. Signals from the telephonic apparatus are fed through a regional interurban station through ground communication channels to one of the receiving-transmitting stations of the space communication system, where they are transformed into radio signals and are directed through a ground antenna to a satellite. Here they are received and amplified, pass through frequency conversion and are relayed to another specialized station of the "Molniya" ground complex. By means of a tracking antenna these signals are intercepted and are fed to a receiver. After reverse conversion of radio signals into electric signals carrying a telephonic communication they are fed along surface communication lines through a local interurban station to a second subscriber. Communication is accomplished in the reverse direction in the same way, that is, the communication system is duplexed, two-directional.

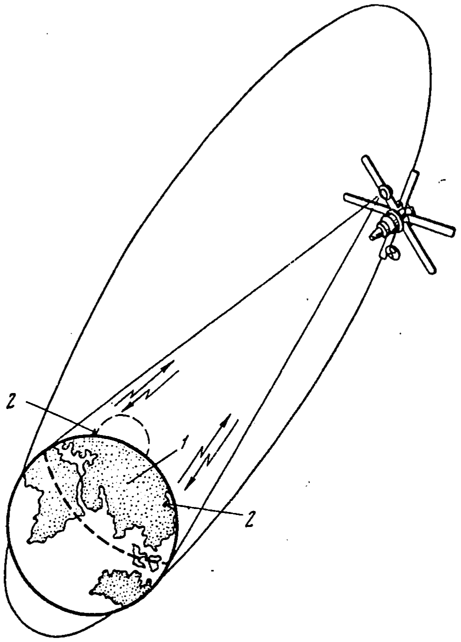

Fig. 17. Scheme for communication using "Molniya" satellites. 1) zone of radiovisibility; 2) earth receiving-transmitting radio communication stations.

The orbital parameters of the "Molniya" satellites are usually as follows: perigee altitude -- 400-450 km, apogee -- about 40,000 km, inclination of plane 65° and period of revolution about 12 hours. Both apogee points are situated in the northern hemisphere (one over the central part of the USSR, the other on the opposite side of the hemisphere). With such parameters the "Molniya" satellite ensures stable communication between Moscow and Vladivostok over a period of 8-9 hours. The three apogee points of the "Molniya" satellite, displaced 8 hours in time, ensure around-the-clock communication between these cities.

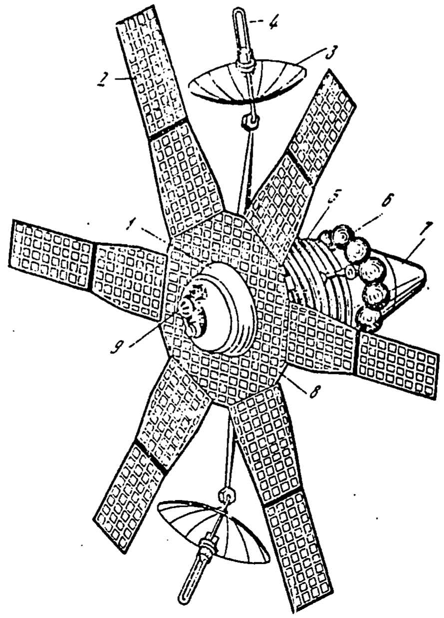

Fig. 18. Schematic view of "Molniya-1" communications satellite. 1) sealed compartment; 2) solar cell; 3) pencil-beam antenna; 4) sensor for orientation of antenna on earth; 5) cooling radiator; 6) supply of working medium for carrying out corrections; 7) correcting engine; 8) heating panel; 9) solar orientation sensor.

The "Molniya-1" satellites carry communication relaying apparatus, a command-programming unit for control of the on-board apparatus, a radiotelemetric device for checking the condition of the satellites, apparatus for correcting the orbit and satellite orientation and antenna systems, an electricity system, including solar cells and chemical current sources, and also instrumentation for radiation dosimetric monitoring, by means of which there is measurement of the intensity of irradiation of on-board systems. The results of these measurements make it possible to evaluate the degree of radiation danger for satellites repeatedly passing through the earth's radiation belts during their motion.

The schematic appearance of the "Molniya-1" satellite is shown in Fig. 18. The operation of these satellites confirmed their high technical characteristics in ensuring communication between Moscow and Vladivostok.

The "Molniya" satellites play an important role in the system for transmitting Central Television programs, interacting with the complex of the "Orbita" ground television network.

Fig. 19. "Orbita" ground station.

Still broader possibilities for the organization of communication were afforded with the launching of communication series of the "Raduga" series into a geostationary orbit. These have a circular orbit and an altitude of about 36,000 km.

Their period of revolution is approximately 24 hours and the orbital inclination is 0°. Launched into a stipulated spot in space relative to the earth, such a satellite seemingly hovers over it because the period of revolution in this case is commensurable with the period of the earth's rotation. The first "Raduga" satellite was launched in 1976 to a point with the coordinates 0° latitude and 99° east longitude, which should ensure constant communication in regions of the earth's surface limited in longitude by ±60° relative to the 99th meridian.

The "Molniya" and "Raduga" satellites, in addition to solving communication problems, are participating in the organization of superdistant television broadcasting. They are relaying the programs of Central Television to the "Orbita" ground network of stations, which are situated in remote regions of the country. The "Orbita" stations ensure secondary relaying of television programs, within a radius of 80-100 km servicing a network of individual use television receivers.

Using the "Orbita" network of stations (Fig. 19), functioning in combination with the "Molniya" communication satellites and those of the "Raduga" series, there is servicing of more than 20 million inhabitants of the Far North, Siberia, Far East and Central Asia. The "Orbita" network is being continuously developed, covering newer and newer regions of the Soviet Union. The programs of Central Television are also transmitted to Mongolia, Poland, East Germany and other socialist countries.

Here we have told only about the two most widely used satellite systems. The fundamental principles for constructing such systems for other areas of their application have much in common.

Space vehicles are also used extensively in other practical investigations. A great volume of such investigations aboard a space vehicle is carried out in the interests of solving individual technological problems.

Experiments with molten metals are being given special importance. The increased attention in this technological field is attributable to a number of space conditions which are nonreproducible on earth. These include weightlessness, and accordingly the absence of convection, buoyancy and other phenomena which under terrestrial conditions create differences in the density of materials after their hardening; a deep vacuum, ensuring rapid elimination of the gases and vapors from the investigated materials; an extremely broad temperature range for possible carrying out of the experiments.

Already in 1969 the first experiment was carried out on the "Soyuz-6" spaceship for the welding and cutting of metals, laying the basis for space technology. An experiment for the fusion and welding of metals was also carried out in the United States aboard the "Skylab" orbital station in the summer of 1973.

The development of space technology assumes obtaining small quantities of materials with special physical properties which are extremely valuable for the electronics, radioengineering and instrument-making industries. The production of such materials even now is feasible and economically justified. According to the optimistic predictions of western scientists, the extensive development of space technology can bring about a real industrial revolution.

Investigation of ecological processes by means of space technology is of vitally great importance for mankind. Only such investigations are capable of giving a qualitative and quantitative evaluation of the influence of man on the earth's biosphere.

Ten years ago this problem excited only scientists; now it is exciting a broad community and competent agencies in many countries.

For the monitoring of the environment it is possible to use satellites for the reconnaissance of natural resources, communication, meteorology, navigation and such spaceships as the "Salyut" and the "Soyuz."

In the United States a satellite system of the LANDSAT type has been developed and is in operation. Its program includes the collection of information on natural resources and the environment, on forestry and agriculture, geology, geography, hydrology, oceanography and ecology.

A broad complex of investigations of the earth as a planet was carried out during the orbital flight of the "Salyut-4" station by the cosmonauts A. A. Gubarev and G. M. Grechko, P. I. Klimuk and V. M. Sevast'yanov, who carried out black-and-white, color and spectrozonal photography of the regions of the Northern Caucasus, Volga, Central Kazakhstan, Pamirs, Sakhalin Island and some sectors of the Baykal-Amur Railroad line.

Multizonal space photography of a number of regions of our country was carried out aboard the "Soyuz-22" by the cosmonauts V. F. Bykovskiy and V. V. Aksenov. Use was made of the MKF-6 camera, constructed in East Germany. The method of multizonal photography is substantially broadening the possibilities of the ordinary photosurvey process. Using photographs taken in different spectral zones, it is possible to synthesize an image both in natural colors and in conventional colors, which makes it possible to obtain the maximum possible color contrasts between stipulated types of objects.

The processing and analysis of these photographic materials even today is giving a considerable effect in the solution of many problems in geology, meteorology, oceanography, etc.

Space photography of the earth has also been carried out extensively from the American LANDSAT satellites. And a number of important results have been obtained. For example, it has been established that there are errors in plotting a number of rivers in the Amazon basin on maps which attain 30 km. Earlier unknown dry river channels have been discovered in South America which may be gold-bearing. The route of the Amazon Highway can be laid out more rationally, reducing the number of bridges. In west Texas it was possible to detect geological structures identified with presence of petroleum. Two unknown lakes were discovered in Iran, etc.

In order to increase the safety of aircraft flights plans call for the use of global satellite systems with a high handling capacity which should ensure the solution of three fundamental problems: determination of the position of aircraft, navigation and communication. It is assumed that such a system is capable of simultaneously servicing up to 100,000 aircraft, giving three coordinates with an accuracy to 15-90 m, a frequency of 1 Hz, and ensure their identification.

In the United States there is discussion of the problem of using photographic materials of the LANDSAT AES for the needs of city construction, the compilation of transportation diagrams and the planning of cities. A study of photographs of the earth's surface delivered by the "Apollo-6" confirmed the possibility of use of space photographs for solving a broad range of problems related to the reconstruction and development of urban territories.

The sphere of practical use of satellites is constantly expanding; newer and newer possibilities are appearing for their practical use for the needs of the national economy and science.

Design Peculiarities of Space Vehicles

The selection and development of the design for a space vehicle must take into account the continuous and prolonged influence exerted upon it by the specific conditions prevailing in space: a deep vacuum, weightlessness, the possibility of entry into meteor streams and the effect of intensive radiation. The design of a space vehicle must ensure its independent functioning under conditions of exposure to these factors during the entire time of the flight. These very same requirements must be imposed on vehicles during their landings on the surface of the investigated planets. In these cases the vehicle is likened to an independent celestial body for which there is assurance of very definite conditions for the operation of all systems and instruments and for the existence of man.

The design elements of the space vehicle include: a frame, consisting of several interconnected metal beams of various shapes, one or more sealed shells (compartments), also playing the role of strengthening elements, and a complex of on-board instrumentation, placed inside and outside the vehicle compartments. The joining of all the construction components of the space vehicle into a single assembly is solved on the basis of engineering computations, being the initial stage in the designing.

The engineering design of a space vehicle involves the optimum placement of the supporting components, compartments, on-board systems, apparatus and units into a unified design intended for launching into space for the purpose of reliable solution, in the course of a definite time, of the functional problems determined by the purpose of the vehicle.

The following requirements must be satisfied in the course of space vehicle designing:

-- minimum possible mass for a stipulated reliability;
-- assurance of minimum loads on the carrier-rocket;
-- optimum configuration with respect to conditions for launching into space;
-- optimum distribution of the internal space in the space vehicle compartments and optimum placement of instruments and assemblies ensuring

the necessary heat regulation, convenient access to them and the possibility of the replacement of units prior to launching;
-- a minimum influence of dynamic loads and nonuniformities in the distribution of mass in flight on the orientation and stabilization systems;
-- the minimum possible movement of the center of mass and change in the moments of inertia during the expenditure of fuel and compressed gas;
-- minimum influence of vibration and the possibility of its extinction during launching and in flight;
-- possibility of improvement in the design of space vehicles in stipulated limits;
-- acceptable cost and the absence of materials in short supply;
-- relative simplicity in fabrication and assembly.

The purpose, range of problems to be solved, degree of their complexity, possibilities of the carrier-rocket, possibility for continuous improvement, economic and other factors determine the diversity of design and makeup plans for space vehicles.

In selecting the layout it is extremely important to have a theoretical and experimental evaluation of the distribution of mass of the space vehicle and its center of mass. The relationship of system and construction parts masses, taking into account the supply of fuel or compressed gas and other expendable materials, must correspond to the limitations imposed on the total mass of the vehicle and be optimum from the point of view of the functions to be performed, reliability, cost, etc. Movements of the center of mass with the expenditure of different components must not exceed the computed values, otherwise the orientation and stabilization systems will operate with an overexpenditure of the working medium.

In the practice of designing of space vehicles there are cases when the developers of individual on-board subsystems and apparatus do not adhere to the restrictions placed on them with respect to mass. Every excess kilogram then becomes an object for careful scrutiny by the Chief Designer, who makes a final decision -- whether to allow the particular unit to be installed or whether to rework it.

The construction parts of modern space vehicles can be classified as compact, expansible and inflatable.

Compact construction parts do not require the movement of individual elements (other than the antennas) and changes in their configuration for reducing the vehicle into a working state. Such construction parts are characterized by a high reliability. The principal problems in their development are: placement of the power supply sources and other units in restricted volumes (on limited surfaces) in the space vehicle body and extremely complex heat-regulating systems.

Expansible construction parts have elements which fold or extend out and they occupy a working position when the vehicle is put into orbit. A distinguishing characteristic of such construction parts is a great freedom in design makeup, simplicity and solution of dimensional restrictions. Among the shortcomings is a lesser reliability and tolerance to vibration, an increase in the mass of the supporting parts and accordingly great moments acting on the orientation and stabilization systems. In such cases the difficulties in theoretical computations and dynamic analyses are complex problems. Designs of this type include such spacecraft as the "Molniya," "Meteor," "Salyut," "Soyuz" and others. The expansible construction parts in them are the panels of solar cells and some antennas.

The inflatable parts have multilayer strengthened envelopes assuming a stipulated shape after inflation and hardness after being put into orbit. Among the merits of such construction parts are the possibility of the expansion of envelopes of great size in space. Among the shortcomings is a loss of internal pressure during prolonged use due to the diffusion of gas through the envelope and leakage through possible holes. The poor construction characteristics of such construction parts and an inadequately reliable expansion lead to their limited use. The "Echo-1" and "Echo-2" satellites are constructions of this type used in the United States.

Construction parts of the first two types have closed housings, which ensures the best conditions for the functioning of the apparatus in space. However, construction components with just a frame (without a housing) are being created in which the instrumentation is placed in partially or completely open form; it is assumed that the instrument units have a low sensitivity to the effects of space conditions, at the same time that some of them can have individual shielding and heat regulation.

The skins of the closed bodies of space vehicles are fabricated either from metal with a low specific weight or from different kinds of high-strength plastic materials. Their construction can be monocoque, corrugated, layered or honeycomb. In some cases strengthening is achieved by the use of stringers (ribs). The choice of the type of skin is governed by the needs for strength and stability with a minimum mass, and also the degree of its adaptability for attachment of vehicle construction parts.

Vibrations exert more than a little influence on the stability and strength of the construction. Their principal source is operation of the jet engine both of the space vehicle itself and the carrier-rocket. Acoustic noise and oscillations arise in this process. The frequency of vibrations falls in the limits from several to thousands of Hz. During the first 5-10 sec after rocket launching the noise level (for example, for the "Titan" carrier-rocket) can attain 165 db at a frequency of 100 Hz and the accelerations can attain 8^x. Compact construction parts, having high resonance frequencies, are less susceptible to vibrations. Riveted construction parts in this case have a better resistance to vibrations than welded construction parts because the time for the damping of oscillations in them is three times less and they have a lower coefficient of intensification of oscillations.

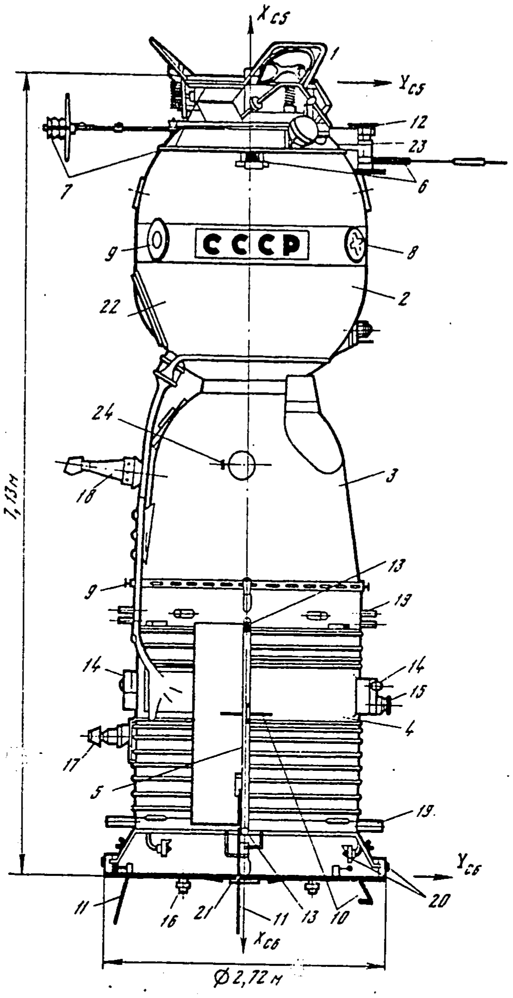

Fig. 20. Schematic diagram of "Soyuz-19" spaceship.
[Key on opposite page]

The choice of configuration of the vehicle is of considerable importance for vehicles stabilized by rotation. In this case a spherical configuration ensures a small value of the ratio of mass to the surface area of the space vehicle, a constant value of the area of projection of the vehicle onto the sun, and also creates favorable conditions for operation of the solar cells, the heat-regulating system and the system for the stabilization by rotation. However, spherical shapes have poor compatability with other construction components. A compromise solution is the choice of space vehicle configuration in the form of a polyhedron.

KEY TO FIGURE 20

1. androgynous peripheral docking assembly
2. orbital compartment
3. descent module
4. instrument-assembly compartment
5. solar cells
6. USW antenna
7. antennas of USW station at frequency used in the United States
8. television antennas
9. antennas for command radio link and trajectory measurements
10. radiotelemetric antennas
11. antennas for communication between crew and earth
12. docking target
13. shipboard orientation lights
14. flashing light beacons
15. solar orientation sensor
16. ion orientation sensor
17. sensor for orientation on IR vertical on earth
18. orientation sight
19. mooring and orientation engines
20. orientation engines
21. approach-correction engine
22. hatch for crew to enter ship
23. television camera
24. windows

Now the most different shapes of space vehicle hulls are being used in space technology: cylindrical, prismatic, in the form of polyhedrons, etc.

Space vehicles can also be designed in more complex configurations. Complex types of space vehicles even have sectional constructions, being made up of several autonomous compartments. As an example, we will consider the design of the "Soyuz-19" spaceship, in which the Soviet cosmonauts A. A. Leonov and V. N. Kubasov in 1975 made a joint spaceflight under the "Apollo-Soyuz" program. Figure 20 is a schematic diagram of the "Soyuz-19."

The "Soyuz-19" consists of three parts: descent module, orbital and instrument-assembly compartments. The launching mass was 6.8 tons, the length was 7 m and the breadth of the solar cells was 8.4 m. If the ship is placed vertically, on the docking units with the carrier-rocket, then in the upper part there will be the orbital compartment, joined to the descent module, and the descent module, in turn, is joined by means of the frontal heat-shielding screen with the instrument-assembly compartment, on which the panels of solar cells are mounted.

The descent module is for holding the crew in the segment in which the ship is put into orbit, for its in-flight monitoring and also during the time of controllable descent and landing. It is a pressurized compartment with two lateral viewing and one special windows. An optical orientation sight is mounted on the latter. The body of the descent module is constructed for the most part from aluminum alloy; the outside is covered by a heat-insulating layer and the inside is covered by heat insulation in combination with a decorative facing. In the upper part of the compartment there is a hatch with a tightly closing cover.

The descent module holds the panel for the cosmonauts, ship's control lever, instruments and equipment for the main and auxiliary systems, containers for the returnable scientific instrumentation and reserve supplies for the crew. The mass of the module is 2.8 tons.

The configuration of the descent module is complex semioval. The front end has a segmented flattening, as a result of which the vehicle acquires aerodynamic lift (aerodynamic quality). It has a system for control of descent with a low-thrust jet engine.

The landing system is of the parachute-jet type, consisting of a complex of parachutes and solid-fuel engines. The parachutes ensure braking of the descent module and its descent with a vertical velocity of about 10 m/sec. The soft-landing solid-fuel engine brakes the vehicle directly before contact with the earth's surface, softening the impact at the moment of landing.

The descent module also carries a system for its salvage in the case of damage to the carrier-rocket at the launching and in the segment in which the ship is put into orbit. It consists of a complex of powerful solid-fuel engines mounted on the ship's head fairing. In the case of damage to the rocket at launching these engines are fired and lift the front part of the nosecone and vehicle to a safe altitude necessary for the parachute to be activated. In the case of damage in the segment when the ship is being put into orbit the solid-fuel engines ensure the overcoming of aerodynamic forces and remove the descent module to a safe distance from the carrier-rocket.

Thereafter the parachute system and the soft-landing engines are activated.

The orbital segment is intended for carrying out scientific experiments, ensuring movement of the crew from ship to ship and for the rest of cosmonauts. The compartment is fabricated from a magnesium alloy and consists of two hemispherical shells joined by a cylindrical insert. On the top of the compartment there is a docking unit with an inner hatch with a diameter of 0.8 m. In the orbital compartment there are two viewing windows; a third window is situated in the hatch cover of the docking unit.

In the lower part of the compartment there is a hatch leading into the descent module and also a lateral hatch through which the cosmonauts enter the ship at the launch pad. Here also are the control panel and the equipment for the main and auxiliary subsystems in the compartment. On the outside of the compartment there are external-view television cameras, antennas of the radio communication and television systems. The total mass of the orbital compartment is 1.3 tons.

The instrument-assembly compartment holds the main apparatus, equipment and subsystems for support of orbital flight. This compartment consists of the transfer, instrument and assembly sections, fabricated from aluminum alloy.

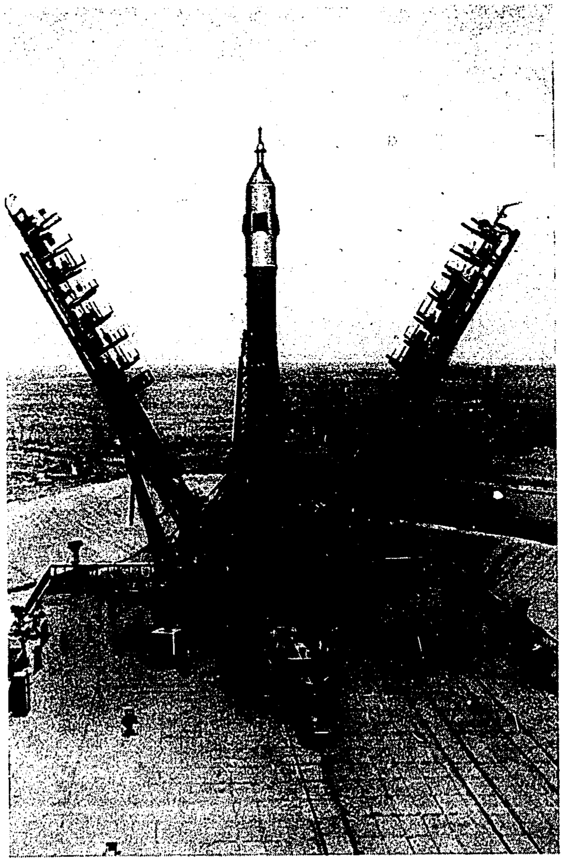

Fig. 21. Carrier-rocket of "Soyuz-19" spaceship.

The transition section has 10 mooring and orientation engines, fuel tanks, and a subsystem for feeding the fuel into the combustion chambers. On the outside of this section there is a small emitting radiator of the heat-regulating system, the upper junctions for the attachment of the panels of solar cells, and antennas of the command radio line. In the sealed instrument section, having the configuration of a low cylinder, there are instruments of the subsystem for orientation and control of motion of the ship, the subsystems for control of the on-board apparatus and equipment complex, apparatus for radio communication with the earth, programming-timing device, telemetry units, instruments and units of the subsystem for integrated electric current supply. On the outer side of the instrument section there is a sensor for constructing the IR vertical on the earth and a sensor for orientation on the sun.

The assembly section is designed in the form of a cylindrical shell which undergoes transition into a conical shape; on the outside of the section there is a large emitting radiator of the heat-regulating system, four mooring and orientation engines, the lower elements for the attachment of the panels of solar cells, and eight orientation engines. Within the section there is an approach-correcting engine, consisting of the main and duplicating jet engines, fuel tanks and subsystem for the feeding of fuel. Here also there are elements for attachment of the radio communication antennas and radio-telemetric system, as well as the ion sensors of the orientation system and electrochemical batteries of the subsystem for integrated electric supply for the ship.

The solar cells, in the form of two "wings," each of which consists of three panels which can be opened up, are mounted on the instrument-assembly compartment. Attached to the end panels are the antennas for radio communication in the short-wave and ultrashort-wave ranges and for the telemetric system. The mass of the instrument-assembly compartment is 2.7 tons, including 0.5 ton of fuel.

In concluding the section we can cite some design specifications for the space carrier-rocket which ensured putting the "Soyuz-19" into circumterrestrial orbit (Fig. 21). The rocket has three stages. The first stage consists of four lateral blocks 19 m in length and with a diameter at the butt end up to 3 m. Each block is supplied with a four-chamber engine which in a vacuum develops a thrust of 102 tons. In addition, in each block there are two additional steering chambers. The second stage is the central block (unit) with a length of about 28 m with a maximum diameter of 2.95 m. This block is supplied with a four-chamber engine (with four additional steering chambers), developing a thrust in a vacuum of 96 tons. The third stage is a block with a length of 8 m and a diameter of 2.6 m; it is also supplied with a four-chamber engine (with additional steering nozzles) with a thrust in a vacuum of 30 tons. Altogether, the carrier-rocket stages and the "Soyuz-19" spaceship have a launching mass of 300 tons.

During launching of the carrier-rocket the engines of the first and second stages are fired simultaneously; the second stage continues to operate after separation of the four lateral units. The third stage is launched at the end of operation of the engine on the second stage and puts the "Soyuz-19" into a stipulated orbit, after which it is separated. The total length of the carrier-rocket with the spaceship under the nosecone is 49.3 m. The maximum diameter along the fins is 10.3 m.

Makeup, Purpose and Operating Principles for Main Subsystems of On-Board Equipment

During its motion in space a space vehicle is regarded as an independent celestial body of artificial origin having definite conditions for operation of its instrumentation and equipment and for the life of the crew. These conditions are ensured by a complex of on-board equipment, which includes a number of subsystems, apparatuses and instruments. The complexity and numbers of the on-board equipment are in direct dependence on the number and complexity of the problems to be solved by the space vehicle and its payload. For example, whereas the first Soviet AES, which was designated the PS-1 (prosteyshiy sputnik -- pervyy = very simple satellite -- first), only carried one radio beacon with a small number of telemetric sensors, on the later spaceships of the "Soyuz" and "Salyut" types the number of subsystems, apparatuses and instruments exceeds a thousand. The task of the first AES included the practical confirmation of realization of man's agelong dream -- emergence into space, and the "Salyut" and "Soyuz," in essence, are multipurpose space laboratories and are intended for solution of a complex of different problems of a scientific and practical nature.

The maintenance of definite conditions on a space vehicle is ensured by means of subsystems for heat regulation, energy supply, radio communications, radiotelemetry and control of motion, docking, landing, vital functions and a number of other apparatuses and instruments. All these subsystems are joined together by a common electrical control, power supply and monitoring circuit, which improves their interaction and functioning. On space vehicles of certain types certain subsystems or instruments may be lacking. For example, automatic space vehicles do not have life support systems and unoriented space vehicles have no subsystems for orientation and control of motion. The most perfect vehicles are the spaceships aboard which there is a crew. They are supplied with a complex of on-board equipment to the maximum possible degree.

A sample, with a certain degree of arbitrariness, classification of on-board subsystems, apparatuses and instruments is shown in Fig. 22. The functional criterion is used here as the basis of their delimitation. Other criteria can also be used.

An examination of the entire complex of on-board equipment is quite complex. Here we will cite only brief descriptions of space vehicle subsystems which are most frequently used and which are most important from the point of view of ensuring stipulated conditions. These to a certain degree should give some idea concerning the complexity of the developed space equipment, about the processes transpiring in the subsystems and the requirements imposed on them.

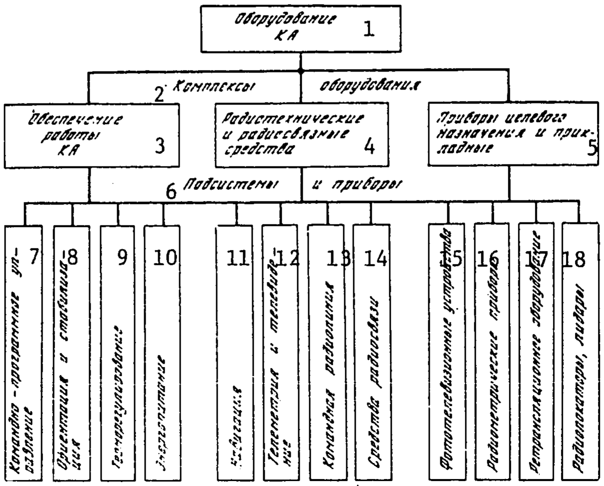

Fig. 22. Classification of the principal types of equipment aboard space vehicles using the functional criterion.

KEY:

1. Space vehicle equipment
2. Equipment complexes
3. Assurance of space vehicle operation
4. Radioelectronic and radiocommunication facilities
5. Instruments for special and applied purposes
6. Subsystems and instruments
7. Command-programming control
8. Orientation and stabilization
9. Heat regulation
10. Power supply
11. Navigation
12. Telemetry and television
13. Command radio link
14. Radio communication facilities
15. Phototelevision devices
16. Radiometric instruments
17. Relaying equipment
18. Radar, lidars

The subsystem for control of the space vehicle includes a programming-timing device and on-board digital computers. Depending on the complexity of the on-board equipment space vehicles can be supplied with them in different combinations.

The programming-timing unit is frequently called the automation or logical unit. In essence it is a small specialized computer intended for solution of a narrow range of algorithms for control of some particular space vehicle subsystem. Most frequently the control algorithm is a sequence of definite commands (series of commands), shaped at constant or variable (depending on the state of the controlled object) time intervals.

The program for the output of commands and the time intervals between them can be set in advance, for example, during the preparation of the vehicle for flight, or be issued in flight from the earth by means of the command radio link.

The universal computer is a more complex and flexible control unit. It ensures the solution of algorithms for the processing of data and control of some number of space vehicle subsystems which are extremely high content. With its use there is an increase in the reliability and accuracy of the processing results and it performs a thorough and careful control and analysis of operation of the on-board subsystems during ground tests and in flight, and also neutralizes the consequences of malfunctioning of individual apparatus elements by means of an equivalent replacement by reserve components. The possibility of constructing electronic computers on the basis of use of micromodules and integrated circuits of a standard type facilitates their operation, reduces size, mass and power consumption in comparison with analog computers.

The structural and functional systems of electronic computers have much in common with digital computers of the stationary type used on the ground. At its input an on-board digital computer is connected to the data-measuring subsystems of the space vehicle (telemetric and navigational), and at the output it is connected to the actuating components of the controlled subsystems.

The operation of the on-board computer can be organized in multiprogramming, multiprocessing or time-separation regimes. Multiprogrammed work is that in which there is simultaneous execution of several commands by one or more working programs. The multiprocessing regime assumes a parallel execution of several dependent programs or parts ("blocks") of one program, that is, those parts of the algorithm which can be executed parallely. In the time-separation regime the on-board computer automatically distributes the computer time among the controlled subsystems of the vehicle.

When using an on-board computer on a spaceship its principal functions are as follows: maintenance of the parameters of the life-support system within normal limits, monitoring of different subsystems on the ship, processing of the results of scientific experiments and investigations and their sampling for transmission to the earth.

We note that universal on-board computers find predominant use on manned orbital stations with a prolonged spaceflight duration. For example, the on-board computer on the "Apollo" ship was intended for the processing of data and subsequent control of the motion subsystem, evaluated the parameters of microclimate and solved a number of problems in control of other subsystems.

Imposed on the on-board computer is the rigorous requirement of simultaneous solution of several problems at a real time scale in accordance with the priority principle. The use of an on-board computer considerably increased the effectiveness of control and unburdened the crew members.

The subsystem for the control of space vehicle motion was designed for changing the parameters of motion of its center of mass and motion about its center of mass. The first form of motion occupies a relatively small time and is associated with the launching and putting of a space vehicle into orbit, orbital maneuvers and landing; the vehicle is acted upon by considerable external forces and jet engines operate. The second type of motion is characteristic for a large part of the space flight when the engines were switched off, the external forces and moments are insignificant. In this case a significant characteristic is the nondependence of motion of center of mass of the vehicle on angular rotations relative to the center of mass. The orbital motion of the space vehicle will be the same both in the case of random rotation about the center of mass and in a case when its spatial position is invariable. However, this does not mean that the vehicle has no need of control. A number of problems solved by a space vehicle require its ordered motion, for which use is made of systems for orientation and stabilization.

The orientation system is the system for the control of motion of a space vehicle leading to its rotation about the center of mass of the corresponding coordinate system by a stipulated angle relative to an external coordinate system. The process of rotation of the coordinate axes is called space vehicle orientation.

The necessity of orienting a space vehicle arises before the firing of the engine so that its thrust vector is directed in the necessary direction; with the transmission of information from a space vehicle by means of directional antennas (for example, from "Molniya" satellites); for obtaining an energy maximum with solar cells; in operation of the astronavigation system, when the space vehicle is oriented on reference celestial bodies, etc.

The realization of these tasks assumes the installation on a space vehicle of orientation systems with different technical specifications. For example, the accuracy of orientation in astronomical determinations and scientific observations attains a few seconds of angle, whereas for the orientation of solar cells an accuracy of 10-20° is entirely adequate. The duration of the orientation process can fall in the range from several minutes to several hours or more. With respect to degree of completeness, orientation systems can be classified as triaxial and uniaxial. Another classification criterion of the system can also be the properties of the orientation axes themselves, to which the space vehicle axes are reduced. It is assumed that these axes are also mutually perpendicular, like the axes of the vehicle itself, have their origin at its center of mass, but the law of their angular motion is unrelated to the motion of the space vehicle.

The latter criterion makes it possible to discriminate three types of orientation system. The first is characterized by a translational motion of the axes, in which they always remain parallel to one another and the space vehicle reduced to them retains its invariable angular position relative to distant stars (convenient for astroorientation). The second type includes orbital orientation axes which during flight in circumterrestrial orbit also rotate; one of the axes passes through the center of the earth, a second lies in the orbital plane, and the third is perpendicular to this plane. Such axes are used for the orientation systems of meteorological satellites, if they on one side are directed in the direction of motion, whereas the other is always directed downward. Then the reduction of the three axes of the AES to the three orbital axes will give the required orientation. The orientation axes of the third type are called "tracking"; they correspond to the approach of one space vehicle to another. These axes do not experience ordered translational or rotational motion, but change their direction arbitrarily in accordance with the relative movement of the space vehicle.

With respect to the method for obtaining controlling moments for orientation, all the systems can be classified as active, passive and combined. Active systems require expenditures of energy from on-board sources. In passive systems orientation is accomplished using the moments arising from the interaction of a space vehicle with the external medium -- magnetic field, gravitational field. Combined systems operate using both types of developed moments. Active systems are flexible and most used; employing them it is possible to force the space vehicle to perform, at the necessary tempo, any maneuvers and with the necessary accuracy adhere to the required orientation whatever may be the external perturbations. The principal merit of passive systems is their economy.

On spaceships the orientation systems can be automatic or manual. In the case of manual orientation the cosmonaut causes the required rotation of the ship by deflection of the control lever.

The makeup of the orientation system includes sensors responsive to space vehicle position and indicating its change; amplification-conversion devices reacting to the changes in parameters picked up by the sensors and converting them into controlling signals; actuating mechanisms creating controlling moments.

The position sensors may be inertial (gyroscopic), with sighting of celestial bodies, with the use of ambient fields (gravitational or magnetic), with sighting of the earth (optical, IR, radio, etc.).

The amplification-conversion devices are intended for the amplification and conversion of sensor signals. They are outfitted with electronic, relay and magnetic or semiconductor amplifiers. The controlling effects in them are produced in specialized computers.

The actuating components ensure the creation of controlling moments due to gravitational, magnetic and other ambient fields (passive) and also the movement of elements within the space vehicle, on-board engines (active).

As an example we will consider the process of full orientation of a space vehicle during its flight on the trajectory earth-moon. This is done using solar and lunar sensors mounted in fixed positions on the space vehicle. The search for the sun and moon is accomplished by rotation of the entire vehicle. First the sun is found and held in the field of view of the sensor. Then the space vehicle begins to rotate around the direction found to the sun with simultaneous search for the moon by the lunar sensor, whose axis is deflected by a specific angle in space. At the moment of interception of the moon the vehicle is braked and its direction is held steady relative to the moon.

Thus, the process of orientation consists of the following operations: rotation -- interception of the sun -- braking -- refinement of orientation on the sun -- second rotation -- interception of the moon -- braking -- second refinement of orientation on the moon.

The stabilization system is intended for restoration of the initial position of the space vehicle impaired as a result of the action of disturbing moments. Its task includes neutralization of the forces tending to change the trajectory of motion of vehicle center of mass. Stabilization of space vehicle position is necessary in the operation of jet engines for the purpose of maintaining the direction of the vector of their thrust unchanged, in aerodynamic descent in the atmosphere and in some scientific investigations.

In contrast to orientation, the stabilization of a space vehicle does not pursue independent purposes, but is an auxiliary task in the control of motion of the vehicle center of mass. The stabilization system operates with relatively large disturbing moments and therefore more powerful actuating components are required for their extinction.

We note that the orientation and stabilization systems frequently interact with one another and use one and the same sensors and a common control circuit. For example, the process of approach of two space ships is in essence the repeated alternation of the orientation and stabilization regimes corresponding to repeated firing and shutdown of the engines.

In addition to orientation and stabilization of space vehicle position it is also necessary to have direct regulation of the velocity of translational motion of its center of mass.

Such a task arises in the operation of the engines in the course of execution of the corresponding space vehicle maneuvers. In a number of cases it is sufficient that the system for the control of motion issue a command for shutdown of the engine when a stipulated apparent velocity is attained. In this case the control of the jet engines is usually accomplished using gyroscopic integrators in which the force of the energy developing during a change in the apparent velocity of translational motion of the center of mass of the space vehicle is transformed into the moment imparted to a gyroscope with a rigorously calibrated velocity of rotation. A measure of the apparent velocity is the angle of rotation (precession) of the gyroscope, accumulating under the influence of this moment.

The subsystem of space vehicle heat regulation is intended for the automatic maintenance of a stipulated temperature regime in the vehicle compartments. The necessity for solving this problem is attributable to nonuniform heating of the space vehicle during its flight on the sunny side and in the earth's shadow. It should be noted that in contrast to terrestrial conditions, in space there is only radiative heat exchange between individual bodies. The space vehicle is acted upon by radiation from the sun, earth or another planet. A space vehicle, as a body heated to a definite temperature, also emits into space heat whose quantity is dependent on the external heat flows absorbed by the space vehicle and internal heat releases due to operation of on-board equipment or the vital functions of the crew.

Temperature drops within stipulated limits of the mean value are allowable under the condition of retention of a balance between absorption and radiation of heat by the vehicle. Otherwise the temperature can change beyond the tolerable values.

The complex automatically maintaining a stipulated heat regime in the space vehicle is known as the heat-regulating subsystem. It includes: sensing elements (sensors) measuring the temperature at definite points in the space vehicle; electronic units shaping the controlling signals (system for the control of heat regulation); actuating components directly acting on thermal processes; radiation surface for radiation of excess heat released in the vehicle; general facing of the space vehicle surface with a given optical coefficient; screening-vacuum insulation.

The activity of functioning of the heat-regulating subsystem as a rule is controlled using the temperature values at the input and output of the heat exchange elements. The greater their difference, the more intensively does the system operate.

The thermal processes in the space vehicle compartments transpire under weightlessness conditions, and accordingly there is no heat convection in them. This makes very difficult the evening-out of temperatures between nonidentically heated elements of equipment, gas volumes and construction of the space vehicle. The problem of eliminating local overheatings and overcoolings in this case is solved due to the heat conductivity of individual construction parts of space vehicles, forced circulation of gas in the compartments, and also the delivery of heat to liquid heat carriers. The heat excess in this case is always conveyed to the radiation panel of the system.

With respect to the principle of operation, heat regulation systems can be classified as active and passive. Active systems ensure forced transfer of the heat excess from its sources to the radiation panel by means of a closed fluid circuit whose actuating component is a hydraulic valve regulating the intensity of circulation of the liquid heat carrier. In simpler types of active heat-regulating systems there is a forced circulation of the gas, which also plays the role of a circulating heat carrier. Passive systems are being developed on the basis of methods of passive heat regulation. These include: special processing of the outer surfaces of space vehicles, ensuring definite values of their optical coefficients (albedo); covering individual parts of the vehicle surface, external elements of its construction and equipment with shielding thermal insulation.

Due to the fact that in computations of the effectiveness of heat-regulating systems it is possible to take into account rather precisely the magnitude of the external and internal heat flows, modern systems are capable of maintaining stipulated temperatures in space vehicle compartments with an acceptable accuracy. Thus, on spaceships their values are regulated in the range ±3°C, and on automatic space vehicles with an accuracy of ±5°C relative to a stipulated value.

The subsystem for unified current supply ensures the supplying of electric current to the entire equipment complex aboard the space vehicle.

As the current sources aboard a space vehicle it is possible to use storage batteries, galvanic and fuel cells, solar cells and apparatus, isotopic generators and nuclear power plants.

In the case of brief space vehicle flights (10-15 days) and a small number of current users the power sources in many cases are storage batteries, since they are the cheapest. The galvanic and fuel cells with respect to energy capacity exceed storage batteries by a factor of 4-5. They produce energy on the basis of the transpiring of electrochemical processes between two working substances (for example, oxygen and hydrogen). However, the most widely used sources are solar cells and apparatus directly converting the light energy of the sun into an electric current. The power of such current sources attains several kilowatts and they have a considerable longevity (up to a year or more) and a high reliability. Nuclear power plants with reactors are in essence small atomic electric power stations adapted for operation under space conditions. Their power also attains several kilowatts. Isotopic generators operate on the basis of release of heat by radioactive isotopes and its subsequent transformation into an electric current. The power of generators of such a type is tens and hundreds of watts.

Usually the primary current sources are connected to a buffer storage battery charged to a nominal value during periods when the power consumption of the on-board equipment is less than the power of the source and which feeds the general net during periods when the power of the current source does not suffice.

The automatic components of the system for unified current supply operate autonomously and perform switchings associated with a change in its regime of operation and control of the principal parameters: current voltage, capacitance, etc.

Space vehicle apparatus is usually fed by a low-voltage (28 and 12 V) d-c current. However, sometimes instruments operating on alternating current are installed and then in their current supply circuits provision is made for the installation of semiconductor elements for converting a d-c current into an alternating current.

The subsystem for life support is intended for creating and maintaining the conditions necessary for the life and activity of cosmonauts in the compartments of the space vehicle. It maintains an artificial gas medium (atmosphere) with optimum physical parameters (pressure, humidity, velocity of movement) and chemical composition, satisfies the crew's need for oxygen, food and water and eliminates the wastes of man's vital functions and other biological objects.

A standard life support system must include the following links:
a) a link for creating and maintaining the required gas medium in the pressurized compartments of a ship during the entire time of a spaceflight. It must compensate the loss of hydrogen, eliminate excesses of carbon dioxide and harmful impurities. On brief flights the loss of oxygen is replenished at the expense of its reserves created prior to the launching (gas cylinders, Dewar vessels, active chemical compounds of oxygen with alkali or alkali-earth metals). In order to eliminate carbon dioxide use is made of filters or alkalis of some metals. During prolonged space flights it is proposed that the oxygen loss be replenished by means of the photosynthesis transpiring in some types of plant organisms;
b) a link for supplying food during brief flights and those of medium duration. During prolonged flights it is possible to use the biomass of plants cultivated aboard the ship;
c) the water supply link. This is created from the supplies of water before the launching (brief flight); during prolonged flights, in addition to the reserve, there must be regeneration of water from the wastes of man's vital functions;
d) the sanitary-household link. Here there is a hygiene unit, a unit for disposal of man's natural wastes and a unit for disposal of remainders from food preparation.

Each link in the system, including the links for physicochemical regeneration and even an individually taken biological link (man and other organism) constitutes an open "flow-through" system. The main condition for its normal functioning is the constant receipt of the necessary initial substances and elimination of the final products.

The on-board complex of radioengineering and radio communications equipment includes means for the navigational, telemetric, television, command and communication support of flight. A number of these means can be developed using an autonomous or "matched" scheme. An autonomous scheme provides for the use of individual communication channels and means of on-board equipment for solving each individually taken problem. The designing of a "matched" scheme is based on use of one communication channel and a general radiotechnical apparatus for solving several problems. "Matched" schemes are more economical from the point of view of use of communication channels, size and mass, and also with respect to energy indices. Navigational, telemetric and command units are moust frequently incorporated into a single apparatus.

Now we will enumerate the makeup and assignments of radiotechnical apparatuses aboard a space vehicle which have been developed in accordance with an autonomous scheme for their use.

1. For the navigational support of space vehicle flight, in addition to strictly autonomous means (such as the "Globus" system, astroorientation devices, etc.), use is made of navigational means of an active type. In this case the vehicle carries a transponder which responds to the interrogation signals of a ground radar station. The problem of determining the navigational parameters of the vehicle is solved by measuring the slant ranges, azimuths and angles of elevation, and also their derivatives.

2. The on-board telemetric unit is intended for primary measurements of the monitored processes aboard the space vehicle, collection, conversion and transmission of the results to a ground radiotelemetric station. For this purpose aboard the vehicle there is a complex of sensors commutating the apparatus and the transmitter with the antennas.

3. The television apparatus is used for visual monitoring, for the control of individual processes aboard the vehicle (for example, approach and mooring of two space vehicles can be monitored using the image on the screen of the TV receiver). In addition, the television apparatus is used for the transmission of visual information to the earth (for example, during the space reports of cosmonauts). The TV equipment includes: apparatus for the perception of images (vidicons), devices for the readout and transmission of information to ground receiving stations.

4. The makeup of the on-board command equipment includes a receiver with a decoder of commands which ensures the reception and identification of commands transmitted by the ground control system.

The radio communication equipment carried aboard a spaceship is used for communication between the cosmonauts and the earth. It includes receiving and transmitting stations in short-wave and ultrashort-wavelength ranges. They ensure radio exchange of different information between the space vehicle and the earth.

The instruments and apparatus for these special purposes ensure a direct solution of the missions assigned to space vehicles. The vehicle is a rapidly moving space platform which carries a complex of different equipment for the solution of scientific and practical problems.

The operation of this equipment is based on use of the method of remote sensing of the underlying surface of the planets (including the earth) from space. This method helps in remote characterization of the nature of formation and conditions of deposition of terrestrial resources, natural parameters, phenomena and the environment by means of carrying out observations and measurements from different types of vehicles. The information basis of the method is the remote reception and registry of the characteristic (natural) and reflected electromagnetic and corpuscular specific radiations, making it possible to investigate objects, phenomena and formations of natural and artificial (for the earth) origin.

The remote sensing of the underlying surface of the planets is a possible result of the fact that each object, phenomenon and formation at a temperature above absolute zero absorbs and radiates electromagnetic energy at definite wavelengths. In the selection, comparison and analysis of the resulting spectral characteristics it is possible to determine the differences between the observed objects and phenomena, making it possible to extract information on their properties.

For practical purposes the electromagnetic spectrum is broken down into several ranges in the following way:
-- less than 0.4μm -- UV radiation;
-- 0.4 - 0.75μm -- visible (optical) part of the spectrum;
-- 0.75μm - 1 mm -- IR part of the spectrum (within this range it is possible to distinguish three narrower regions: 0.75 - 3μm -- near-IR range or the region of reflected IR rays, 3-30μm -- middle-IR range or thermal-IR region, 30μm - 1 mm -- far IR range);
-- 1 mm - 1 m -- microwave part of spectrum.

There are two remote sensing methods: active and passive.

The active method is based on use of instruments and apparatus generating and emitting energy, as a result of whose interaction with objects and phenomena of interest to us gives rise to a reflected signal received by on-board detectors.

The information characteristics of the reflected signal (intensity, polarization, etc.) make it possible to identify the observed objects or phenomena. These include: panoramic radar stations, side-view stations, stations with a synthesized aperture, radioaltimeters, scatterometers, lidars (laser rangefinders).

On the basis of passive methods it is possible to develop instruments which in themselves do not have the capacity for radiating electromagnetic radiation. These are different types of detectors which sense the natural and reflected radiation emanating from the surface of the planet or its atmosphere. These should include visual observations (the detector is the human eye), photo- and television apparatus, radiometers, spectrometers.

In this case there is a possibility for establishing an unambiguous correspondence between the spatial distribution of spectral, energy (brightness) and polarization characteristics of radiation of terrestrial objects and their appearance, state, chemical composition, physical and biological properties.

The technical and operational characteristics of the remote sensing apparatus enumerated here must correspond to the requirements imposed on onboard space apparatus of a different purpose. There are specific requirements on resolution, periodicity of observations of definite regions, scale of observations, scanning zones, angles of the field of view, orientation, accuracy in spatial-temporal tie-in and scanning.

Now we will consider some peculiarities of the most widely used instruments and apparatus.

Cameras are used for surveying the planetary surfaces. Their working range 0.3-1.1 μm is limited in the direction of the IR part of the spectrum by the sensitivity of the photographic film, and in the direction of the UV by the transparency of the objectives. There are single- and multirange cameras which pick up the visible image on black-and-white or color film. Multirange cameras make it possible to obtain multispectral photographs characterized by a high resolution in discretely selected parts of the optical range. The resolutions of modern films are estimated at from 100 lines per mm (color films in the visible range and films in the IR range) to 1,000 lines per 1 mm (black-and-white films for the visible range with an object contrast 1,000-1).

The accuracy of photoregistry of visible images is so great that virtually all modern maps of the terrain are compiled using a photographic survey (for the most part from aircraft, and recently using a space vehicle).

Television cameras are extremely high-speed scanning microphotometers and are well adapted for the purpose of remote sensing of radiations from aircraft and flight vehicles in space (meteorological satellites, natural resources satellites). The detectors of the registered radiations in this case are sensing surfaces (photocathodes), the images on which are projected by means of optical objects. In the best models of modern detectors (superorthicons, vidicons with ray return) the best resolution attainable is estimated at 10,000 lines for a detector area of 50 x 50 mm.

Radiometers can be of three types: IR, superhigh-frequency and polarimeters. In these the collectors used are different types of directional antennas and the detectors are: in IR radiometers -- semiconductor elements sensitive to IR radiations in the near zone; in superhigh-frequency radiometers -- receiving circuits for the corresponding ranges, amplifying the received radiation; in polarimeters -- elements sensitive to visible and UV radiations, which with the corresponding processing makes it possible to measure the angle of rotation of the radiation polarization plane, whose value is dependent on the type of observed formation.

Spectrometers, in contrast to radiometers, have a collector with selective frequency properties, which makes it possible to discriminate narrow spectral sectors of absorption (emission), characteristic, for example, for water vapor, definite chemical elements, complex formations, etc.

The following types of spectrometers are known: IR, UV, superhigh-frequency and correlation.

Radar instruments are capable of carrying out measurements of distortions of natural radiation when it is reflected or absorbed by a remote object. A frequency change is a measure of the relative radial velocity of an object and the distance to it is determined from the time between transmission of a pulse and return of the reflected echo and the polarization characteristics indicate the physicochemical properties of the observed object. The schemes for construction of space vehicle radar instruments differ little from the schemes for ground radar stations.

Lidars are also active instruments. They sense the energy reflected by the object in the visible or near-IR range. Different types of lasers are the source of the radiated signal.

PROCESSING AND ANALYSIS OF ROUTINE (OPERATIONAL) INFORMATION. ADOPTION OF DECISIONS

Basic Concepts and Principles

The control processes in "earth - space vehicle" systems are accompanied by different flows of information whose basic purpose is ensuring the effective realization of controlling functions assigned these systems. In a general case the term "information" can be interpreted as some totality of the communications determining the measure of our knowledge about various events, phenomena, facts and about their interrelationship.

Any communication with which we deal in the theory of information is the totality of information about some system. It is obvious that if the state of the system is known in advance it would make no sense to transmit the communication. A communication acquires sense only when the state of the system is unknown in advance, random.

Information on a space vehicle can be considered as its reflection in some material system, which can exist independently of whether this information is used by anyone or at any time. However, whereas information or some representation can exist independently of man, one can speak of the value of the information, about its cost to the user, only strictly in relation to man, who needs this information, in relation to the process in which it is used.

The operation of man-machine systems for control of a space vehicle is not very effective if there is no objective approach to the perception of information concerning the space vehicle. In this connection one of the principle requirements on controlling processes in the "earth-space vehicle" system is a minimizing of the influence of the subjective approach to the perception of information communications about the vehicle. A correct, that is, an objective understanding of communications is assisted by the presence of feedbacks in the control system which are used for monitoring the controlling processes.

In the processes of perception, transmission, storage and use of information the latter can be subjected to a number of operations of the following form.

1. Storage of the received information on some material carrier.

2. Transformation of information into a more convenient form for subsequent use.
3. Transmission of information from its source to a detector with subsequent registry on a long-term carrier.
4. Sorting, synthesis and processing of information using a number of established criteria facilitating its perception in a man-machine complex.
5. Analysis of information or its logical processing, ensuring proper understanding of the controlled processes transpiring aboard the space vehicle.
6. Use of the results of processing and analysis of information for adopting a decision on vehicle control.
7. Evaluation of information with respect to reliability, correctness and timeliness.
8. Elimination of information after it has become too old or unnecessary.

A space vehicle as a material body with very definite technical specifications during its functioning is subjected to the influence of the surrounding medium and at the same time for attaining definite goals strives to exert a corresponding effect on it. A change in the characteristics of the surrounding medium results in a change in the form of space vehicle operation. This situation is graphically confirmed during a flight to Venus or any other planet when the space vehicle is successively subjected to the influence of an external medium with changing characteristics. First these are the physical parameters of the earth, then circumterrestrial space, then the vehicle enters the interplanetary medium, and finally is subjected to the medium on the planet of destination. For normal functioning on the space vehicle provision must be made for special measures taking into account the nonidentity of the influence of different external media.

It is evident that the effectiveness of space vehicle control in such cases will be dependent, on the one hand, on the availability of information on the surrounding medium and its changes (information on external conditions) and on the other hand, on the information characterizing the performance of the space vehicle as a technical assembly (information on external conditions). Thus, the space vehicle itself is the primary source of both types of information.

Both types of information are transmitted to earth using different radiotechnical, radiocommunication and television subsystems. However, the basic flow of information from the space vehicle to the earth passes through the channels of navigational and radiotelemetric subsystems.

The navigational subsystems, which may be, for example, radar stations with or without interrogation, phase systems or systems for measuring the Doppler frequency shift, by direct (or indirect) measurements determine the spatial position of the space vehicle relative to ground command-measurement points (CMP) at each stipulated moment in time. By means of subsequent computations and operations with the navigational information it is possible to solve individual problems in evaluating the changes in the dynamic characteristics of the space vehicle, determine some parameters reflecting the functioning of its engine (for example, it is most common to compute the value and direction of the space vehicle velocity vector before and after operation of its engines). Similarly, an evaluation is made of operation of the elements and apparatus for orientation and stabilization.

The telemetric subsystems send to the space vehicle control circuit information on the external and internal conditions, which are evaluated by a very definite (finite) set of physical parameters. They include pressure, temperature, illumination, angular positions of individual apparatuses and the space vehicle itself, number of activations of the instruments, etc. It must be noted that the complexity of the design of space vehicles, the great number of monitored instruments and apparatuses and the great number of experiments carried out are evaluated using an extremely significant volume of telemetric information. As we already mentioned earlier, on ships of the "Soyuz" type the number of measured physical parameters attains thousands, which under the condition of a rather high frequency of interrogation of each parameter requires wide-band channels for data transmission. This is confirmed by simple computations. Assume, for example, that the subsystem for telemetric measurements has a frequency of interrogation $F_0 = 50$ Hz, and each measurement is characterized by 10 binary digits. Then the data flow is $5 \cdot 10^5$ binary digits per second. Under the condition that the session for reception of data from the AES can continue 300-600 sec the total quantity of information registered on the earth in one communication session attains $(1.5-3.0) \cdot 10^7$ binary digits.

The totality of the information transmitted from a space vehicle to the earth by means of navigational, telemetric and other subsystems during a definite time interval determines its information content, which is an important technical parameter of the control system. This parameter is used in planning the "earth - space vehicle" communication channels, and also plays the role of an input parameter in developing ground subsystems for the collection and processing of information.

In order to accomplish the task of control of a space vehicle there is no need for rapid processing of the entire flow of data transmitted to the earth since in the control algorithms and in the routinely analyzed information not all the parameters monitored aboard the space vehicle are used. This fact exerts a substantial influence on the planning of subsystems for the processing and collection of routine information. By the term "routine information" is meant the information which is used directly in the process of control of a space vehicle, and accordingly it can also be called "controlling."

Routine information is the input information of control algorithms and on its basis a decision on the output of control commands is made. Besides this information, nonroutine data are also transmitted from aboard the space vehicle, these data not exerting a direct influence on the control processes.

This can include, for example, information on some scientific experiments not requiring periodic processing.

The problem of selecting routine information can be regarded as a semantic problem and its solution is obtained most frequently on the basis of mathematical-statistical methods. It is usually assumed that most space vehicles can be effectively controlled on the basis of routine information (operational information), constituting about 15% of the entire quantity of information transmitted from the space vehicle to the earth. However, in individual cases, when particularly complex vehicles are put into space, and also poorly studied experiments are carried out, the quantity of routine information can increase to 30-50% of the total volume of information.

A solution of the problem of automated processing of information in the "earth - space vehicle" control system is assigned to computer systems which include a definite number of matched homogeneous or inhomogeneous computers and other apparatuses ensuring the reception, processing and output of the final results to the users. Depending on the purpose, the computation systems of the "circuit" can be universal and specialized. Universal computers are intended for the processing of navigational and telemetric information; specialized computers are used for the processing only of a definite type of information.

In those cases when computer systems include computers of the universal type the possibilities of processing of both types of information can be determined by the presence in the system of special devices for hookup with the radiotechnical facilities of the CMP, the facilities for transmitting data to the space vehicle control center, and apparatus for display of the processing results.

In the course of control of a space vehicle the computation systems for the processing of navigational and telemetric data operate in an operational regime which is characterized by the fact that such systems operate at a real or quasireal time scale and have a high degree of automation of the processes of reception of information, its processing and the dissemination of the results to users. The capacity of their operational memory is sufficiently great and the external storage units play a relatively small role.

The structure of the computation system for the processing of data provides for the presence of computers at the command-measurement points and at the Space Vehicle Control Center. The control of the vehicles is ensured by data and command-operational communication channels. The computer system for the processing of data, being a subsystem of the control circuit, in all its distinguishing criteria can be classified as a complex system, that is, has a hierarchical organization, purposefulness of functioning, great number of elements, presence of information connections among the elements. There is also an interaction among the elements. From the point of view of centralization of control the data-processing computer system can operate in centralized, decentralized and mixed control systems.

In the case of total centralization, as the controlling unit of the system there is a computer "dispatcher" (or operator) at the Space Vehicle Control Center, coordinating the load on the computers and their interaction in the process of solution of the problem. In a decentralized system with "homogeneous" computers any computer can play the role of "dispatcher."

Both types of centralization of control for a computer system for the processing of information can function in the space vehicle control circuit.

Processing of Navigational Data

The processing of navigational data makes it possible to compute the trajectory of motion of a space vehicle in orbit. If the forces perturbing the vehicle are equal to zero or are precisely known, it is sufficient to determine the six initial conditions, that is, x_0, p_0, z_0, $\dot{x}_0$, $\dot{y}_0$, $\dot{z}_0$ in a geocentric coordinate system for some moment in time. However, it is impossible to obtain these values directly using radiotechnical systems, and therefore other parameters are actually measured, these being called the navigational parameters of motion. The navigational parameters are determined in a coordinate system related, in the case of autonomous control, directly to the space vehicle, and in the case of a nonautonomous control, to the CMP, that is, in a topocentric coordinate system, which is called the coordinate-measuring system. The center of such a system is matched with a point on the earth's surface where a command-measurement point is situated. The x-axis lies in the plane of the local horizon and is directed to the north; the y-axis coincides with the local vertical and the z-axis is selected in such a way that the coordinate system is right-handed. A topocentric system corresponds to a spherical system in which the position of the space vehicle is stipulated by the radial range R, the azimuth α and the elevation angle β.

When carrying out navigational measurements from a CMP it is customary to determine the topocentric coordinates of the space vehicle: R, $\dot{R}$, α, $\dot{\alpha}$, $\dot{\beta}$. Instead of azimuth and elevation angle, in many cases measurements are made of the direction cosines of the vehicle line of sight, and also their time derivatives.

The navigational parameters are related to the initial conditions by definite mathematical dependences. Accordingly, for computing the unperturbed trajectory of a space vehicle it is sufficient to have the results of measurements of the six independent navigational parameters at one and the same time. If a single measurement is made from one CMP, such parameters will be R, $\dot{R}$, α, $\dot{\alpha}$, β, $\dot{\beta}$. When several points are used it is possible to measure not all six parameters, but only some of them. For example, the six initial conditions necessary for computing the trajectory are obtained using the results of range measurements only, but from six CMP distributed in a definite way.

When the results of measurement from one point are used for determining the trajectory the measurement system is called "one-point"; otherwise it will be called "multipoint." With respect to the number of different measured navigation parameters the systems can be single- and multiparameter.

When using a one-point system, not measuring all six parameters, a determination of the trajectory is possible only with multiple measurements. For example, for obtaining the six initial conditions of unperturbed motion of the vehicle it is necessary to have six independent measurements. Due to the relative motion of the space vehicle and the earth the results of nonsimultaneous measurements from one point are related to different points in space, which in definite cases ensures a nondependence of the measurements.

Using navigational measurements of radio systems, point estimates of navigational parameters are made. These are fed out in the form of discrete readings at the end of the time interval of each individual measurement. Each determined value of the navigational measurement of the parameters contains systematic and fluctuation errors. An effort is made to decrease them, using the corresponding types of processing of the received signals. Primary, intermediate and secondary processing are distinguished.

Primary processing involves an evaluation of the parameters of a radio signal carrying information on navigational parameters. It is accomplished directly in the measurement systems.

Secondary processing involves a determination of the space vehicle trajectory on the basis of measurements carried out using radio systems, prediction of their motion and allowance for correcting maneuvers. It is accomplished at command-computation centers.

Intermediate processing involves a preparation of the results of evaluation of the navigational parameters of the radiosignal, reducing it to a form convenient for secondary processing. It can include, for example, the scaling of the measured Doppler frequency into radial velocity. Intermediate processing is carried out at command-measurement and command-computation centers or in both places simultaneously.

The operation of the computation facilities for the processing of navigational information in this case can be represented in the following way. The measurement facilities of the CMP carry out a period of trajectory measurements in which, by one method or another, it is possible to determine the navigational parameters of the space vehicle. The collected data are fed to the computation facilities of the CMP; they are transformed into a form convenient for processing on an electronic computer and are transmitted through communication channels to the computation center at the Space Vehicle Control Center. Data are accumulated as the space vehicle moves through the zone of visibility of the CMP. After the number of measurements is adequate for determining the space vehicle orbit, all the data are registered in the operational memory device of the computer and the direct process of computations begins. On the basis of the computed parameters of motion of the space vehicle it is possible to calculate the necessary instructions for operation of the ground radiotechnical stations. In order to make a number of the results of computations more graphic, and also for projection of the space vehicle trajectory of motion onto the surface of the earth, these are represented on special visual aids (displays, illuminated diagrams, maps, etc.).

Collection and Processing of Telemetric Data

The complex of facilities for the collection and processing of telemetric information also forms a separate and clearly defined subsystem which has functional relationships with other subsystems: the input section is connected to the output of the data-telementric system and the output section is connected to the facilities for data analysis. With respect to a number of criteria characterizing complex systems, the subsystem for the collection and processing of telemetric information, like the system for the processing of navigational information, can be classified as a complex system.

The computation facilities of the subsystem can solve problems in the primary, secondary and operational processing or collection of telemetric information. This classification was predetermined by different requirements on the form, volume, time, accuracy and reliability of dissemination of the results of the processing to users in different stages of the development, testing and operation of a space vehicle.

The primary processing includes operations associated with the scaling of the telemetric information. The essence of these operations is the analytical conversion of data measured by the radiotelemetric facilities from a relative scale, usually expressed in percent, to the scale of physical parameters, that is, into units of temperature, pressure, etc. Such processing facilitates the processing of the perception of information in the stage of its analysis. In addition to scaling, primary processing ensures monitoring of the reliability of data and the grouping of the results on the basis of different criteria for the purpose of more convenient use. The results of primary processing can serve as the initial data for routine analysis of the state of the space vehicle and the carrying out of secondary processing.

Secondary processing is more profound. It has elements of logical analysis, as a result of which it is sometimes called logical processing. The basis for secondary processing is computation processes carried out using more complex algorithms reflecting some process investigated aboard a space vehicle. As the algorithms it is possible to use systems of differential, difference and algebraic equations in which the results of the primary processing are in the form of variable coefficients. The results obtained in this stage are of value for a more rigorous and thorough analysis of the state and behavior of the space vehicle.

Operational processing includes individual subproblems in primary and secondary processing and differs from the considered stages for the most part in the volume and times of representation of the final results, which are the initial data for routine analysis and forming of decisions on space vehicle control.

All our further exposition will relate for the most part to the stage of operational processing of information used in the space vehicle control circuit.

The territorial spacing-out of the Control Center and the command-measurement points dictates that the control system include facilities for the collection of telemetric information. Using these, both processed and unprocessed data from telemetric measurements can be transmitted to the Space Vehicle Control Center. The collection facilities include elements for the conversion, collation, and transmission of data, as well as increasing their reliability. Depending on the communication channels used between the measurement points and the Control Center it is possible to distinguish ordinary and wide-band systems for the collection of telemetric information.

The subsystem for the processing and collection of controlling, or, as it is more commonly called, operational telemetric information, is determined as the totality of the interconnected and coordinated homogeneous and inhomogeneous electronic computers, matching apparatus, communication facilities and other elements ensuring automated processing, collection and dissemination of the results to users.

The subsystem for the processing and collection of operational telemetric information is a multiphase, multichannel and multicircuit system for the purpose of mass servicing, subject to the influence of a number of random factors. It is assumed that the subsystem input receives an input flow of session communications (requirements) having the properties of ordinariness, absence of aftereffects and nonstationarity. These assumptions are not a rough abstraction. They make it possible to carry out investigations of the subsystem, obtaining results which are acceptable with respect to accuracy.

At the system output we obtain a communication determined as the minimum necessary quantity of processed telemetric information with a stipulated accuracy, reliability and time characteristics, making it possible to carry out space vehicle control and to monitor its state in the course of the current or subsequent communication sessions.

It follows from the definition that there are quite high operational-technical requirements for the subsystem which are limited by rigid time intervals allocated for vehicle control during the communication session.

The elements of the subsystem include:

-- input operational elements ensuring matching of the input flow of information with the computation capabilities of the electronic computer used and reduction of the information to a form convenient for its processing;

-- a one- or multiprocessor, territorially spaced system ensuring the processing, documentation, storage and collection of the results of processing;

-- control panels and panels for the processors, and also the subsystem as a whole;

-- radio, telephone or telegraph communication channels, ensuring the exchange of information among elements of the subsystem;

-- output operational elements intended for the display of the results of processing on individual or group viewing apparatuses, and also preparation and transmission of the processed (or unprocessed) information through communication channels;

-- mathematical support, including a complex of algorithms, working programs, instructions, methods, calibration curves and other documentation making it possible to carry out automated processing and collection of information.

Figure 32 is a block diagram of the subsystem. It clearly shows the presence of direct connections and feedbacks among all the principal elements of the subsystem, which is necessary for constant monitoring of their functioning and control.

A distinguishing characteristic of the subsystem for routine processing, which includes processors, is its operation on a real (quasireal) time scale, that is, the rate of processing of data is commensurable with the rate of its receipt, as a result of which there is no accumulation of data in the buffer memory units in the subsystem. This is a very important quality of such systems, ensured, on the one hand, by a high productivity of the processors used, and on the other hand, by the matching of the quantity of data arriving for processing with the computer capabilities of the subsystem.

The processing of operational telemetric information is the process of carrying out some sequence of computation and logical operations making it possible to obtain results reflecting the picture of control of a space vehicle or its individual subsystems in the form required for analysis. On the basis of the collected data it is possible to establish the quantitative and qualitative characteristics of processes aboard a space vehicle. The basis for the mathematical processing of routine information is the complex of employed algorithms and working programs determining the structure of the computation scheme and the form of the final results.

The results of processing of operational data are fed out in the form of functional dependences on one or more variables, that is, in general form we obtain a function in the form $y = f(x_1, x_2, \ldots, x_k)$, where y is the value of the measured parameter of the function and $x_1, x_2, \ldots, x_k$ is the totality of the arguments.

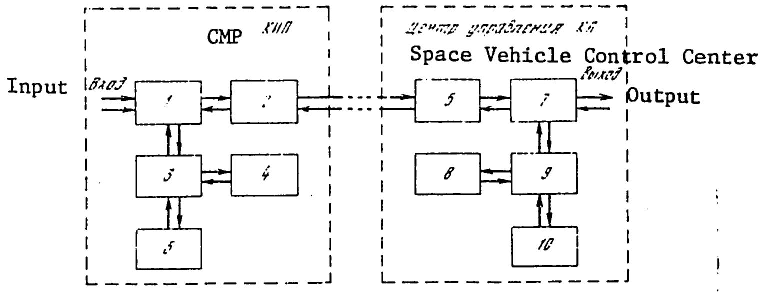

Fig. 32. Block diagram of system for the processing of operational telemetric information. 1) apparatus for connection to radiotechnical station; 2, 6) connection with communication channels; 3, 9) electronic computer; 4, 8) alphabetical-digital printout unit; 7) device for connection with other processing elements; 5, 10) apparatus for display of results.

In order to make the results more graphic and in order to accelerate the analysis these results can be supplemented by meaningful communications which improve the process of perception of information. In this case the results of processing of routine telemetric information are formed as alphabetical-digital line communications; each separately taken output result corresponds to one line. This method for the output of results is realized in alphabetical-digital printout units and at the same time is displayed on wide-format screens of graphic radiotechnical and optical apparatus.

The principal requirements imposed on the subsystem for the processing and collection of data follow from the general requirements which must be satisfied by the automated system for control of a space vehicle. We will formulate them in the following form.

1. The subsystem must ensure the processing and collection of the optimum amount of operational telemetric information both with respect to the number of parameters and with respect to the number of measurements (records) of each individually taken parameter.

2. The time of representation of the processed information must meet the requirements of space vehicle control in the current or subsequent communication session with it.

3. The results of processing of routine information with respect to accuracy characteristics must ensure an error-free analysis and subsequent correct adoption of a decision on space vehicle control.

4. Unreliability of information, that is, the appearance of incorrect results or false information, must insofar as possible be excluded.

Now we will examine these requirements from the point of view of their technical feasibility.

The analysis and evaluation of the optimum amount of operational telemetric information necessary for the effective control of a space vehicle involve a problem of the compromise type. On the one hand, for a thorough and objective analysis of the state and behavior of a space vehicle it is necessary to have a sufficiently great amount of routine information. On the other hand, these requirements are limited by the computation capabilities of the subsystem.

The problem of choosing the optimum amount of information in this case can be solved successfully by the mathematical statistics method. Its application is possible because the process of collection and processing of data fully corresponds to the fundamental statistical tests method, called the sampling method.

In such cases the stochastic characteristics of the random values arriving at the input of the subsystems are not investigated on the basis of theoretical considerations, but by means of the statistical processing of some finite set of experimental data accompanying the process of subsystem functioning. The final goal of such investigations is obtaining numerical parameters and functions reflecting the stochastic properties of the investigated process.

The process of sampling of operational information is usually carried out in two stages: in the first stage there is selection of the totality of parameters most important for analysis of the parameters, which later can be used as functional values in the systems of equations to be solved; in the second stage there is a sampling of the most important (informative) elementary measurements for each selected parameter of the operational telemetric information.

The essence of the sampling method is as follows: on the basis of theoretical investigations of the analytical dependences characterizing each telemetric subsystem of the space vehicle and experimental data obtained in the course of their tests and checkings, from the general set of telemetric parameters (program for space vehicle telemetric measurements) it is possible to select some number of k-parameters. Then, knowing a priori the law of change of each parameter as a function of time, it is possible to determine the minimum necessary sample of the number of elementary measurements in the time interval of the communication contact with the space vehicle.

For problems in the monitoring and control in an automated system for the control of a space vehicle the sampling of the parameters of operational telemetric information is accomplished in most cases using the following scheme. First, there is an artificial choice of the parameters, at the will of the researcher, and then a biased sampling on the basis of predetermined criteria (maximum information content of the parameter, inadequacy of data, poor study of the investigated process or phenomenon, importance of the parameter, etc.). The number of parameters can vary in dependence on the volume and quality of the space vehicle statistical tests, and also the extent of study of the investigated processes and phenomena.

Now we will examine the second stage in sampling, assuming the choice of the most important part of the elementary measurements for each selected parameter of operational information. The criteria for the choice will be the dynamics of change of the parameter during the period of time of reception of the telemetric data, the presence of extrema and their frequency, the presence and total number of triggerings of sensors of a special type, etc. For the further analysis we introduce the concept of a special general set of measurements of operational telemetric information which will include the total quantity of information present in the communication for a specific communication contact.

The sequence of processed measurements for slowly changing parameters is considered as some sample in which there is an evaluation of the distribution of probabilities of a change in the parameter under given conditions. Sometimes the sampling problem is solved by computing the position of the center of grouping of points, their scattering characteristics, asymmetry, excess, etc. These characteristics can be obtained empirically (by sampling) using the results of processing of telemetric data.

The presence of extrema in rapidly changing parameters and the moments of triggering of signal sensors conforms to a random law and is usually not predicted. Information from these measurements is usually of considerable importance and fully enters into the sample of the telemetric communication.

The utilization factor for the information, taking into account the samples for the parameters and the number of their measurements in the course of a communication session with the space vehicle, plays a significant role in the subsystem for the processing of operational technical information because in the last analysis it is the principal factor in the information load on the subsystem and on the communication channel. The value of this factor also exerts an influence on operation of the facilities for analysis of the operational information results, having definite handling capacities.

The subsystem for the collection and processing of operational telemetric information with the adopted structure and mathematical support has very definite time characteristics in which an operational communication with a standard number of alphabetical-digital symbols is processed and transmitted to the space vehicle control center within an approximately fixed time interval. This interval consists of several time expenditure components: accumulation of the necessary volume of telemetric information in a magnetic recorder, its readout and input into the processing system, the computation process proper and the dissemination of the final results through the communication channel or directly to the users.

In those cases when the facilities for the reception of telemetric data and its processing are situated at the Space Vehicle Control Center, no time is expended on the transmission of the results through the communication lines and the process of reception of telemetric information is commensurable timewise with the computation process and the first results of the communication, fed out in a sequential code, appear at the output apparatus of the system, usually after one or two minutes, which is determined for the most part by the speed of the electronic computer and its input and output elements. If the duration of the communication session with the space vehicle exceeds this time, under the condition of use of macroanalysis of information the operational control of a space vehicle in the current communication contact becomes possible.

If for space vehicle control it is necessary to use communications with operational telemetric information, processed by a number of peripheral CMP, the time expended on the entire cycle of processing and transmission becomes commensurable with the duration of the communication session (for space vehicles with low orbits). In such a situation the analysis and adoption of a decision are accomplished in the inter-session interval and the output of control commands is accomplished in the next communication contact.

In the case of a high dynamics of the space experiments carried out (orbital correction, docking, landing, etc.) the rapid processing and analysis of the operational volume of telemetric information are accomplished directly from the open recording tapes, that is, at the rate of reception of the telemetric information. The mentioned regime is characterized by minimum time delays.

The requirements on the accuracy of data processing must be matched with the accuracy characteristics of the radiotelemetric channel. Otherwise there will be an unjustifiable increase or decrease in the accuracy of the results. In most cases the problems involved in space vehicle control do not require high processing accuracies. A systematic error of 1-3% relative to the scale of telemeasurements is considered entirely admissible for ensuring the carrying out of an analysis of the state of the space vehicle with an acceptable probability. The only exception may be individual quite "precise" space experiments in which the required processing accuracy must be equal to the accuracy of their telemetric measurement.

The reliability of operational telemetric information is characterized by the presence in these data of errors of a random nature which lead to incorrect results, and as a result, to an incorrect analysis of the space vehicle state. Errors of a random nature can arise in the processes of transmission, processing and storage of information. Their cause is the effect from additive or multiplicative noise.

The sources of additive noise may be thunderstorm discharges, radioemissions of cosmic bodies and formations, noise of industrial origin, thermal fluctuations, fluctuations of the electric current, and also specially created noise.

The sources of multiplicative noise include processes with measurement of the parameters of the medium in which signals are propagated (such as fadings in the short-wave communication channels), technical malfunctions of instrumentation, poor regulation or imperfection of the apparatus employed.

It is impossible to preclude the influence of additive and multiplicative noise, but all possible measures are always used for detecting unreliable information. For example, use is made of methods for increasing the excess of information and detecting unreliable information.

There are a number of methods for increasing reliability which can be classified into three groups: systemic, or organizational, instrumental and programmed. In the system for the collection and processing of routine information all these methods find use, but most frequently in different combinations.

In the input of the subsystem section, during the period of each communication contact with the space vehicle, there is receipt of the full volume of transmitted telemetric information and in this connection the subsystem is a continuation of the channel for the information telemetric system, but with a predominance of computation functions. This makes it possible to classify the subsystem for the collection and processing of operational information as a data-computation system of the statistical type, which operates with the input telemetric flows of different form, length, content and intensity.

The characteristics of these data flows are in direct dependence on the real space conditions, determining the intensity of the communication contacts with the space vehicle. The subsystem for the collection and processing of operational information, functioning in the closed control circuit of the space vehicle in each a priori known communication session, is a mass servicing system. Its operation is characterized by the receipt of telemetric information at random moments in time. The randomness factor is present in the temporal scatters of the beginning and end of each communication contact.

The totality of communications during a definite time interval forms a flow -- a sequence of communications with a random alternation of the moments of their appearance in time. If all the communications in this flow have an identical priority with respect to sequence of processing, only the moments of receipt of the communication are taken into account. In this case the flows of communications are called homogeneous.

When the communications in the flow are not of equal importance for servicing the subsystem, that is, there are definite evaluations of each communication with respect to priority, the flow will be called nonuniform. Communications with a higher priority must be serviced by the subsystem first, and communications with a lower priority, second.

The subsystem for the collection and processing of operational telemetric data can be classified as an information system and therefore from the entire totality of effectiveness indices we will be interested in indices characterizing its handling capacities. Their numerical estimates establish the dynamics of servicing of the input flow of telemetric information and also determine what part of this flow services the subsystem when emergency and conflicting situations prevail.

The subsystem is evaluated most completely using a fundamental index -- the total handling capacity, which is determined by the ratio of the mean number of communications processed by the subsystem in the interval to the mean number of communications arriving in this same interval.

What is the data collection process like? Usually the servicing of each individually taken space vehicle is accomplished by a system of several territorially spaced CMP whose facilities accomplish the reception and processing of session information. The results obtained by each CMP are transmitted to the space vehicle control center with a stipulated routineness and reliability. The solution of this problem is ensured by a special data collection system which is an integral part of the control system.

Automated data-collection methods are used in the control circuit. Their use provides for the collection of processed and also unprocessed navigational and telemetric information.

In order to deliver both types of data to the Control Center it is possible to use the following types of communication channels, differing in transmission rate:
-- low-speed channels (using telegraphic lines) -- transmission rate several tens of binary digits per second;
-- medium-rate channels (using telephonic lines) -- transmission rate several thousand binary digits per second;
-- high-speed, or wide-band, channels (combinations of telephonic channels, radio relay and television channels) -- rate of transmission hundreds of thousands of binary digits per second.

The automated data-collection system includes the following elements: at the CMP -- apparatus for the reading of information from punched tapes, punched cards, magnetic tapes or from the computer output. At the Space Vehicle Control Center the reception of information is with a puncher of paper tapes, a magnetic recorder or directly on an electronic computer. The system also includes elements for checking information for reliability, control panels, and components for control of the collection process.

For duplicating the operation of the computers at the CMP and for a number of other problems (for example, a detailed analysis of the primary data) there is a possibility of transmission of the entire volume of unprocessed data from it to the Space Vehicle Control Center. The collection system includes wide-band communication channels (radio relay, television and satellite) ensuring the transmission of data at the rate of its reception at the CMPs.

It should be noted that the problem of collecting data from remote (many thousands of kilometers) points is a complex engineering-technical problem and requires considerable material expenditures.

For solution of the problems involved in the processing and collection of data, in addition to technical facilities, it is necessary to have the corresponding mathematical support. This includes algorithms, work programs, instructions, methods and initial data on the basis of which it is possible to carry out the processes of computation and transmission of data through the communication channels.

The development of mathematical support is an extremely time-consuming process requiring great expenditures of mental energy of different specialists: mathematicians, programmers and operating technicians.

The process of developing mathematical support is divided into a number of the following stages.

1. Formulation of problem. In this stage there is formulation of the purpose of solution of the problem, its content is laid out and the number and nature of the values used in the computations is also indicated. The formulation of the problem must be formalized in such a way that there is only one interpretation.

2. Mathematical description of the problem. Deriving and writing formula schemes and other mathematical dependences expressing solution of the formulated problem, this being called the mathematical description of the problem. It should contain a full list of the initial data, initial conditions, computation variants, and establish the accuracy of all the computations carried out in solution of the problem.

3. Selection of a numerical method. Numerical methods make it possible to reduce the solution of any problem to the successive carrying out of four arithmetical operations and the comparison procedure, that is, using them any computation process is broken down into elementary operations. The selected method is written as a precise description of the sequence of performance of elementary operations with all the initial data for obtaining the sought-for result and this is called the algorithm for solution of the problem. The algorithm is written in the generally employed language of mathematical symbols, word descriptions and clarifications, that is, in such a form in which all the peculiarities of the computation process are presented in detail.

4. Programming (writing of the algorithm in algorithmic language). In this stage the algorithm is represented in the form of a sequence of operators and other language elements. Use is now made of computer orientation algorithmic languages. The decision algorithm is broken down in detail into elementary parts and the programmer manually writes each part in the form of an equivalent construction of algorithmic language.

The conversion of the algorithm into computer language is accomplished using a computer. For this purpose the computer is instructed to write the algorithm in algorithmic language, after which, by means of a special translator, this algorithm is transformed into a series of computer commands.

5. Programm debugging. This stage is necessary for detecting and eliminating the errors arising in developing the programs. One of the variants of the program is computed manually and is called a control or debugging program. Then this same variant is checked on a computer. With coincidence of the results it is assumed that the program was compiled correctly.

After debugging the programs are transmitted to servicing personnel for solving the problems of data processing and collection.

The solution of the problems of processing and collecting navigational and telemetric information includes a great number of clearly defined operations, each of which requires a definite number of work programs. Their totality forms a full program which can include up to 40,000-50,000 computer codes (commands). Programs of such a volume can be assigned to the class of large programs.

As a rule, the writing of such programs requires several thousand man-days (assuming present-day norms), as a result of which work is done in advance on their development and debugging.

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Data Analysis

An investigation of complex systems, which includes most space vehicles, is based on solution of the problems of analysis and synthesis of data.

The analysis problem involves a study of the state, behavior and properties of a space vehicle under the condition that one knows the characteristics of the surrounding medium, structure (model) and numerical values of the parameters characterizing the subsystems and the space vehicle as a whole. The results of solution of the analysis problem are usually the numerical values of the special indices of effectiveness of individual space vehicle subsystems, on the basis of which it is possible to determine the generalized (vector) index of vehicle effectiveness. Taking into account the presence of complex correlation and functional relationships among individual space vehicle subsystems and the characteristics of the surrounding medium, we note that the process of determining the generalized indices of the effectiveness of space vehicles is extremely complex and involves considerable difficulties. Their overcoming is based on a reasonable reduction in the number of the special indices of effectiveness and on the introduction of a number of disciplining limitations. This path makes easier the formalization process and at the same time worsens the accuracy of solution of analysis problems.

The synthesis problem involves selection of the optimum structures of a space vehicle or its internal parameters with stipulated characteristics of the surrounding medium and taking into account the limitations imposed on the space vehicle. Sometimes the synthesis problem is formulated as the problem of seeking the structure of the vehicle or its internal parameters, giving a stipulated value of the generalized effectiveness index. It follows from what has been said that the necessity for solving synthesis problems arises for the most part in the stage of planning of a space vehicle. Accordingly, we will not deal with the methodology for solving problems of this type.

An analysis of the functioning of a space vehicle (or its individual subsystems) begins with the formulation of the specific problem, in which there must be a clarification of the main purpose of the analysis and a concise setting forth of the principal conditions and limitations taken into account in solution of the problem.

The next stage is a meaningful description and precise formulation of the problem. Here it is necessary to define clearly the content of the problem, establish the limits of its solution, clarify the principal factors exerting an influence on the processes or space vehicle systems to be analyzed. In essence, this initial stage in the analysis is the most important because the proper solution of any problem is dependent primarily on how truly it is understood what in actuality it represents and what its complexity is.

As a result of this stage in working through the problem the analyzing specialist must clearly understand the purpose and objective of the system to be analyzed, clarify the information on the medium and system parameters and establish the totality of the assumptions within whose framework the problem is solved.

The problem can be considered formulated precisely if the information used for the solution is complete (adequate for obtaining a result) and noncontradictory. In this same stage there is a choice of the index of effectiveness of the system to be analyzed.

The next stage in the work is formalization of the problem -- formulation of a model of the system and forming of an analytical representation of the selected effectiveness index.

The model of the system, obtained in the formalization stage, has the following properties:
-- nondependence of the results of solution of the problem on the specific physical interpretation of the sense of elements of this model, that is, on the physical nature of the object described by the formulated model;
-- high content, that is, the capacity of the model to reflect important aspects and properties of the real process to be analyzed;
-- deductivity, that is, the possibility for constructive use of the model for obtaining a result with use of the means and methods of the scientific field in whose terms the problem was formalized (the model was constructed).

In developing the model it is necessary to clarify the factors exerting an influence on the course of the process to be analyzed or on the results obtained, select those of them which are subject to a formalized representation (that is, can be expressed quantitatively), insofar as possible combining the detected factors on the basis of common criteria, shortening their list, and establish the quantitative relationships among them.

The formulation of a model of a space vehicle is a highly important and complex stage in working through the problem of its analysis. The fact is that the high-content and deductivity requirements are essentially contradictory. Thus, in satisfying the high content requirement, in the model the greatest number of parameters of the process being analyzed are taken into account as precisely as possible. But in this case the model becomes more complex, which in turn makes difficult its investigation and the obtaining of high-content results. On the other hand, the desire to obtain an analytical result in the simplest way leads to a necessity for simplification of the model, which lessens its content. The art of the researcher makes it possible in the development of a formal model of the analyzed process to achieve a reasonable compromise ensuring the possibility of obtaining nontrivial results in a not excessively simplified model.

The development stage is followed by an investigation of solubility of the analytical problem, this consisting of several substages: investigations of fundamental solubility, choice of the solution method and investigations of the technical feasability and desirability of solving the problem by the selected method.

In an investigation of the fundamental solubility of the problem the specialist determines whether among the means and methods of the scientific field in whose terms the model is formulated there are those whose use makes it possible to obtain a result. If in such a way it is essentially impossible to obtain a solution, it is necessary to return to the stage of formalization of the problem, because in this case the model does not satisfy the deductivity requirement.

The choice of the solution method occupies a highly important place in the general scheme for working through the problem and is dependent primarily on whether the model of the analyzed space vehicle system is determined or stochastic.

The model is called "determined" if the information on the state and behavior of the system in some time interval makes possible a complete description of behavior of the system outside this interval. However, if this cannot be done, for example, because some or all of the system parameters are random, the model is stochastic. The nature of the used model (that is, whether it is determined or stochastic) is determined, on the one hand, by the content of the problem to be solved, the nature of the surrounding medium and the parameters of the system to be analyzed, and on the other hand, by the required accuracy in solving the analytical problem.

Since the analyzed space vehicle systems are subject to the influence of a great many physical parameters of a random type and it is impossible to describe their future behavior completely with the necessary accuracy, the models of analysis of systems of vehicles belong to the stochastic type.

The mathematical approach for describing such systems may be systems of differential, difference equations or a system of polynomials in which the variable coefficients are the numerical values of the measured parameters characterizing the current behavior of the analyzed systems of space vehicles.

After choice of the method for solving the problem it is necessary to investigate it from the point of view of technical feasibility. This problem is worked through on the basis of data on the programming-equipment outfitting of the computation process. If the number of operations required for carrying out the computation procedure is high and it is impossible to carry it out with available computers in the acceptable times, it is necessary to return to one of the earlier stages in working through of the problem. Next a study is made of the problem of feasibility of solving the problem. Here the fundamental criterion is assumed to be the time factor. It is assumed that solution of the problem is infeasible if the result of the solution is outdated by the time it is obtained and use of the result for making a decision makes no sense.

The final stages in solution of the analytical problem are the preparation of an algorithm and its programmed realization on an electronic computer. The "output" results make it possible to evaluate the quality of working through of the problem of analyzing the system in all its stages. If, using the results, it is possible to evaluate the special and generalized indices of effectiveness of the space vehicle, it is assumed that the working through of the problem is completed; otherwise it is necessary to return to one of its earlier stages.

The final stage involves the use of the results of analysis of the state and behavior of the space vehicle for formulating and adopting the corresponding decisions concerning control of the vehicle ensuring the optimum implementation of the missions assigned to it.

In order to solve the problems involved in this analysis, a number of methods have been developed and used and are employed in dependence on the requirements imposed on the space vehicle control process.

Microanalysis method. The essence of this method is an analysis of individual elements, instruments and apparatuses from whose totality the space vehicle consists, and also special measurements using them. Their choice is ambiguous and is determined by the analytical problems and the purpose in the general space vehicle scheme. When using microanalysis a study is made of the structure of each of the defined elements, their function, combination and range of possible changes in the parameters, after which a generalized analysis is made of the process of functioning of the space vehicle in general.

Thus, the problems of microanalysis are the following: define the space vehicle elements which are subject to analysis, study the structure of the defined elements, reveal their functions and ascertain the relationships among the elements (functional and correlation).

It is important to note that the possibilities of microanalysis with respect to an exhaustive investigation of a complex space vehicle system are limited due to the following circumstance. The practical realization of the most important stage in microanalysis -- defining of the space vehicle elements to be investigated -- involves a necessity for overcoming contradictions between the desire for the most detailed possible analysis of each of the vehicle elements and the real possibilities of the information-measurement and information-computation subsystems of the control system.

In actuality, if the "dimensions" of the elements are selected large, the problem of determining the relationships among them and their interaction in the interests of analysis as a whole will be solved easily, but at the same time it will be difficult to study each of the elements. On the other hand, it is possible to select each of the space vehicle elements so small that it will be relatively simple to study its individual structure. At the same time, the totality of the relationships among the elements and the description of their interaction are considerably complicated.

The practical realization of the microanalysis method requires considerable capabilities of computers with respect to speed and the volume of the operational memory. The restrictions on existing computers with respect to these parameters make difficult solutions of problems of microanalysis in the time segments necessary for operational control of a space vehicle. This factor impedes the broad application of the microanalysis method, which is used for the most part in solution of the nonoperational problems in investigation of individual space vehicle subsystems.

The microanalysis method, making possible a detailed analysis of the course of the investigated process and all possible factors exerting an influence on it, is very convenient and necessary in different scientific experiments and also in clarification of the facts of anomalous operation of individual instruments and apparatuses aboard space vehicles.

Such investigations usually are unrelated to the process of direct control of a space vehicle and can take a considerable time. The results and conclusions obtained in this case are used in subsequent launchings of space vehicles or are generalized in the form of different scientific investigations.

Macroanalysis method. The essence of macroanalysis is determined by the specific peculiarities of complex control systems. We have already noted that a space vehicle is an object of a discrete nature, consisting of a large number of individual instruments, apparatuses and assemblies. It therefore follows that it can be considered not only as an object having a microstructure, but also as a macroscopic object. In the microanalysis process the analyzing specialist has the possibility, acting differently on the space vehicle inputs, to analyze its reaction to the corresponding input effects. The more diverse are the effects imparted to the space vehicle inputs, the more detailed can be the clarification of its state and behavior. At the same time, the effectiveness of the set of input effects is fundamentally related to the diversity of the output parameters. If the vehicle reacts in an unpredicted way to each new combination of input effects, the testing and analysis must be continued. It is possible to cope successfully with the diversity of the output parameters of the space vehicle only when there is a diversity of input parameters.

Thus, the macroanalysis method makes it possible to clarify the state and behavior of the space vehicle on the basis of the input and output information. However, there is a definite limit to such information. In other words, if on the basis of available data it is possible to construct a system precisely duplicating the behavior of the analyzed system in the entire set of used input effects, the macroanalysis problem can be considered solved. In practical problems it is impossible to test all conceivable relationships between inputs and outputs. In the macroanalysis process researchers consciously limit themselves to an analysis of the behavior of the system only in a set of effects of interest to them, that is, in the situations in which the system reaction is of practical value for the subsequent adoption of a decision on its control.

The use of the macroanalysis method assumes allowance for a series of the following circumstances: the amount of analyzed information is limited by the handling capacities of the measurement and computation subsystems of the space vehicle control system and also the subjective possibilities of the person requiring this information; the time interval allocated for solution of macroanalysis problems must not inhibit the general process of space vehicle control; when carrying out the macroanalysis it must be remembered that the determined values are measured and transmitted through the radio channel in the presence of noise, by virtue of which they are random values.

The realization of the macroanalysis method under practical conditions is based on the performance of some volume of operations preceding the launching of a space vehicle. These include:
-- precise determination of the number of individual elements, instruments and assemblies included in the macroanalysis;
-- clarification of the minimum necessary number of input and output parameters in each analyzed space vehicle apparatus;
-- evaluation of the effectiveness of the analyzed apparatuses in the stage of their full-scale tests in the laboratory, workshop or in a polygon under operational conditions close to real;
-- preliminary preparation of the necessary volume of documentation with respect to all the enumerated operations, making it possible, with the necessary completeness, accuracy and routineness to analyze the designated space vehicle apparatuses in the course of the orbital flight under the most characteristic normal and anomalous conditions.

In addition to the data extracted from the considered operations, the macroanalysis method assumes extensive use of the results of processing of navigational and telemetric information, which is received from a spacecraft and which is registered by ground information-measurement facilities.

These results reflect the past and present and afford a possibility for predicting the future state of the space vehicle and its individual subsystems.

For convenience in perception and for accelerating the macroanalysis process the processed results, by means of instrumental-programmed methods, are integrated and are displayed using different visual observation equipment by the group method. Each group of results characterizes a subsystem individually taken for analysis. Such an approach makes it possible to take into account the influence of the functional and correlation relationships between the results and makes it possible for the specialist to concentrate his attention on the specifically analyzed subsystems of the space vehicle.

Operational macroanalysis method. In some cases, when the adoption of decisions on space vehicle control is accomplished in extremely small time intervals, during which the computers cannot feed out final processed results for analysis, use is made of the operational macroanalysis method.

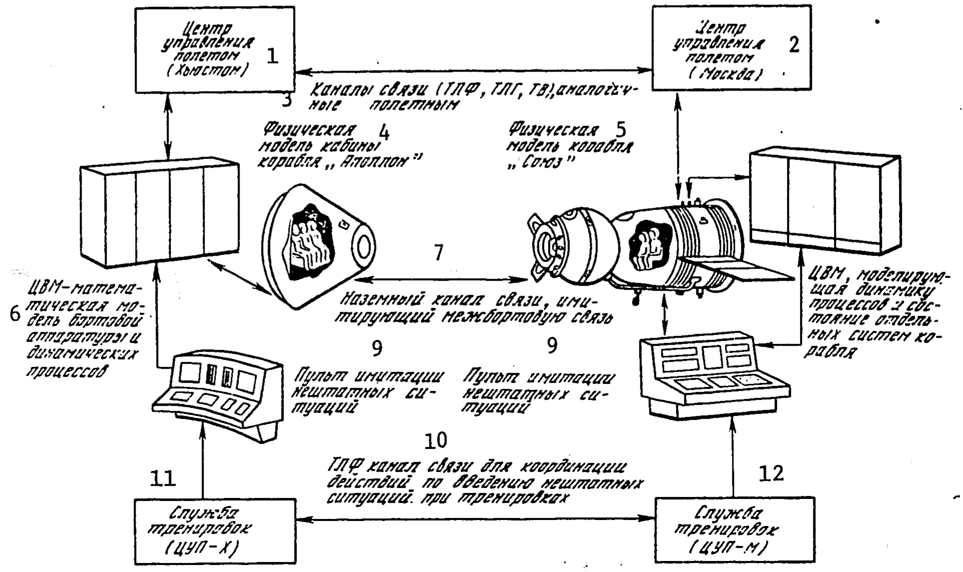

Fig. 33. Diagram of modeling of flight in trainers at the control centers for the "Soyuz-19" and "Apollo" spaceships.

KEY:

1. Flight Control Center (Houston)
2. Flight Control Center (Moscow)
3. Communication channels (telemetry, telegraphic, TV) similar to those in flight
4. Physical model of "Apollo" ship cabin
5. Physical model of "Soyuz" ship
6. Computer -- mathematical model of on-board apparatus and dynamic processes
7. Ground communication channel simulating communication between ships
8. Computer modeling dynamics of processes and state of individual ship systems
9. Panel for simulating nonstandard situations
10. Telephonic communication channel for coordination of operations for introducing nonstandard situations during training sessions
11. Training service (Houston Flight Control Center)
12. Training service (Moscow Flight Control Center)

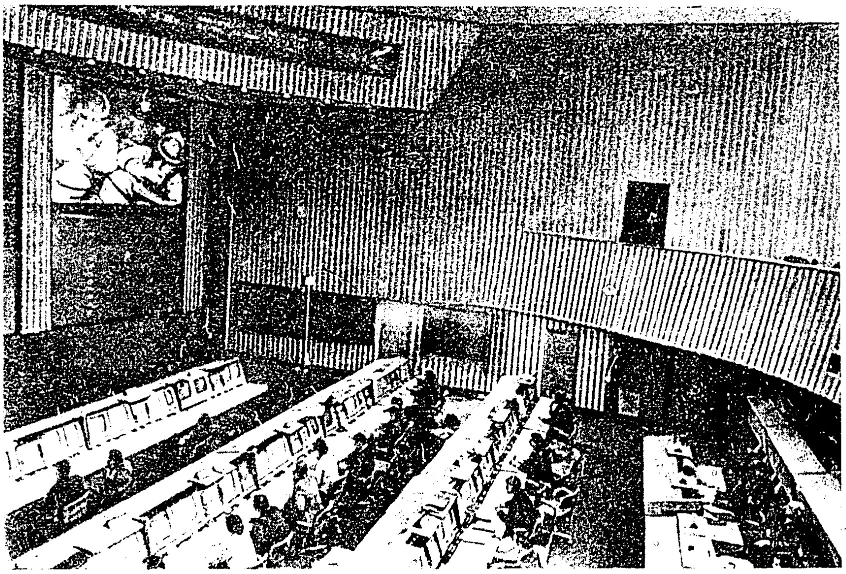

Fig. 34. Moscow Space Vehicle Flight Control Center. Interior of hall with information displays and communication facilities.

The information basis for such an investigation is materials from the open registry of navigational and telemetric parameters recorded in special recorders at ground reception facilities.

Operational macroanalysis is carried out by skilled specialists using unprocessed information at a relative measurement scale. In this case the rate of analysis is extremely high and corresponds to the rate of registry of information. It should be noted that such a method makes it possible to solve the problem of analysis of the state of the space vehicle for the most part from the qualitative side. An analysis is usually made of a small number of monitored instruments and apparatuses and for adoption of a decision on control of the space vehicle information of the following type, for example, is fed out: "on - off," "norm -- not norm," "signal present -- signal absent" etc. These communications, with a knowledge of the general situation aboard the space vehicle and in the surrounding medium, are extremely valuable in the realization of the controlling programs which are planned for implementation. Examples of the implementation of operational macroanalysis are monitoring, control of on-board apparatus which is responsible for a soft landing on a planetary surface, approach and docking operations, etc.

Physical modeling. The essence of the method is the reproduction of the analyzed processes in a physical model. As such a model it is common to use an operational model of a space vehicle of the same type as the investigated model. In this case the physical processes transpiring in the original and the model are similar.

The physical processes in complex space vehicles are described by a combination of differential, difference and integral equations containing a great number of variables, a direct relationship among which is difficult to establish (or sometimes it is impossible) by analytical procedures in acceptable time intervals. The physical modeling method makes it possible to overcome these difficulties by means of selecting as the model a space vehicle of the same type in which the dependence between different parameters can be discovered by direct measurements.

Physical modeling is an extremely graphic method for determining the influence of different parameters on study of the processes transpiring aboard the space vehicle. Moreover, using it one can rather rapidly determine the reasons for anomalous situations and damage to the on-board instrumentation and find the optimum solution on the basis of the maximum possible elimination of their consequences.

When a real analogue of the investigated space vehicle is used as a model, we have an identity of elements, structure and macrofunctions.

Mathematical modeling is based on the use of some combinations of mathematical relationships (formulas, equations, inequalities, logical conditions, operators, etc.) for analysis of the space vehicle which determine the structure of the space vehicle and describe its behavior. The mathematical model of a real vehicle is the same as an abstract or formalized representation, making it possible to study a space vehicle by mathematical methods.

The complexity and diversity of the physical processes transpiring aboard the space vehicle do not make it possible to develop absolutely adequate mathematical models for them. Such models reflect only the most important patterns of the analyzed processes or on-board systems.

As a rule, the mathematical model contains a description of a great many possible states of the space vehicle or its individual systems and a description of the law in accordance with which the space vehicle passes from one state into another.

Each state is characterized by the numerical values of several parameters and therefore is a vector state.

The law in accordance with which a space vehicle passes from one state to another is usually characterized by discrete state spaces and the process of its evolution is stochastic.

The success of the solution of analytical problems on the basis of mathematical modeling is for the most part dependent on the complexity of the analytical description of the behavior of a space vehicle. Accordingly, the following principal methods for the use of mathematical models for analysis of space vehicles are possible: analytical analysis, analysis on the basis of numerical methods, modeling on analog computers and modeling on digital computers.

An electronic computer is the most universal means for the use of mathematical models. In this case the mathematical model is transformed into a modeling algorithm, in accordance with which information is produced in the computer describing elementary phenomena of the analyzed process, taking into account their relationships and mutual influences. A necessary part of the circulating information (results of the analysis) are printed out and used for the analysis. In most cases the modeling on an electronic computer of the processes transpiring in any space vehicle system is accomplished taking random factors and their simulations into account. This method is frequently called the statistical modeling method.

A peculiarity and some inconvenience in the method is that by virtue of allowance for random factors in the modeling the results obtained in single modeling of the analyzed process must be regarded only as a realization of a random process. Each of such realizations individually cannot serve as an objective characteristic of the analyzed system. Therefore, the sought-for values are usually determined using data from some number of records when their values acquire statistical stability (on the basis of the law of large numbers) and can be adopted as approximate values entirely suitable for analysis.

The methods of physical and mathematical modeling of a space vehicle and its individual systems find use for analysis in launchings of complex vehicles. We will examine their use in the launching of the spaceships "Soyuz-19" and "Apollo" in accordance with a program carried out in 1975.

The modeling complex recreating processes on the "Soyuz-19" ship included a physical model (ship simulator) and a mathematical model incorporated in the computers at the Control Center. An analysis of the processes transpiring on the ship was accomplished in full volume both in the training stage at the Flight Control Center and in the course of the flight.

The work of the modeling complex can be represented in the following way (Fig. 33). The crew is in the mock-up cabin, representing an analogue of the ship (physical model) with a full coincidence of the interior and the control panel. The simulator is connected to a digital computer (mathematical model) simulating individual ship systems and the processes transpiring in them, whose parameters are difficult to obtain with a physical model (thermal processes, charging pressure, spatial movement).

The crew, working in the simulator, issues commands from the panel and receives information on the state of the ship. Radio commands are sent to the simulator from the Control Center.

The simulator and the mathematical model send information on the state of the ship to the Control Center.

Thus, at the Control Center and in the simulator there is a possibility for "playing through" the entire flight of the ship on earth.

In the simulator and mathematical model it is possible to introduce different failures of the system through a special panel, which enables the crew and flight control personnel to show their knowledge and the means for successfully dealing with nonstandard situations and thereby make preparations for possible unexpected events during real flight.

During the "flight" of ships on earth the actions of the crew and Control Center were also checked out under complex conditions (fire, depressurization), requiring immediate transfers of the crews into their ships, undocking and landing.

During the training sessions all the communication channels operated. The complete volume of telemetric information was fed from models of the "Soyuz" and "Apollo" ships, located in Soviet and American laboratories. The computation complexes at the centers processed this information and transmitted this information to displays for analysis and adoption of decisions. The control services adopted control decisions in the same order as in subsequent real flight.

The control of spaceships and the facilities of the command-measurement complex during the period of training sessions and real flight was accomplished from a special room (main control hall) located at the Control Center and supplied with apparatus for the visual display of the results of processing of different kinds of information for group and individual use. Figure 34, which shows the general interior, illustrates the wide-format wall displays and the working places of the operators, arranged in several rows, and the means for individual display and communication adjoining them.

Special training groups participated in this work. Their task included the maximum complication of the "flight" of both ships. For this purpose in the course of modeling of the "flight" the greatest possible number of "failures" of the on-board and ground systems was introduced. These "failures" were unknown in advance either by the control personnel or by the crews.

The simulation of nonstandard situations in the course of such training sessions played an important role in the preparation of the control services of the center, which long before the real flight were psychologically prepared for their possible appearance and the most rapid possible elimination of the consequences which arise.

The most important planned operations of the program were repeatedly practiced in models. For example, the launching of the "Soyuz" and "Apollo" -- with all possible deviations -- was practiced 12 times, the docking and transfers of the crews -- 14 times, the undocking -- 10 times and the descent of the "Soyuz" -- 12 times.

Thus, on the basis of physical and mathematical modeling, long before the launching there was a "playing through" of all the operations for control of the "Soyuz" and "Apollo" ships, which made it possible to detect and eliminate shortcomings in the flight plan, inadequacies of technical equipment and organizational structure. On the basis of data on the training sessions it was concluded that the control services were ready for undertaking of the flight.

In the stage of preliminary preparation of the flight, thus, studies were made of the a priori results of analysis of information, obtained from physical and mathematical models which during implementation of real ship flight were subjected to comparative analysis with data transmitted from aboard the ship. In the case of their correspondence the operations indicated in the plan were realized in a stipulated sequence. Such an operating scheme for the Flight Control Center is characterized by a high routineness and reliability, which is usually required when there is assurance of manned flights with a high degree of complexity.

Adoption of Decisions

The adoption of a decision and its subsequent realization by the actuating components of the "earth-space vehicle" control circuit is the final and an especially important operation in the entire flight control process.

In the automated control system the adoption of a decision on control of a space vehicle and all the ground services of the circuit used for this purpose is based on an analysis of the incoming information on the state of the space vehicle and the elements of the command-measurement complex. The adoption of a decision is the prerogative of the flight director, who is given the necessary rights and authority and has the responsibility for carrying out the control tasks with the required effectiveness.

We note that until recently the adoption of a decision was based on subjective qualities (experience, intuition, etc.) of the person who adopted the decision. Only recently the science of adoption of decisions was developed, and still later the mathematical theory of adoption of decisions. The development of the theory of adoption of decisions is constantly stimulated by the appearance of new problems in the control of different objects and the development of the corresponding mathematical approach.

The problem of adopting a decision arises most acutely in the case of appearance of conflicting situations. The simplest examples of such situations are usually formulated in the terms: "expenditures - effectiveness." The desire to obtain a system with a high efficiency is contradictory to the necessity of limiting the expenditures of the corresponding material resources.

The situation is called problematical if the number of possible reasonable decisions in it exceeds unity. The number of possible decisions can be finite or infinite, with a known or unknown number. In the latter case one can speak of "decision space."

In those cases when the set of possible decisions is finite, the choice of the best of them can be made on the basis of an investigation of a number of variants. Then as the optimum a decision is adopted which is the best from the point of view of a stipulated effectiveness index. The evaluation and choice of an optimum decision under the condition that their total possible number is relatively small are carried out on the basis of an examination of the problems of analysis of the system with different inputs, each of which corresponds to its variant of the decision.

Thus, in the process of functioning of complex control systems the process of adoption of a decision is realized as the problem of choice of control, shifting the system from the stipulated into the desired. The adopted decision can correspond to some specific situation, but also can contain more abundant information concerning the desirable behavior of the system in dependence on the developing conditions. Such a method for stipulating behavior is called the strategy of behavior. The choice of a definite strategy of behavior means the setting of the totality of rules in accordance with which entirely definite decisions are made in dependence on the past, present and future states of the system and medium in which this system functions. Therefore it should be noted that the problem of finding a rational (in one sense or another) strategy of behavior is substantially more difficult than the problem of choice of a decision in some specific situation. The quality of the decision or strategy of behavior selected in this case, that is, the effectiveness of control, is determined by the numerical values of the corresponding effectiveness index.

From the purely mathematical point of view the problem of the choice of optimum control in some specific situation is formulated as the problem of seeking the vector X, providing the extremal value (maximum or minimum, in accordance with the meaningful criterion) of the index of effectiveness of control -- the "target" or "purpose" function E(X). However, if reference is to the choice of the optimum strategy of behavior, the corresponding problem, as a rule, is interpreted as the problem of seeking the vector function X(t), providing the extremal value of the "target" or "purpose" functional $Y = \{X(t)\}$. Definite limitations are usually imposed on the components of the X vector (the same as on the components of the vector function X(t)).

In conclusion we will say that in formalization of the problem of choice of an optimum strategy of behavior the problem of quantitative validation of the decision using several effectiveness indices does not remain determined and the final choice of a decision is determined by the act of will of the persons adopting the decision. The task of the researcher (analyst) is to have at his disposition an adequate volume of data, making possible a thorough evaluation of the advantage and shortcoming of each variant of the solution and, relying on them make a final choice.

In those cases when a space vehicle or its individual subsystems act in automatic control regimes and the influence of the subjective factor on control processes is reduced to a minimum, the problem of adopting a decision is assigned to different automatic apparatus or regulators. Thus, in the process of spatial orientation of a space vehicle the mentioned effects of perturbing moments are automatically "extinguished" by actuating components on the basis of commands (decisions) of the gyroscopic or other control system. In the case of a "soft" landing on the moon the adoption of a decision and a command for the firing of the braking engine are formed automatically when attaining a stipulated altitude. In both cases the adoption of a decision is accomplished by programming, providing for an influence of a priori and a posteriori effects on the space vehicle.

Due to the fact that the space vehicle is acted upon by a great many random factors, characterizing the external medium and its state at each stipulated moment in time, and their full allowance is physically impossible, the control process is accomplished under conditions of some indeterminancy and risk.

Under these conditions the problem of adopting a decision can be interpreted as a problem in seeking decisions in a "two-component game," one of the components being nature and the other being the space vehicle. A peculiarity of the "nature" player is that it does not strive to draw advantage due to the erroneous actions of the second player; it behaves neutrally relative to its actions. Games of such a kind are called statistical, in contrast to antagonistic and other games. The "nature" player can have the following information: the set of states $\sigma_1, \sigma_2, \ldots, \sigma_n$; the set of possible actions or strategies X; the distribution of probabilities of the state of nature $P(\sigma)$; the set of outcomes Y; the functions of evaluation of the outcomes $\varphi(Y)$ which can serve as functions of usefulness of the actions X leading to the outcome Y.

Since the outcome (result of control) Y unambiguously is determined by the parameters σ, X, it is possible to compute the distribution of probabilities $P(Y/X)$ and accordingly the mean value of the usefulness function.

Thus, the problem of adopting a decision under uncertainty conditions can be reduced to the problem of mathematical programming in which there is a maximizing of the value of the usefulness function (efficiency) $U(X)$.

In the formulas for the usefulness functions the probabilities of the outcomes can be determined on the basis of either a priori information on the state of nature or a posteriori information. In this connection the statistical games can be games without an experiment or games with an experiment.

The carrying out of experiments and their necessity are dictated by the difficulty in the mathematical formalization of many control processes transpiring in the space vehicle as a result of their qualitative novelty and complexity. The complex of experiments -- and by this is meant various investigations and tests of the vehicle and its individual subsystems in the stages of development and construction -- makes it possible, in advance, to refine their behavior under artificially created conditions closest to real, which on the whole increases the usefulness function (efficiency) of the space vehicle. In this stage the main control problem is worked out -- the optimum solution is found on the basis of the analyzed (input and output) information.

The results, which include a complex of formulated controlling decisions, following in a definite sequence and tied in to a time scale, are formalized in the form of a highly informative or graphic "network" flight plan. The necessity for timely formulation of such a plan is determined by the rigorous requirements of space vehicle operational control.

Since the dynamics of the space vehicle and the processes transpiring in it is extremely high, all the optimum decisions during the planned control must be formulated in advance. In this case the control process is reduced to on-going monitoring of the state of the space vehicle and the realization of the planned operations.

The flight plan is an extremely important document. For all practical purposes it reflects the operation of the "space vehicle - earth" circuit in the course of the entire period of space vehicle functioning. The content of the plan includes a list of communication contacts with the vehicle, the range of operations and experiments carried out in each session, the number and designations of the command-measurement points and the means for supporting the space flight, the range of controlling commands and the list of operational information necessary for analysis of the state of the space vehicle during the period of the session. All the plan operations and the range of the adopted decisions with the anticipated results with their realization are tied in to a uniform time scale whose initial reckoning point is usually the time of launching of the space vehicle, then scaled to the zonal time.

Equally important for space vehicle control is also a list of preformulated variants of the decisions which must be made in various most probable anomalous situations, the possibility of whose appearance is not precluded. This list gives a series of the most acceptable recommendations and decisions, making it possible to minimize the possible consequences of anomalies appearing aboard the space vehicle in the shortest time intervals.

In those cases, when the choice of a variant of the decision is not provided for by the flight plan and the list of anomalous situations, the decision is made on the basis of a routine analysis of the collected information, taking into account experimentation and sound reasoning. Under such conditions space vehicle control is considered most complex and important. The adoption of a decision is made easier if one takes into account the mathematical-statistical methods for the analysis of information from past communication sessions, and also on the basis of already conducted launchings of space vehicles of a similar type. An analysis of the functional and correlation relationships among the individual subsystems of a space vehicle, in some cases making possible a routine clarification of the reasons for the anomalies and a formulation of the probable ways to eliminate them, also can be extremely important.

It should be noted that the problem of adoption of decisions also has a psychological aspect, since a decision is made by man with his characteristic subjective peculiarities. In this connection it must be emphasized how important it is to have a direct dialogue between the person making the decision and the specialists carrying out the analysis of information and the formulation of the possible variants of the decisions. Only with such a dialogue is it possible to clarify in detail all the "pros" and "cons" of any selected decision and the contribution or input of the director will be determined by his ability to weigh all the positive and negative consequences of the adopted decision.

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