ROCKET-SPACE DEVICE ENGINEERING AND INFORMATION SYSTEMS
Vol. 3, Iss. 1, 2016, pp. 57–65

System and Technical Aspects of Development of the Ground-based Automated Control Complex for Spacecraft of Scientific and Socio-economic Purposes and Measurements till 2025

M.Yu. Kislyakov[1], **N.S. Logachev**[2], **A.M. Petushkov**[3]

[1]candidate of engineering science, [2]doctor of military science, [3]candidate of engineering science
Joint Stock Company "Russian Space Systems", Russia
e-mail: [1]kisl60@mail.ru, [2]vn_i_op@mail.ru, [3]alexandr.petushkov@gmail.com

Abstract. The peculiarities of spacecraft control perspective technologies and main trends in their practical usage, as well as arising problems, are examined. The following spacecraft control technologies are considered: ballistic and navigational provision, information-telemetric support, control via satellite relays, and integration of spacecraft data communication channels. Moreover, a preliminary plan for perspective technologies realization and the image of a perspective ground-based automated control complex for spacecraft of scientific and socioeconomic purposes and measurements is substantiated.

Keywords: ground-based automated control complex for spacecraft of scientific and socioeconomic purposes, information support technology for spacecraft control.

Introduction

According to the project of Russian federal space program for the 2016-2025 period, it is planned to substantially expand the composition of the orbital groups of spacecraft of scientific and socioeconomic purposes and measurements, to carry out a number of principally new space projects, including interplanetary, to broaden the international space cooperation. The solution of these tasks will require significant development of the existing ground-based automated control complex for spacecraft of scientific and socioeconomic purposes and measurements (GBACC SC SSPM).

To meet this challenge it is possible to use either extensive or intensive approach to GBACC SSPM development. Solely extensive development, such as increasing the number of ground facilities, cannot meet the requirements for a modern spacecraft control complexes, it is imperative to search for ways of intensive development based on the introduction of advanced spacecraft and measurements control technologies.

Presently, a number of trends to improve satellite control processes that significantly affect architecture of the future GBACC SSPM is being developed and implemented. The most important ones are:

the use of consumer navigation equipment [1];

development of information-telemetric support [1];

utilization of relay technologies:

- using relay satellites (RS) in geostationary orbits [1,3];
- using RS in low orbits [2,4,5];

the use of network control technologies [3,4,5];

integration of data transmission channels [4].

A detailed examination of these trends is the subject of the research into the design of spacecraft control systems, this article will examine the implementation of these particular trends and their influence on the architecture of future GBACC SC SSPM.

1. The use of consumer navigation equipment

Ballistic and navigational spacecraft flight support includes measurement of current navigational parameters (MCNP) of the spacecraft's movement. Currently, the main BNS technology is the direct MCNP from ground stations. The advantage of the ground-based measurements are their maturity, simplicity, and reliability. The drawback is a heavy workload of ground facilities. Thus, the Resource ERS satellites requires 6-7 daily MCNP sessions with geographically dispersed control and measurement stations on 2-3 adjacent circuits, that is 50-60% of the total number of communication sessions with the spacecraft on the daily interval. The use of consumer navigational equipment (CNE) significantly reduces the number of communication sessions and reduces the requirements for the number of control facilities and their spatial layout.

Using radio-navigation field of fully-deployed GLONASS system allows globally and continuously determine the position of the spacecraft in orbit on altitudes from 200 to 2000 km, with critical errors of up to of tens of meters and using cm/s units for the components of the velocity vector, which limits the application of the CNE in the spacecraft in highly elliptical orbits, geostationary orbit, during a flight to the Moon, as well as in upper stage rockets, when delivering a spacecraft to the geostationary orbit.

The navigation support of spacecraft in orbits of over 2000 km can be performed by discrete radio navigational field. Space-time discretization of a radio navigation field is caused by determinancy of antenna patterns of navigational satellites, as well as the impossibility of radio emission into the upper hemisphere, and radio shadow due to the screening effect of the Earth.

Under these conditions, for SC on elliptical orbits with a perigee under 200 km and apogee over 2000 km, it is advisable to use a technology that combines the determination of spacecraft movement parameters based on individual of the radio navigational field during the perigee phase with the prediction of movement parameters during the apogee phase of the flight, followed by a refinement of movement parameters based on the discrete radio navigational field, that can be generated by even one navigation satellite.

For the particularly precise work, requiring knowledge of the center of mass of the consumer spacecraft with margin of error of several meters (for example, when docking, carrying out scientific experiments, etc.), the differential method of navigation can be used.

The widespread use of GLONASS / GPS navigation systems will provide significant economic benefits, since even a significant increase in the number of satellites in a constellation and increased requirements for accuracy and timeliness of orbit determination, does not require more ground-based measuring devices, reducing the number of measurement sessions of current navigation parameters and the volume of measurement information in spacecraft computer.

Thus, the analysis of technical system features of navigational and ballistic support of advanced satellites allows us to conclude that in the near-term outlook ground-based automated control complexes will employ a combined NBS technology that will utilize both GLONASS / GPS signals and ground-based MCNP. The use of ground-based facilities, primarily, will be necessary for the spacecraft, flying on highly ecliptic, geostationary, lunar and interplanetary orbits, as well as for upper-stage rockets.

To further expand the scope of consumer navigation equipment on board of a spacecraft it is necessary to further develop the theory of navigation definitions in discontinuous field.

2. Improving information-telemetric support

Currently, large amounts of telemetry data are one of the main factors that increase the load of ground-based radio equipment, communications equipment, and ultimately MSRS. The introduction of advanced methods of information-telemetric support of spacecraft will increase the capacity of ground-based automated control complexes for spacecraft of scientific and socioeconomic purposes and measurements.

ITS technology is currently being implemented by using the primary mode of telemetry, involving the transfer of complete telemetry data streams from spacecraft through a standalone radio channel or CIS channel, as well as the use of generic control information transmitted through the CIS channel.

The basis for further development is the introduction of new antenna systems, compression of telemetric data, processing of telemetric data on board of a SC, the use of packet telemetry.

The basis of modern technologies to reduce the redundancy of transmitted messages is comprised of algorithms of syntactic and semantic compression of telemetric data.

Syntax compression involves increasing the amount of information carried by each transmitted character of telemetric data. It is based on unconventional presentation of data telemetry as their images that reduce the structural redundancy of telemetric data. Semantic compression reduces the temporal redundancy of transmitted data. It is based on aperture methods of reducing of telemetric data redundancy, associated with the establishment of thresholds, which need to be reached for data to be considered a significant result of telemetry, and, therefore, transmitted.

Combining different compression methods in conjunction with computing and algorithms for reverse recovery of telemetry, which are represented in finite fields, it is one of the approaches to the construction and improvement of advanced on-board telemetry systems.

Compression of telemetric data allows to reduce the amount of information transmitted by 5-10 times and to increase by 5-6 dB the equivalent power of the radio link. This means that the required reception reliability will be provided with a decrease in the requirements to the effective surface of the antenna systems by 8-10 times, which will create conditions for the use of smaller diameter antenna systems. The ability to use small-sized antenna systems creates conditions for reliable reception of telemetric data when deploying small radio systems on mobile vehicles, thereby increasing the performance, mobility and adaptability of ground telemetry complexes. In addition, the compression of telemetric data allows relaying of reduced telemetric messages using MKSR, conventional satellite relays, as well as transmission of the results of telemetry through standard telephone channels.

Creating variously based mobile means for receiving and processing telemetric data will significantly improve the efficiency of deployment of information support facilities for carrier vehicle launches, which is especially important for the information support of launches from Vostochny Cosmodrome.

Thus, it is now possible to significantly improve the information-telemetric support, as well as the characteristics of ground-based facilities for receiving and processing of telemetric data. It is necessary to harmonize approaches to the implementation of promising methods and deadlines for their implementation.

3. Utilization of relay technologies for SC control

Ground-based control and measurement stations (CMS), that provide navigation-ballistic, information-telemetric and command support solutions must be separated by latitude and longitude to ensure the maximum possible continuous zone of radio visibility over the territory of Russian Federation for all possible inclinations of spacecraft orbits and rocket flight paths.

Expanding the range of spacecraft orbit inclinations, transfer of a significant proportion of starts to Vostochny Cosmodrome potentially requires the creation of a new ground-based tracking stations, i.e. extension of GBACC SC SSPM infrastructure. A possible solution to this problem, the creation of variously based mobile measuring stations, has been mentioned above.

Another solution is creation of a spacecraft control and information gathering network using data relay satellites. This communication technology will make the processes of spacecraft control and collection of measurements from carrier vehicles independent on the zones of radio visibility of ground-based facilities; the technological cycles of spacecraft control, collection of measurements from carrier vehicles will become adaptive.

The inclusion of RS into the spacecraft control loop has a number of technical problems that determine the modes of their application. The following problems are determinative:

establishment and maintaining of the communication channel(s) between the SC and the RS;

establishment and maintaining of the communication channel(s) between the SC and the ground-based station;

establishment and maintaining of the communication channel(s) between the RS (if intersatellite link is in use);

data flow control in communication channels.

3.1 Application of relay spacecraft control technologies using relay satellites in geostationary orbits

It is sufficient to use only 3 RS spaced by approximately 120 degrees in a geostationary orbit for global coverage.

A typical RS has antennas for receiving both low-data-rate signals from SC in multistational access mode (MAM), and high-data-rate signals in individual access mode (IAM).

In MAM mode uses antennas with circular pattern, providing virtually instantaneous link establishment between RS and SC. Low data rate of this link makes it suitable only for short message exchange, in particular, for messages such as “Contact the GCC”.

The IA mode uses a spot beam antenna, which makes it necessary to calculate target designations for antennas, to take into account their rotational capacity, the process of mutual targeting of antennas, link establishment, antenna rotation during the communication session, termination of a data exchange session. Additional link establishment and termination activities reduce the effective data exchange time. The number of IA channels is limited, so it is necessary to individually allocate the time of communication sessions in this mode.

A major shortcoming of employment of RS in a geostationary orbit is the necessity of high-energy radio systems and a significant latency in data transmission channels.

These problems while establishing a physical data link make it imperative to further develop data transfer procedures of intersatellite links: employment of typed messages; combination of command and software, telemetric, and target data streams; the use of batch processing of messages; the use of data compression techniques and other ways to improve the exchange rate.

So far only a few countries have found the solutions to the challenges of designing such systems (see Table 1).

The USA has the most experience; their TDRSS system has been in operation since 1983. Presently, the third generation of RS is developed and deployed. The system has a global coverage, ability to work in different frequency bands (except the optical), communication devices of SC and carrier rockets are perfected. CP are able to communicate with each other, thus ensuring the communication of client SC with ground stations in near-real-time mode.

China has developed and deployed a national “Tianlian-1” system, it was tested in the orbit. The improved “Tianlian 2” system is under development.

Russian Federation has deployed the “Luch-5” RS system, but to date no spacecraft (except for ISS ROS), rocket carriers or boosters are equipped with the required client equipment.

In 2016 European space community plans to deploy its EDRS relay system [3], originally for communication with the satellites over Europe, the Mediterranean and North Africa. By 2019 it is planned to launch two additional satellites to provide global coverage. The onboard relay equipment, including laser-based, has passed testing in space.

Table 1 Status of development of relaying systems based on RS in GSO

Name (country)	Start of use	Number of SR (coverage)	Client SC altitude range	SR-SR Link	SC-RS range	No. of channels in IA mode	No. of channels in MA mode		Development stage
TDRSS (USA) (Third generation)	1983	3 (global)	Up to 10000 km	+	S, Ku, Ka	2 - S 2 - Ku or 2 - Ka	RS to SC 2 to 300 Kbit/s	SC to RS 5 to 1.5 Mbit/sec	In use
“Tianlian” (China)	2008	3 (global)	n/a*	-	n/a	n/a	n/a	n/a	In use
“Tianlian-2” (China)	n/a	3 expected (global)	n/a	n/a	n/a	n/a	n/a	n/a	In development
«Luch-5» (Russia)	2016	3 (global)	Up to 2000 km	-	S, Ku	S- up to 5 Mbit/s Ku - up to 150 Mbit/s	4 channels up to 256 kbit/s		deployed
“Luch-5M” (Russia)	2021	1	Up to 2000 km	-	S, Ku, Ka Laser communication	same 600 Mbit/s	same		In development
EDRS (ESA)	2016-2017 2019-2020	2(Europe) 4(global)		-	-S, Ku, Ka Laser communication	n/a 1.8 Gbit/s	n/a	n/a	Demonstration tests in space

*n/a - no data available

Fig. 1 Orbital formation of the O3b system: 16 satellites in a circular equatorial orbit with H = 8000 km.

3.2 Application of relay spacecraft control technologies using relay satellites in low Earth orbits

Currently, work is underway to create LEO multi-satellite communication systems and broadband information exchange. By design, these systems must work with low-energy handset type terminals, or a small-sized mobile and stationary transceivers, providing them with global continuous communication with any area of the Earth. To ensure global coverage, some systems establish the intersatellite relay links between the spacecraft of the system within the orbital plane and spacecraft in different planes.

Examples of such systems are the “Iridium”, “INMARSAT”, “Globalstar”, “Orbcom”, “Messenger”, etc.

Such systems potentially make it possible to maintain control of low-altitude spacecraft without the use of powerful transceiver equipment and ground-based CIS, which is especially important for small spacecraft. Lower, compared to the CP in the GSO, orbital altitude can significantly reduce the data transmission latency and simplify the solution of technical problems associated with such latency. The information exchange protocols, used in these systems, are available to a wide range of developers and consumers.

In 2005 JSC “Russian Space Systems” developed and launched TNS-type spacecraft for testing small spacecraft control using low-orbit communication systems. The results were satisfactory, new nanosatellites are being prepared for launch [2].

Google is presently the pacesetter in the field of low orbit relay systems. It currently deploys the O3b orbital system [5], consisting of 16 SC in the equatorial orbit at an altitude of 8000 km (Fig. 1). The O3b constellation will provide broadband connectivity within the 45/-45 degrees south and north latitude. One of the anticipated areas of application is providing small satellites with communication with ground stations. A higher the orbit, compared to the aforementioned, allows to extend the variety of spacecraft orbits, that can take advantage of this virtual SDTS to communicate with the MCC and consumers, similarly to the TNS-type SC.

Creation of low-orbit satellite networks for SC control and target data transfer is an important development direction for small spacecraft control systems, which has a great potential. It is necessary to accelerate the perfection of low-altitude communication systems for command of small-sized spacecraft. So far few real steps were made in this direction.

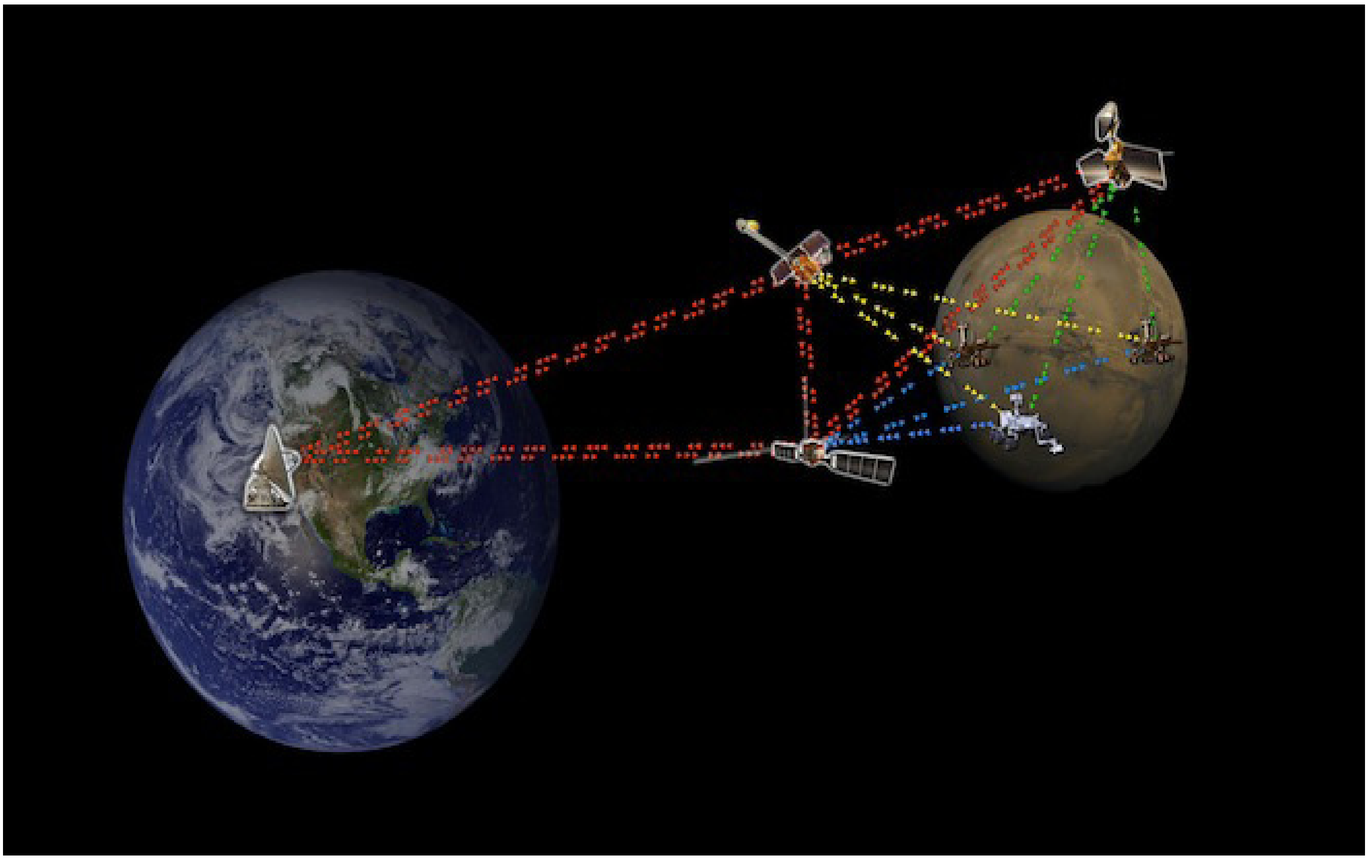

Fig. 2 Network design variant for information exchange with the lunar modules

4. Network spacecraft control technologies

The introduction of the relay spacecraft control and target information (TI) transmission technology leads to the following conclusion: the spacecraft control and TI transmission system becomes an analogue of a distributed computing network in which it is advisable to use standardized communication protocols, rather than create dedicated hardware and software. Consequently, the next important direction of spacecraft control technology development is creation and implementation of common standards (formats, protocols) for information exchange between on-board and ground-based equipment, regardless of the type of information transmitted, with the transition, in the long term, to packet-switching [4]. The introduction of the network protocols would eliminate the need of specialized ground-based facilities for processing and transmitting of various types of information, significantly reducing the number of specialized facilities, while increasing the employment of multipurpose facilities. The entire set of tools of the integrated GBACC SC SSPM and on-board SC control systems will be unified into a single computer network conforming to the multi-tiered architecture of open systems.

The results of THC-type spacecraft testing showed that the technical implementation of network protocols is viable and that it makes it possible to create fundamentally new technologies for small spacecraft control and development of control complexes.

Another trend in small spacecraft development is the creation of multi-satellite (cluster) systems [4], in which, to put it into computer networks terms, one spacecraft acts as a server and communicates with the MCC, while the others become clients of the local network. In its essence, it is a counterpart of the widespread local area networks. The application of this idea to the data exchange and spacecraft control systems is promising, at least in terms of increasing the efficiency of information exchange between the interacting SC, reducing the number of ground-based control stations and the number of required communication sessions. This is ensured by the ability, if the network is sufficiently developed, for any ground station to establish contact with any satellite, regardless of its location in space, without waiting for its

Table 2 Suggested trends of implementation of the primary and interrelated advanced spacecraft control and information exchange technologies.

Name of the advanced technology of spacecraft control	Suggested trends of implementation of the advanced spacecraft control technologies
Using the on-board consumer navigation equipment GNS GLONASS / GPS for MCNP for the transmission of information as a part of TMD. Integrating circuits of trajectory and telemetry control.	On-board control complexes for future space and rocket vehicles, boosters, complexes of measurement, information collecting and processing facilities for launch vehicles, ground-based spacecraft control complexes.
Utilization of relay technologies for SC control and communication	Relay systems, on-board and ground-based control complexes for future rocket and space equipment, future UCMS, consumer relay equipment.
Utilization of the on-board systems for control, diagnostics and automated recovery of SC equipment.	On-board control complexes for future rocket and space equipment.
Development of a system for forming and sending the “Call Earth” signals using relay systems.	On-board and ground-based control complexes for future SC.
Implementation of coordinate-time control in place of program-time control.	On-board control complexes for future spacecraft, boosters, launch vehicles, MCC.
Using the target radio link to deliver command-program information on board of the spacecraft and TMD transmission.	On-board control complexes for future spacecraft, Earth remote sensing data receiving stations, satellite communications stations, MCRS information receiving and transmitting stations.
Synchronization, phasing and correction of the on-board time scale based on the signals from GNS Glonass / GPS using on-board GCE.	On-board control complexes for future rocket and space equipment.
Intellectualization of information processing and decision-making on control levels of automatic SC control systems.	On-board control complexes for future SC, hardware-software complexes of MCC.
Streamlined spacecraft control and measurement technologies.	Ground-based control complexes, boosters, complexes of measurement, information collecting and processing facilities.
Batch telemetry, TMD compression.	Future onboard relay systems, onboard CMS, future GCMS, CMS, CSC.
Automated trajectory measurements by telemetry signals using the GCMS.	Future NPRS. On-board control complexes for rocket and space equipment.
Using existing low-altitude satellite space communications systems (“Inmarsat”, “Globalstar”, “Orbcom”, “O3b” and others.) and VHF stations for data exchange with rocket and space equipment.	On-board and ground-based control complexes for small SC.
The use of mobile command and measuring facilities to the increase the coverage and control and management efficiency.	Future mobile measuring and command stations.
Application of navigational pseudolites, located on the Earth’s surface to improve the accuracy and efficiency of the spacecraft control in GSO and HEO using GNS GLONASS / GPS.	GLONASS, On-board control complexes for future SC.
Creating a local radio navigation field for navigational satellites in high orbits	GLONASS, On-board control complexes for future SC.
Using the very long baseline interferometry for NBO of interplanetary spacecraft.	Ground-based control complex for ISC.
The use of network technologies of information exchange.	Service communication and data transmission system, the GCC and the SCU of future satellites.

entry into the zone of the immediate radio visibility, including using relay channels, i.e. using the asynchronous mode of SC control and data transfer (Fig. 2).

Analysis of the problems of space communication has led to the conclusion about the need to develop fundamentally new protocols [5]. Interplanetary networking protocols are called Bundle protocols. The biggest difference between the Bundle protocols and TCP/IP is that the transmitted information packets are not lost if they fail to reach the destination; they are accumulated and stored in special nodes until it is possible to resume the transmission.

DeepSpaceNetwork, developed by NASA (USA), which is used to communicate with the spacecraft beyond the Earth, already supports Bundle protocols. The International Space Station also has a number of nodes to support these protocols and is in fact already a part of the interplanetary Internet.

Two Martian satellites, MarsReconnaissanceOrbiter and MarsOdyssey, support a prototype version of the software needed to build such networks. The two Mars rover vehicles, Opportunity and Curiosity, also use these protocols.

Practical implementation of networking information exchange methods of spacecraft control becomes a feasible task, especially for the spacecraft that will be controlled through relay satellites. We propose to start working on this task after 2020.

5 Integration of data transmission channels

Challenges in the aforementioned specific areas encourage setting high level tasks as well: if the data is transferred through network protocols in packet data exchange mode, what does prevent the unification of individual radio channels (CPI, TMD, MCNP, TI) into a single channel?

Therefore, one of the promising development directions of GBACC SC SSPM, considering the need to ensure the sufficient promptness of spacecraft control, consists in a significant increase in the data rate of all communication channels, including CIS channels. However, increasing the volume of transmitted information makes it necessary to expand the radio bandwidth, which, as a consequence, leads to a deterioration in noise resistance [1]. A possible solution is implementing the batch processing and routing of data streams mentioned above. Table 2 contains generalized suggestions for the implementation of the primary and interrelated advanced spacecraft control and information exchange technologies.

Conclusion

The analysis of SC control technologies has shown that in the development of GBACC SC SSPM in 2015-2016 the greatest efforts should be directed to the modernization of existing facilities, introduction of new facilities, implementation of the existing SC control, data transmission and processing technologies.

As a result of implementation of these technologies an efficient GBACC SC SSPM should be created, which should utilize modern standardized control and measurement facilities and meet world-class standards.

References

1. Kukushkin S.S., Rudakov V.B., Makarov M.I. Analiz problem sozdaniyaperspektivnykhtekhnologiyizmereniyiupravleniyakosmicheskimisredstvami [A problem analysis of development of the perspective measurements and control technologiesof spacecraft].*Raketno-kosmicheskaya tekhnika. Informatsionnye sistemy I tekhnologii. Nauchye trudy. V 2-kh tomakh* [Rocket and space engineering. Information systems and technologies. Proceedings in two volumes]. Vol. 1. Moscow: NII KS im. A.S. Maksimova, 2012, pp. 86-108. (in Russian)

2. Limanskaya T.V., Sergeev A.S. Odnopunktnoe upravlenie gruppirovkoy malorazmernykh KA [One-station control of the small-sized spacecraft constellation] *Uspekhi sovremennoy radioelektroniki* [Modern radioelectronics achievements]. Moscow: Radiotekhnika, 2013, №1, pp. 78-82. (in Russian)

3. *European data relay system (EDRS*). Available at: http://www.esa.int/spaceinimages/2014/06/european_data_relay_system_EDRS. (in Russian)

4.*Nizkoorbital'naya kosmicheskaya sistema personal'noys putnikovoy svyazi i peredachi dannykh* [A low-orbit space system for personal satellite communication and data transmission] Pod red. General'nogo konstruktora mnogofunktsional'noy kosmicheskoy sistemy personal'noy sputnikovoy svyazi I peredachi dannykh, prezidenta OAO "Sputnikovaya sistema "Gonets"A.I. Gal'kevicha [Edited by A.I. Gal'kevich, designer general of the multifunctional space system of the personal satellite communication and data transmission, president of "GONETS Satellite Company public corporation"]. Tambov: OOO "Izdatel'stvo Yulis", 2011, 169 p. (in Russian)

5. *Kosmicheskiy mezhplanetnyy internet* [Space interplanetary Internet]. Available at: http://www.rubroad.ru/ magazine/hardware/3389-google-pridumala-kosmicheskij-mezhplanetnyj-internet. (in Russian)