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MORE ABOUT THE PROBLEM OF OPERATIONAL PROCESS N SATELLITE TELECOMMUNICATION SYSTEMS

The article presents methodological background research results for operational process control in satellite telecommunication systems with limited onboard resources.

Keywords: *satellite information-telecommunication system, planning strip delight.*

Review of Recent Research and Publications

Among the objectives set by Ukrainian National Special Scientific and Technical Space Program for 2013-2017 and the Concept of State Space Policy developed for the period until 2032 [1, 2] the overriding priority status has been given to the development of space technologies and their integration into the real national economy sector and national security and defense areas as regards remote sensing and improvement of space systems (SS) providing telecommunication, navigation as well as to the other space information systems (SIS). Any SS may be characterized by presence of a space segment in its structure, i.e. orbital support facilities integrated into one or more spacecraft (SC). With regard to SIS the spacecraft performs a role of a carrier for **information system** hardware, i.e. special onboard equipment (SOE) providing collection and generation of target information (TI). It can include electrooptic devices, radars, scanners, sensors, photo and television equipment, repeaters, transmitters, receivers, antenna systems, etc.

Furthermore, any SIS shall include a telecommunication system (TCS) as its essential element providing information exchange between the orbital and the ground facilities.

Because of diversity of SIS and their tasks (observation, monitoring, detection, identification, data collection and data transfer, survey, communication, etc.), we shall use a unifying term “attendance” of surface facilities (SF), where possible for the sake of brevity.

In this article, for clearness purposes, we shall only deal with observation space systems (OSS) representing complex satellite TCS which provide special information of national and international significance. For OSS the term SF "attendance" shall primarily mean collecting information from specified land areas and monitoring facilities and its transfer to surface facilities.

Electromagnetic rays (EMR) which are formed or reflected from SF in the optical and / or radio frequency are the primary information sources for any OSS. Depending on the information source and the method of information receipt we shall distinguish the following OSS: electrooptic observation systems (EOOS) radar observation systems (ROS) photographic observation systems (POS), ets.

Such OSS have specific elements, i.e. **orbiting vehicles** placed *away* from the ground facilities, *distributed* in space and time, moving *continuously*, with *limited* onboard *resources*, operating in *difficult conditions* of outer space.

SC *carry* optical and / or radio SOE, whose main function is review of specified areas and / or monitored objects , collection of EMR, generation and transmission of TI to the Earth. SC used for this purpose provides global and continuous observations cover large areas, high speed, invulnerability of facilities etc.

At the same time SC make OSS a complex telecommunication system, requires considerable financial costs for its development and operation and outer space as the environment requires special arrangements to ensure high reliability, survivability and noise immunity of space vehicles.

Besides SOE SC have a *control* system, support and auxiliary systems, which are usually joined into onboard information, control, security, support and other complexes. Similar complexes are to be identified within OSS ground facilities. The interaction of the above onboard and ground systems is implemented via satellite TCS which elements can be constructively distributed in the specified complexes.

Such TCS include *auxiliary information* in addition to main information, i.e. target information transmitted from the spacecraft to the ground by *radio* "air-to-earth." The information contains data about position of the spasecraft in time and in space, their technical condition, operation modes, onboard resources and provides synchronization of onboard and ground facilities.

Additionally, from the results of information processing command information shall be generated and transferred to the spacecraft via *radio* "air-to-earth" in the form of *control* programs and commands. Ultimately, the flows of command and supporting information shall provide receipt of required TI in respect of its *composition, volume and quality*.

Traditionally OSS are mostly used to fulfill a ***scheduled program,*** when TI users request observation of particular areas of the Earth in advance, and the system control center (SCC) plans the work of orbital and land devices, makes an appropriate spacecraft control program (SCP) and consistently implements it within a scheduled time.

For this purpose, SCC takes into consideration a supposed position of the spacecraft in time and space at the moment of survey, though without any influence thereon due to objective laws of orbital motion.

In other words, SCC shall be forced to a significant degree to *adapt* to the available mutual position of the SC and the observed SF. This results in mostly episodic, irregular observation sessions in respect to the same SF.

In the existing and projected SS designed for detailed observation this problem is slightly compensated by designed spacecraft angle maneuvers. However, this requires rational planning of space observation routes.

Meanwhile, as the experience of recent events in the world shows, OSS can be one of the main sources of information to addres ***operational challenges***, i.e. tasks which must be performed instantly or within a limited time period any time of the year and day in the interests of defense, security, prevention of man-made disasters, crises and emergencies.

Problem Statement. Consequently, there is a fundamental ***discrepancy*** between OSS's *normal operation capabilities* and *special requirements* of customers ordering operational observations of specified SF.

In this case, a problem of space observation process control for ***quick receipt*** of TI with limited onboard resources appears. Currently, Ukraine can use its own, foreign and combined (own and foreign) OSS to receive TI. These "combined" systems (in the sense of *integral use of information*) shall be appropriate considering the limited financial, economic and technical capabilities of Ukraine. In these circumstances, when promptness is a requirement, the space observation control problem is divided into two components:

a) The problem of *efficient control* of domestic orbital spacecraft;

b) The problem of *rational choice* of suitable foreign OSS.

Research Task. The Purpose of the Article. To solve these problems we suggest to (Fig. 1):

1. Analyse the existing technology, the theory and practice of process control in satellite and telecommunication systems, and, based upon results, choose rational solutions for above problems.
2. Develop a versatile alphabet for a formalized description the status of orbital and ground OSS devices and the processes occurring in them, and based thereupon, synthesize a number of relevant models with their in-service program.

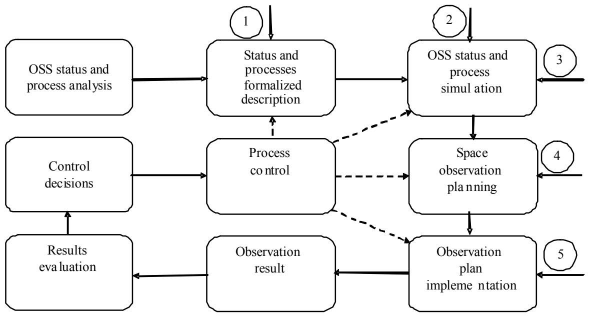


Fig.1. Space observation process control: 1–scientific methodological tool; 2–software; 3 – order; 4 – restrictions; 5 – external and internal factors

3. Based on the orders from TI users, simulate the process of space observations of the target areas and / or facilities with application of domestic and foreign OSS.
4. Make a plan of space observations based upon the simulation results with the organizational, technical, financial and other restrictions for a specific situation.
5. Implement the plan taking into account predictable and unpredictable external and internal factors and to assess the quality of the received results.
6. If necessary, adopt and implement the required decisions regarding control over the devices and processes occurring in them, including correction of the formalized description, synthesized models and their in-service program, methodological background for planning and implementation of the plans.

Presentation of Basic Material of Research

In the context of the above, the author of the article offers a number of approaches to process control in telecommunication satellite systems in addressing operational challenges. In particular, as shown in the analysis, the organization of process control should be based upon the basic requirements for OSS, i.e. prompt receipt of maximum useful TI of desired quality within a scheduled time of the day and the year from the specified areas of the Earth with minimum resource expenditures and with affordable costs. Therefore, it is advisable to switch from the traditional control of OSS devices to processes control within the system (the process approach). This means that the main control objective shall be more receipt of TI with required contents and quality than ensuring the proper functioning of orbital and ground devices filfilling scheduled program. With this approach in mind, we could allow some deviation of individual parameters in OSS technical devices from requirements and of SC location in time and space from normal orbit parameters, etc.

In this case, in order to promptly fulfill operational tasks we can: use both our own and available foreign spacecraft; redirect SC to required SF using angular maneuvers; use TI received during non-standard OSS functioning; use TI from the archive and other spacecraft; adjust own SC through the orbit correction, etc.

Additionally, the term "observation process control" should include not only the operations directly influencing the process (simulation, planning, SCP tailoring and implementation, and monitoring of the results), but selection, ordering, purchasing and other operations as well.

Such a broad interpretation of the control process is essential because of the use of TI from foreign OSS and the need to parry negative impact caused by external factors on the quality of the TI.

As concerns the formalized description of the status and the processes in OSS (see. Fig. 1), the author's articles [3, 4] further develop TCS processes formalization method as a basic one for further simulation. It is based upon a set-theoretic approach with integral use of analytical, logical and logical and analytical functions and their geometrical interpretation.

To this end, we have developed a corresponding alphabet, which includes both individual designations and logical, analytical, and logical and analytical dependences describing processes of ordering, planning, monitoring and generation of TI and its transmission, device and process control, status of orbital and ground devices, external and internal conditions of their operation, actions and decisions taken by support staff, and also customers and users of TI.

The formalization is based upon a mathematical tool of the set theory, combinatorial analysis, ambiguous and multiple-valued logic. Spatio-temporal phenomena in OSS are formalized using the SC flight theory, and the process of TI receipt is formalized based upon the information theory.

Based on the formalized description, we offer a number of generalized models enabling receipt of TI. One of these models is shown in Fig. 2.

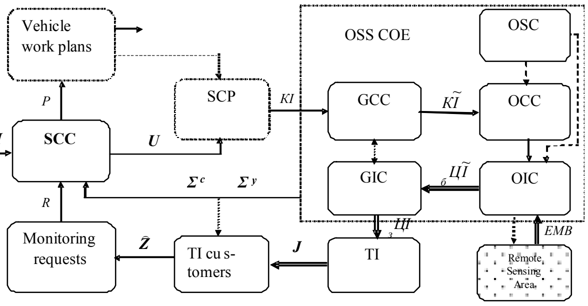


Fig. 2. Model of the process of TI receipt in OSS

As you see in Fig. 2, customers relying on the available information solutions, predict their needs in the target information $\mathbf{J}^{\text{н}} = \left\{ J_e^{\text{н}} \right\}, e = \overline{1, E}$ and taking into consideration data capabilities of OSS $\mathbf{J}^{\text{м}} = \left\{ J_j^{\text{M}} \right\}, j = \overline{1, J}$ submit corresponding requests for survey of specified areas $\hat{\mathbf{Z}} = \left\{ \hat{Z}_u \right\}, u = \overline{1, U}$.

Meanwhile, one request may have orders to monitor several areas from several types of SC in several SOE modes within several time intervals, etc. So, generally such a request may be formally written as a compound set:

$$\hat{\mathbf{Z}}_{\text{ю}} = \begin{Bmatrix} \{Z_u\}, \left\{\gamma_u^Z\right\}, \{d_{\text{з}}\}, \{P_m\}, \left\{\gamma_m^P\right\} \{K_{\text{г}}\}, \\ \{\text{Б}_z\}, \{\text{Ч}_i\}, \{\alpha_s\}, \left\{X_\beta\right\}, \left\{C_{\text{и}}^{\Pi}\right\} \end{Bmatrix}, \quad (1)$$

where arguments are subsets: customers $\{Z_u\}$ and their priorities $\left\{\gamma_\epsilon^Z\right\}$; specified monitoring dates $\{d_{\text{з}}\}$; specified areas $\{P_m\}$ and their priorities $\left\{\gamma_\epsilon^P\right\}$; SC types or numbers $\{K_{\text{г}}\}$; SOE types $\{\text{Б}_z\}$; monitoring modes $\{\text{Ч}_i\}$; permissible elevation of the Sun α_s; cloud cover over the area $\left\{X_\beta\right\}$; preferential PPI $\left\{C_{\text{и}}^{\Pi}\right\}$.

Based on requests received, SCC generates operation plans $\mathbf{\Pi} = \Pi_u\left(\{\text{З}_\alpha\} \neq \varnothing\right)$ to use OSS devices during orbit passes $\mathbf{B} = \{B_n\}, n = \overline{1, N}$ and a respective set of SCP $\mathbf{U} = \left\{U_\delta\right\}, \delta = \overline{1, \Delta}$, taking into account OSS data capabilities $\mathbf{J}^{\text{м}} = \left\{J_{\text{ж}}^{\text{м}}\right\}, \text{ж} = \overline{1, \text{Ж}}$, its status $\mathbf{\Sigma}^{\text{c}} = \left\{\Sigma_\chi^{\text{c}}\right\}, \chi = \overline{1, X^{\text{c}}}$ and conditions of its functioning $\mathbf{\Sigma}^{\text{y}} = \left\{\Sigma_\chi^{\text{y}}\right\}, \chi = \overline{1, X^{\text{y}}}$.

To formalize the processes in TI channels we suggest a process approach with application of base characters with an extensive system of indices. An algorithm for TI receipt with application of electrooptic onboard information complexes (OIC) may be an example of such an approach:

$$\begin{gathered} {}_{\text{з}}\text{EMB}_*^* \to {}_{\text{зс}}\text{EMB}_*^* \to {}_{\text{б}}\text{EMB}_*^+ \to {}_{\text{б}}^{\text{a}}\text{ЦI}_*^+ \\ \to {}_{\text{б}}^{\text{ц}}\text{ЦI}_*^+ \to {}_{\text{б}}^{\text{к}}\text{ЦI}_*^+ \to {}_{\text{б}}^{\text{к}}\text{Ц}\tilde{\text{I}}_*^+ \to {}_{\text{бс}}^{\text{к}}\text{Ц}\tilde{\text{I}}_*^+ \end{gathered}, \quad (2)$$

where ${}_{\text{з}}\text{EMB}_*^*$, ${}_{\text{зс}}\text{EMB}_*^*$ are mixtures of useful, useless and interfering EMR in optical and radio frequencies on the Earth in Cp1environment;

${}_{\text{б}}\text{EMB}_*^+ = \left\{ {}_{\text{б}}\text{EMB}_{\text{o}}^+ \vee {}_{\text{б}}\text{EMB}_{\text{p}}^+ \right\}$ is useful EMR in optical and/or radio frequencies on board the SC;

${}_{\text{б}}^{\text{a}}\text{ЦI}_*^+$, ${}_{\text{б}}^{\text{ц}}\text{ЦI}_*^+$, ${}_{\text{б}}^{\text{к}}\text{ЦI}_*^+$ is useful TI in the form of analog, digital signals and data frames generated on board the SC from useful EMR;

${}_{\text{бс}}^{\text{к}}\text{Ц}\tilde{\text{I}}_*^+$ is useful TI in the form of digital radio signals, transmitted from the SC into Cp2 environment.

For formalized description of TI receipt conditions we have proposed a logical function (LF) system. For example, suppose you must formally describe the process of TI receipt in observations of m-area conducted by EOOS devices in n- orbit pass. Let's introduce LF for the status of the devices and conditions of their functioning, i.e. of OSS orbital devices $\Phi_{\text{m}}^{\text{n}}(\text{O})$, optical visibility of the areas from the SC $\Phi_{\text{m}}^{\text{n}}\left(\text{F}^{\lambda}\right)$, radio coverage of surface facilities from SC $\Phi_{\text{m}}^{\text{n}}\left(\text{F}^{\text{f}}\right)$, astronomical and ballistic conditions $\Phi_{\text{m}}^{\text{n}}(\text{A})$ and the status of surface facilities $\Phi_{\text{m}}^{\text{n}}(\text{H})$. Then the objective conditions in respect to SCC for TI receipt may be described by the following double-valued LF:

$$\Phi_{\text{m}}^{\text{n}}(\Sigma)=\begin{cases}1, \text{if } \Phi(\text{O})\wedge\Phi\left(\text{F}^{\lambda}\right)\wedge\Phi(\text{A})\wedge\\ \wedge\Phi\left(\text{F}^{\text{f}}\right)\wedge\Phi(\text{H})=1;\\ 0, \text{if } \Phi(\text{O})\wedge\Phi\left(\text{F}^{\lambda}\right)\wedge\Phi(\text{A})\wedge\\ \wedge\Phi\left(\text{F}^{\text{f}}\right)\wedge\Phi(\text{H})=0.\end{cases} \tag{3}$$

If $\Phi_{\text{m}}^{\text{n}}(\Sigma)=1$, then the common operating environment (COE) is favorable and the SC can fully fulfill its mission with desired quality. On the contrary, when $\Phi_{\text{m}}^{\text{n}}(\Sigma)=0$, it is considered that OSS can't fulfill its mission with required quality of TI due to objective reasons. Other components in the expression (3) shall be described similarly. LF used to describe processes and phenomena provides a transition from the absolute value scale variables to the normal non-dimensional value scale. This LF property proves to be convenient in solving comparative analysis tasks, in optimization, and in taking technical, managerial and organizational decisions.

The author's articles [4, 5] further develop a method predicting controllability of the specified SF by space vehicles. It differs from the known methods by integrated account of the orbital parameters of a spacecraft, non-sphericity of the Earth, technical specifications of SOE in the calculations of the Earth monitoring parameters and the original visibility function for specified SF.

Simultaneously, the author considers peculiarities of SF attendance by space vehicles, when there are objective suspension time intervals due to the peculiarities of the orbital motion of the SC in respect to the rotating Earth. In this case, SOE swath consistently moves uncontrolled on the Earth's surface, reaching SF selectively. Regarding the above, there appears an urgent task to predict controllability of specified SF for practical planning of operational services.

In [4] we offer to define the conditions for controllability of any observation area by a function of visibility o the area from a spacecraft in п - orbit pass (Fig. 3):

$$\Phi_{\text{p}}(\text{п})=\begin{cases}1, \text{if } \left(\lambda_{\text{o}}^{\text{л}}\le\lambda_{\text{p}}^{\text{п}}\right)\wedge\left(\lambda_{\text{o}}^{\text{п}}\ge\lambda_{\text{p}}^{\text{л}}\right)=1;\\ 0, \text{if } \left(\lambda_{\text{o}}^{\text{л}}\le\lambda_{\text{p}}^{\text{п}}\right)\wedge\left(\lambda_{\text{o}}^{\text{п}}\ge\lambda_{\text{p}}^{\text{л}}\right)=0,\end{cases} \tag{4}$$

where $\lambda_{\text{o}}^{\text{л}}$ and $\lambda_{\text{o}}^{\text{п}}$ are geographic longitudes of the left and right swath edges with relation to the sight axis; $\lambda_{\text{p}}^{\text{л}}$ and $\lambda_{\text{p}}^{\text{п}}$ are geographic longitude of the left and right area boundaries with relation to the sight axis.

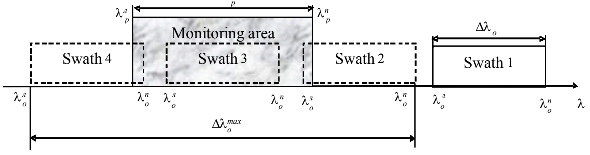


Fig. 3. SC swath covering the area

The area is under control, if $\Phi_{\text{p}}(\text{п})=1$, and is not controlled, if $\Phi_{\text{p}}(\text{п})=0$. If it is necessary to determine not only the facts but also the degree of controllability of a specified area, we can use one-dimensional swath "coverage" ratio of the area.

For example, in the situation shown in Fig. 3, this ratio can be found as relations of geographical latitude of the controlled part of the area to its full geographic latitude, which shall be appropriately described by a logical analytical function (LAF)

$$\text{K}_{\text{н}}=\begin{cases}\left(\lambda_{\text{p}}^{\text{п}}-\lambda_{\text{o}}^{\text{л}}\right)/\Delta\lambda_{\text{p}},\\ \text{if }\left[\left(\lambda_{\text{o}}^{\text{л}}\le\lambda_{\text{p}}^{\text{п}}\right)\wedge\left(\lambda_{\text{o}}^{\text{п}}\ge\lambda_{\text{p}}^{\text{п}}\right)\right]=1;\\ \Delta\lambda_{\text{o}}/\Delta\lambda_{\text{p}},\\ \text{if }\left[\left(\lambda_{\text{o}}^{\text{л}}\ge\lambda_{\text{p}}^{\text{л}}\right)\wedge\left(\lambda_{\text{o}}^{\text{п}}\le\lambda_{\text{p}}^{\text{п}}\right)\right]=1;\\ \left(\lambda_{\text{p}}^{\text{л}}-\lambda_{\text{o}}^{\text{п}}\right)/\Delta\lambda_{\text{p}},\\ \text{if }\left[\left(\lambda_{\text{o}}^{\text{л}}\le\lambda_{\text{p}}^{\text{л}}\right)\wedge\left(\lambda_{\text{o}}^{\text{п}}\ge\lambda_{\text{p}}^{\text{л}}\right)\right]=1;\\ 0, \text{if }\left[\left(\lambda_{\text{o}}^{\text{л}}>\lambda_{\text{p}}^{\text{п}}\right)\vee\left(\lambda_{\text{o}}^{\text{п}}<\lambda_{\text{p}}^{\text{л}}\right)\right]=1.\end{cases} ,(5)$$

Fig. 4 shows the geometric interpretation of ratio (5) for different relations between the sizes of controlled areas and swath.

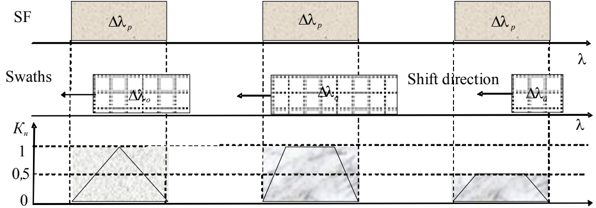


Fig. 4. Concept of one-dimensional coverage ratio

The proposed rate (5) is one- dimensional (contrary to two-dimensional or flat). It may be convenient for selection of relevant SC according to maximum coverage a specified area and planning of operational use of such SC.

In order to provide control over detailed monitoring from space, the author has developed an analytical model for SF attendance [5,6], which takes into consideration SC orbit parameters, technical specifications of SOE and the shape of its swath (conical, pyramidal), off-pointings of SOE sight axis from nadir in roll and / or in pitch and various models of the Earth (flat, spherical, ellipsoidal).

For example, let's consider one of the most difficult situations Ξ_{122} (cone, turn-out in roll, spherical surface of the Earth). Suppose SC swath is a right circular cone with an apex angle 2χ, SOE sight axis coincides with the height of the cone. Due to corner SC manoeuvre in roll its swath and SOE sight axis are deviated from nadir at an angle η. SC is at an altitude H. In this case, the projection of the conical swath onto the spherical surface of the Earth shall be transformed into a quadric ovoid surface, i.e. "deformed spherical ellipse" (DSE), whose axes are the globe arcs.

Article [5] provides the following formula for calculations of major DSE axis, which is simultaneously, is SC swath width

$$L_a = R_з \left\{ \begin{aligned} &\pi - 2\chi - \arccos\left[\frac{R_з + H}{R_з} \sin(\chi - \eta) \right] \\ &- \arccos\left[\frac{R_з + H}{R_з} \sin(\chi + \eta) \right] \end{aligned} \right\}, \qquad (6)$$

where $R_з = 6371$ km is the average radius of the Earth.

Minor DSE axis shall be the arc

$$L_b \approx 2R_з \left[0{,}5\pi - \chi - \arccos\left(\frac{R_з + H_\eta}{R_з} \sin\chi \right) \right], \qquad (7)$$

where $H_\eta = KA_2 = H/\cos\eta$ is distorted due to SC "height" roll.

Using the obtained results, we can roughly calculate the swath projection area considering expressions (6) and (7) as

$$S_{122} \approx 0{,}5\pi\ L_a L_b, \qquad (8)$$

We can calculate the area surveyed from circular or nearly circular orbits within the observation time $\Delta t_{сп}$ as

$$S_{сц} \approx S_{122} + \frac{L_a\, R_з \sqrt{\mu_0 / (R_з + H)}}{R_з + H} \Delta t_{сп}, \qquad (9)$$

where $\mu_0 = 3{,}986 \cdot 10^5 \text{km}^3/\text{s}^2$ is a gravitational parameter of the Earth;

When the field of vision of SC turns away from nadir in roll by an angle η, the SC swath width on the Earth's surface shall be as follows:

$$L_{захв} \approx L_a + 2L_\eta, \qquad (10)$$

where $L_\eta \approx H\,\mathrm{tg}\eta$ is a linear distance between the SC tracks and SOE sight axis.

The author's works [7, 8] are devoted to the synthesis of a logic and analytical model of SC angular motion, which allows for qualitative analysis and quantitative evaluation of the influence of angular motion parameters upon the volume and quality of TI. Besides, this model provides practical routes for specified SF attendance. The model is based upon formalized description of TI receipt processes in OSS and of angular motion control during programmed SC turn maneuvers and SC precession orientation and stabilization.

In these circumstances, the referred stages of spacecraft angular motion shall be described by a logical function including SC program turn angles $v^{пр}$ and their errors $\Delta v^{пр}$; time $t^{пр}$ for program retargeting of SC; errors in precision guidance Δv and stabilization of the spacecraft $\Delta\dot{v} = \dot{v}$; time $t^{у}$ for SC stabilization after retargeting.

For example, a logical function of SC angular motion quality using a multiple valued logic in one of the channels of the orientation and stabilization system shall be as follows:

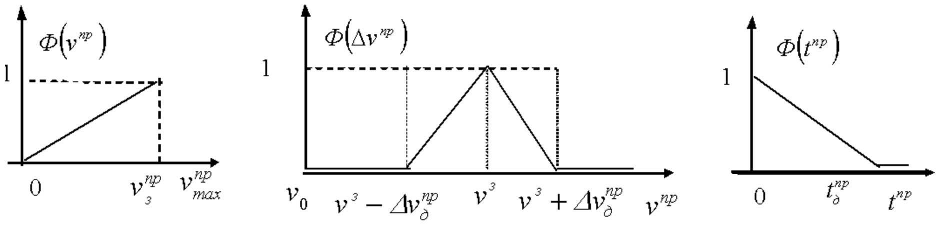
$$\Phi(\Psi) = \begin{cases} 1,\ \text{if}\ \Phi\left(v^{пр}\right) \wedge \Phi\left(\Delta v^{пр}\right) \wedge \Phi\left(t^{пр}\right) \wedge \\ \qquad \wedge\, \Phi(\Delta v) \wedge \Phi(\dot{v}) \wedge \Phi\left(t^{у}\right) = 1; \\ \Phi(\varsigma)_{\min},\ \ \text{if}\ 0 < \bigcap_{\varsigma} \Phi(\varsigma) < 1, \\ \qquad \varsigma = \left\{ v^{пр}, \Delta v^{пр}, t^{пр}, \Delta v, \dot{v}, t^{у} \right\}; \\ 0,\ \text{if}\ \Phi\left(v^{пр}\right) \wedge \Phi\left(\Delta v^{пр}\right) \wedge \Phi\left(t^{пр}\right) \wedge \\ \qquad \wedge\, \Phi(\Delta v) \wedge \Phi(\dot{v}) \wedge \Phi\left(t^{у}\right) = 0. \end{cases} \qquad (11)$$

Expression (11) has a rather clear physical meaning, since it combines all the requirements to the orientation and stabilization system itself and SC angular motion control laws in conducting detailed observations. If necessary, each of the factors in the expression (11) can be assigned weighting factor. The arguments of the formula (11) are LAFs with the following meaning:

LAF of potential angular maneuvers $\Phi\left(v^{пр}\right)$ suggests the technical capability of the orientation and stabilization system to provide reorientation of SC field of vision within the specified angles $v_з^{пр}$. It can be defined by the following analytical expressions, $v_з^{пр} \geq 0$ (Fig. 5, a).

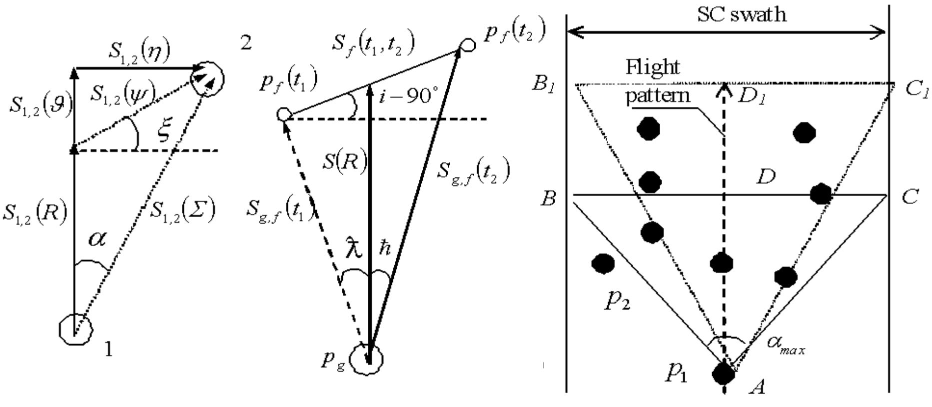
$$\Phi\left(v^{пр}\right) = \begin{cases} 1,\ \text{if}\ \left| v_{\max}^{пр} \right| = v_з^{пр}; \\ \left| v_{\max}^{пр} \right| \big/ v_з^{пр}\ \text{if}\ 0 < \left| v_{\max}^{пр} \right| < v_з^{пр}; \\ 0,\ \text{if}\ v_{\max}^{пр} = 0. \end{cases} \qquad (12)$$

LAF of SC program turn accuracy $\Phi\left(\Delta v^{пр}\right)$ characterizes the range of angles and absolute errors in their working out by the orientation and stabilization system. If we assume a linear model of TI quality degradation depending from the size of these errors, then this function shall have the form shown in Fig. 5, b, and shall be described by the following analytical expression $\Delta v_д^{пр} \geq 0$:



a в c

Fig. 5. Functions describing SC retargeting processes



a в c

Fig. 6. More about the problem of practical routes generation

$$\Phi\left(\Delta v^{пр}\right)=\begin{cases}1, \text{ if } \left|\Delta v^{пр}\right|=\left|v^{пр}-v^3\right|=0;\\ 1-\left|v^{пр}-v^3\right|/\Delta v_Д^{пр} \text{ if } 0<\left|\Delta v^{пр}\right|\le\Delta v_Д^{пр};\\ 0, \text{ if } \left|\Delta v^{пр}\right|=\left|v^{пр}-v^3\right|>\Delta v_Д^{пр}.\end{cases} \quad (14)$$

LAF of SC program turn time $\Phi\left(t^{пр}\right)$ characterizes the speed of the orientation and stabilization system. It shall be described by the following analytical expression (Fig. 5, в):

$$\Phi\left(t^{пр}\right)=\begin{cases}1, \text{ if } t^{пр}=0;\\ 1-t^{пр}/t_Д^{пр}, \text{ if } 0<t^{пр}\le t_Д^{пр};\ t^{пр}\ge 0;\\ 0, \text{ if } t^{пр}>t_Д^{пр}.\end{cases} \quad (15)$$

Regarding the problem of spacecraft motion control in general and angular motion control in particular, there is an objective number of almost independent processes and the task of SCC is mainly to "adjust" them for specified purposes. In these circumstances, there is a need for such a route (pattern) for SOE sight axis, which could best meet most requirements of TI consumers. In order to solve this problem, in [8] we synthesized geometric models for SC field of vision targeting upon the specified SF taking into account the rotation of the Earth (Fig. 6).

Fig.6,a shows a case when it is necessary to retarget a spacecraft from Facility 1 to Facility 2. In these conditions, the result vector of sight axis displacement is expressed through vectors of orbital and angular displacement as the vector sum ($\bar{S}_{1,2}(R)$, $\bar{S}_{1,2}(\eta)$):

$$\bar{S}_{1,2}(\Sigma)=\bar{S}_{1,2}(R)+\bar{S}_{1,2}(\eta). \quad (16)$$

The orbital displacement vector $\bar{S}_{1,2}(R)$ is characterized by its uncontrollability in this case. Its circular orbit module with an altitude H_0 shall be determined from the linear velocity of the spacecraft V_0 and the orbital flight time interval $\tau_{1,2}^R$.

The vector component (6) $\bar{S}_{1,2}(\eta)$ is controllable. It shall be determined from the angular maneuver time $\tau_{1,2}^{\eta}$, the angular velocity of the spacecraft $\dot{\eta}$ and the orbit altitude H_0, the first two parameters being controllable.

The module of result vector (6) and the angle of its orientation with regard to SC flight pattern (track angle) α, which jointly determine a strategy for SOE sight axis retargeting from Facility 1 to 2 shall be written as:

$$S_{1,2}(\Sigma)=\sqrt{S_{1,2}^2(R)+S_{1,2}^2(\eta)}, \quad (17)$$

$$\alpha_{1,2}=\text{arctg}\left[S_{1,2}(\eta)/S_{1,2}(R)\right], \quad (18)$$

Dependencies (7) and (8) show that for the circular orbits, successful field of vision retargeting from one SF to another depends on the relative position of these objects and their location relative to the route, as well as on the technical capabilities of the orientation and stabilization system. Angular movements of SF in the SOE field of vision and orbital motion of the spacecraft creates a complex picture of the mutual movements. Therefore there is a fundamental need to control angular motion of the spacecraft.

Based on the obtained results we synthesized a complex model, which takes into account the orbital motion of the spacecraft, orbit inclinations, facility movements due to the Earth's rotation and movements of SOE field of vision due to control of angular motion of the spacecraft. The resulting picture of these processes is shown in Fig. 6, b.

The module of SOE field of vision movement from facility p_g to facility p_f, which is located at the latitude ϕ, due to the Earth's rotation during the orbital flight of the spacecraft $\tau_{1,2}^{R}=t_2-t_1$ to facility p_f sysshall be determined as (see. Fig. 6, b):

$$S_f(t_1,t_2)=V_з(t_2-t_1)\cos\phi\sin i. \qquad (19)$$

Then the SC angular motion control law shall consider the result vector

$$\bar{S}_{g,f}(t_2)=\bar{S}_{g,f}(t_1)+\bar{S}_f(t_1,t_2), \qquad (20)$$

Based on the obtained results, we made a concept for practical attendance of facilities located within the swath of the spacecraft (Fig. 6, b). According to the concept it is advisable to give preference to the facilities that have a higher priority and are closer to the flight pattern of the spacecraft.

In order to divide the specified facilities into objectively suitable (OSO) and objectively unsuitable (OUO) for service, it is good to use an instant service area (ISA), which is part of the swath area shaped as a triangle ABC (Fig. 6, b) becoming further a rectangle with an infinitely remote side $B'C'$. This zone moves on the flat surface of the Earth along the route of SOE sight axis at a speed of the ground point (GP). The SF covered by the ISA shall be ascrobed to OSO, other objects (for example, SF p_2 in Fig. 6, b) – to the category of OUO. To automate the calculations, we developed an analytical ISA model, which is based on the following approach:

1. According to the formula (8) we can calculate angle α_{max} provided $\eta=\eta_{max}$, angle α_{max} being determined from interrelation of linear speeds in roll $\dot{\eta}$ in V_o orbit, i.e. from the dynamics of SOE sight axis movements:

$$\alpha_{max}=\text{arctg}\left[H_o\dot{\eta}/V_o\right]. \qquad (21)$$

2. Based upon specified angular positions of separate SF p_g and p_f we shall calculate corresponding route angles $\alpha_{g,f}$ according to the formula:

$$\alpha_{g,f}=\text{arctg}\left[S_{g,f}(\eta)/S_{g,f}(R)\right]= \text{arctg}\left[\alpha_{max}\tau_{g,f}^{\eta}\Big/\tau_{g,f}^{R}\right]. \qquad (22)$$

3. By comparing route angles of separate SF (22) with maximum angle (21), we can ascribe correspondent facilities to OSO or OUO according to the rule:

$$\Re_f=\begin{cases}p^{+}, & \text{if } \left|\alpha_{g,f}\right|<\alpha_{max};\\ p^{0}, & \text{if } \alpha_{g,f}=\alpha_{max};\\ p^{-}, & \text{if } \left|\alpha_{g,f}\right|>\alpha_{max},\end{cases} \qquad (23)$$

where p^0 is a subset of objects located on the interface (on the lines AB and AC in Fig. 6, b).

To develop possible routes for OSO attendance considering the introduced restrictions and "cutting back" of the specified objects according to the rule (13) we can use a direct enumeration method.

In order to provide the ability to select practical routes from the resulting set of rational routes, we have introduced several significant choice criteria, and based thereon, we've done multi-criteria decision optimization. For this purpose, we've used a nonlinear compromise scheme

$$Y(\lambda,K)=\sum_{i=1}^{I}\lambda_i\left[1-K_i(\Re_\mu)\right]^{-1};\ \sum_{i=1}^{I}\lambda_i=1, \lambda_i\ge 0, \qquad (24)$$

where $\lambda_i=\text{const}$ components of the importance are vector for Λ optimization criteria; $K_i(\Re_\mu)$ are standard route optimization criteria.

Based on the proposed concept for practical facility attendance, the following optimization criteria have been selected:

a) Total priority of SF in μ route. Obviously, the routes with $\Sigma\gamma_f(\mu)\to max$ or a correspondent standardized criterion $K_\gamma(\mu)\to 1$ will be the best.

b) sum of track angles on the specified route $\Sigma\alpha(\mu)=\sum_{f=g}^{F^\mu}\left|\alpha_{g,f}(\mu)\right|$.

This criterion characterizes the degree of deviation of SOE sight axis track on this route from the spacecraft flight pattern. Smaller criterion values indicate less energy consumption during SC retargeting and better TI quality. Therefore, it is advisable to choose routes, where $\Sigma\left|\alpha(\mu)\right|\to\min$ or a correspondent criterion $K_\alpha\to 0$.

A contraction formula for practical application according to above criteria shall be as follows:

$$Y(\mu)=\frac{\lambda_\gamma}{K_\gamma(\mu)}+\frac{\lambda_\alpha}{1-K_\alpha(\mu)},\ \sum_{i=1}^{4}\lambda_i=1,\ i=\gamma,\alpha. \qquad (25)$$

For convenient comparison and choice of best solutions we advise to use standardized contraction values

$$\hat{Y}(\mu)=Y(\mu)\Big/Y_{max},\ 0\le\hat{Y}(\mu)\le 1,\ Y_{max}=maxY(\mu). \qquad (26)$$

Minimum standardized contraction values (16) shall be a criterion for selection of practical route for attending specified SF, and an algorithm for such routes can be formally presented as follows:

$$\tilde{\Re}^{p}_{\mu}(f) = \underset{\mu=\overline{1,M}}{\underline{opt}}\,\hat{Y}_f(\mu) = \arg \underset{\mu=\overline{1,M}}{\underline{\min}}\,\hat{Y}_f(\mu). \qquad (27)$$

Besides the results summarized above, the author has obtained some other results as well.

For example, in [9] he developed a method for adaptive setting of the attendance area coordinates, which, in contrast to the known method accounts for the geometric shape of the area and the position of the projected SOE swath at the time of survey, allowing economical use of the informational resource of the satellite TCS. In [10] the author improved the method of SF attendance without SC retargeting. It provides retrieval of maximum performance function on the progressive development of orbit enabling to improve information content of space images at the stage of operational planning.

In [11, 12] the author developed methods for TI receipt by ground devices of satellite TCS in low power capacity of the information radio line and the initial vagueness of signal structure.

Generally, the obtained results enable to improve up to a point the efficiency of space-based observation control with regard to the necessary requirement to ensure the requisite speed in attending specified SF.

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ДО ПРОБЛЕМИ УПРАВЛІННЯ ПРОЦЕСАМИ В СУПУТНИКОВИХ ТЕЛЕКОМУНІКАЦІЙНИХ СИСТЕМАХ ПРИ ВИРІШЕННІ ОПЕРАТИВНИХ ЗАВДАНЬ

С.П. Фриз

У статті запропоновані результати розробки методологічних основ управління процесами в супутникових інформаційно-телекомунікаційних системах при вирішенні оперативних завдань в умовах обмежених бортових ресурсів.

Ключові слова: *супутникова інформаційно-телекомунікаційна система, смуга огляду, смуга захоплення.*

К ПРОБЛЕМЕ УПРАВЛЕНИЯ ПРОЦЕССАМИ В СПУТНИКОВЫХ ТЕЛЕКОММУНИКАЦИОННЫХ СИСТЕМАХ ПРИ РЕШЕНИЯ ОПЕРАТИВНЫХ ЗАДАЧ

С.П. Фриз

В статье представлены результаты разработки методологических основ управления процессами в спутниковых информационно-телекоммуникационных системах при решении оперативных задач в условиях ограниченных бортовых ресурсов.

Ключевые слова: *спутниковая информационно-телекоммуникационная система, полоса обзора, полоса захвата.*