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Features of RadioAstron Mission Control

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Abstract—Support means of the *Spektr-R* spacecraft flight and features of the Mission Control Center operation and spacecraft control are considered. Software for scheduling and preparing sessions of controlling and simulating for the spacecraft operation are considered. The problems of ballistic navigation support of the spacecraft flight are presented. Ground spacecraft control segment and software for analyzing and imaging telemetric information are considered.

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INTRODUCTION

The operation of the RadioAstron space observatory is based on the implementation of the method of Very Long Baseline Interferometry (VLBI) using the space radio telescope created at Lavochkin Research and Production Association connected with the Earth by a high-data-rate radio channel. The structure of space–ground radio interferometer includes the Mission Control Center of the *Spektr-R* spacecraft flight (MCC-SR based on MCC of Lavochkin Association), the Science Experiment Scheduling Center (SESC based on Astro Space Center of Lebedev Physical Institute, ASC LPI), Science Data Processing Centers in ASC LPI and Space Research Institute RAS (IKI), Ballistic Center (BC based on Keldysh Institute of Applied Mathematics, KIAM), network of ground stations of Ground Control Segment, GCS (Kobalt-R using the TNA-1500 antenna (Special Research Bureau of Moscow Energy Institute, SRB MEI) in Medvezhyi Ozera near Moscow and Klen-D using the largest in Russia antenna system P-2500 near Ussuriysk), network of Ground Tracking Stations (GTS) in Pushchino based on the RT-22 antenna (ASC LPI) and the Green Bank observatory (USA), ground radio telescopes, interested research centers, and individual researchers.

Due to the high performance demonstrated by the created scientific instrument, the ground-space interferometer, currently, in the project, in addition to the Russian radio telescope in Kalyazin, the numerous foreign radio telescopes, including the largest radio telescopes in the world, are included. The need for the early long-term scheduling of its participation is an important feature of the RadioAstron mission.

Organizing elements of the mission are MCC-SR providing scheduling the spacecraft and GCS operation, as well as SESC providing scientific program scheduling, operation of ground radio telescopes and GTS. The general control is the Main Operational Control Group (MOCG) headed by the Lavochkin Association and uniting together specialists from enterprises of scientific and technical cooperation, including the developers of onboard spacecraft systems.

ORGANIZATION OF THE *SPEKTR-R* SPACECRAFT CONTROL

The feature of the operational organization of the space-ground radio interferometer and MOCG services is the need for synchronous interaction of a large number of different elements of the mission, some of which (ground radio telescopes, control stations, etc.) are actively used in other programs.

Experience in spacecraft operation for scientific investigation shows that the main criteria for the effectiveness of scientific programs are as follows: the amount of time for scientific research in a defined calendar period and the efficiency and reliability of the MCC staff at the urgent change of the observation program or operation modes of scientific equipment [2]. These parameters are achieved by the choice of an optimal control scheme, the construction of appropriate scheduling technology, the implementation of the program for scientific observations and communication sessions, the development of hardware and software support, coordinated technologies of communication sessions and scientific observations, and the optimal construction of a ground control complex (GCC).

Spacecraft control in flight is performed by specialists at the Lavochkin Association who participate at all stages of the project from designing systems to spacecraft ground tests. During the flight control of the *Spektr-R* spacecraft, MOCG solves the following main problems: organizing the coordination of interaction of all elements of the ground segment, schedul-

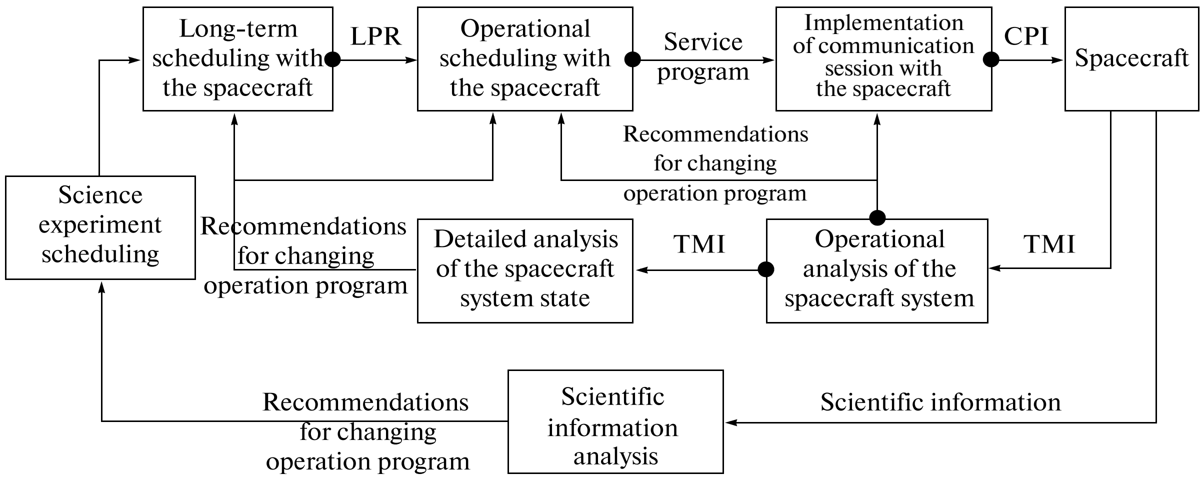

Fig. 1.

ing the spacecraft control operation in order to perform scientific observations, organizing and implementing communication sessions with the spacecraft, an analysis of operation of the onboard spacecraft system, MCC and other elements of the ground segment, ballistic and navigation flight support, and receiving scientific information from the spacecraft by ground tracking stations and transferring it to the interested organizations for further processing.

The control of the *Spektr-R* spacecraft is implemented by the closed scheme conventionally shown in Fig. 1.

The technology of the *Spektr-R* spacecraft control takes into account the following requirements characteristic for this mission: using network structures in the ground control segment of the spacecraft, means of flight scheduling and controlling united by a common network; integrated project scheduling, when the operational result of the scheduling program for the previous stage is used to schedule the next stage of the program (in the pre-approved forms); using the common typical constructions at all stages of scheduling as basic elements (typical session program, units, typical arrays of spacecraft control systems); the automation of the process for the technological cycle of the spacecraft control (forming long-term program of operations with the spacecraft, forming command-program information (CPI) and scheduling control session, process of the session implementation); providing automatic receiving telemetry (TM) streams, processing and controlling all TM parameters and conducting an automated online analysis of the TM information in MCC-L; the automation of the analysis of the state of onboard systems and the spacecraft as a whole according the results of secondary processing the TM data up to the level of NORM/NON-NORM in order to detect promptly at an early stage the dangerous trends in the operation of the onboard systems and to form recommendations to remove emergency situations arising on the spacecraft; application of mathematical simulation, means of data processing and visual imaging the simulation results in the problems of testing the programs of the spacecraft control and the problems of an analysis of system functioning using the TM data to improve the reliability of control; a possibility to adapt program-algorithm support (PAS) of the spacecraft control in flight to the changing conditions for operation of the scientific equipment and service systems; using when spacecraft controlling the working documentation and hardware and software for scheduling, preparation and implementation of the communication sessions processed when performing ground complex spacecraft tests.

The main stages of the technology cycle of the mission control are: scheduling, implementation, and post-session data processing. Scheduling the mission operation has a three-level structure. Long-term scientific scheduling (for the period up to one year) is the first, top level. It includes collecting applications for scientific experiment implementation, evaluating their realizability, compiling a list of priority sources and compiling the research program, determining the compromise sequence of operations with the spacecraft to implement the program of scientific observations in view of all interested sides and all factors affecting the program implementation (ballistic restrictions, restrictions in the operation of the spacecraft systems and ground means). At this stage, an estimate of the realizability of the program of scientific observations is performed. Medium-term (one month) scheduling details the program of the spacecraft operation, confirms operating the GCC means and a network of ground radio telescopes, specifies the observation times of investigated sources and determines times of the session for laser ranging, regions for SRT and the Plazma-F complex operations, times of control sessions in view of zones of visibility and distance taking into account functional restrictions on ground and onboard means, possibilities of pointing to the ground tracking stations with the narrow-beam antenna, providing energy and thermal balance, etc. Operational scheduling (for one day) includes testing CPI and the program of checking for the prsence of errors in spacecraft operation on the imitating and modeling bench for compliance with the given program during the control session.

Specially developed software is used for the schedule that is intended to form the code commands for the spacecraft control, compile arrays of flight tasks (FT), edit control commands and FT modes, compile communication sessions, and to check applications and communication session for the temporal and structural CPI restrictions. The implementation of these problems in automatic and semi-automatic modes allowed us to exclude errors in program formation, increase the efficiency of solving the scheduling problems and control reliability, and to reduce the total time of preparation of the control session. The complex of scheduling programs is constructed by the modular principle and includes the editor of the programming session, the editor of FT compiling, the editor of code commands, the editor of control commands with the parameters, the editor of arrays of digital information, the generator of CPI arrays, and the module of the application formed for spacecraft operations. Each editor has an intuitive interface and powerful editing means controlled for the correctness of the input information and protection against errors introduced by the operator.

To check the programs for the session and for spacecraft operation in the autonomous mode, we use the imitating and modeling bench on which we perform the integrated (from session to session) mathematical simulating of the spacecraft operation, the result of which is protocol for simulation and the spacecraft TM information. If necessary, for physical simulation, we use a complex bench made by the developer of the Onboard Control Complex (OCC), Moscow Experimental Design Bureau Mars. When processing the protocol of simulation, the verification is performed in the automatic mode. To illustrate the simulation results, the time diagram of the flight output in the text and graphic view. This scheme of the scheduling organization allows us to use the spacecraft resources the most efficiently.

The implementation of the communication session includes transmitting to the spacecraft the command and program information, as well as the operational control and an analysis of the technical state of the spacecraft system. To ensure the high reliability of control and transmission of radio commands to the spacecraft the special control means, means of verifying and confirming the command transmission have been developed. Methods of implementing communication session support for the transmission of radio commands in automatic and manual mode allow us to visually image receipts of transmitted commands and digital data arrays. Methods of TM data analysis allow us to perform the complex operational control of the spacecraft state using several generalized display forms. When implementing the planned operational program, all service information on the spacecraft state is promptly processed and controlled in MCC-SR; the access of SESC is ensured in the online mode.

Information exchange is performed using a specially organized project network for data transmission, as well as public communication channels. Access to the common information space of the project for each participant is determined according to the agreed-upon regulations. Post-session data processing consists of the detailed analysis of the technical state of the spacecraft onboard systems and the refinement of the parameters of the spacecraft mathematical model according the results of processing the protocol of the session implementation. A detailed analysis is also carried out using specially designed software.

Developed methods of controlling and scheduling certainly will be reflected in future projects of Lavochkin Association, such as astrophysical spacecraft of the *Spektr* series, meteorological spacecraft of *Elektro-L* and *Arktika* series designed on the basis of the Navigator space platform.

BALLISTIC AND NAVIGATION FLIGHT SUPPORT

When preparing to control of the *Spektr-R* spacecraft flight, the concept of the maximum automation of solving the problems of Ballistic and Navigation Support (BNS) was accepted. This approach allows one to reduce the possibility of errors permitted due to the human factor and increase the productivity of the BNS duty operators.

Ballistic and navigation support of the *Spektr-R* spacecraft flight solves the following problems: the determination of the spacecraft motion parameters (in order to ensure the spacecraft control and connect scientific experiments); the calculation of target indications for ground control stations and ground tracking stations; determination of orbit parts, where it is possible to perform laser ranging in view of functional restriction of laser ranging stations; the calculation of the spacecraft orientation parameters (in view of functional restrictions on the spacecraft orientation) to provide scientific observations, to perform laser ranging and to provide the spacecraft thermal mode; checking the possibility of the implementation by the spacecraft of the scientific observational program prepared by ASC; the calculation of reference ballistic information to schedule operations with the spacecraft and the spacecraft control (the prediction of the spacecraft orbit parameters, calculation of shadow intervals, radio visibility zones, etc.); and the preparation of the ballistic data to support operations of the onboard control complex for subsequent transfer to

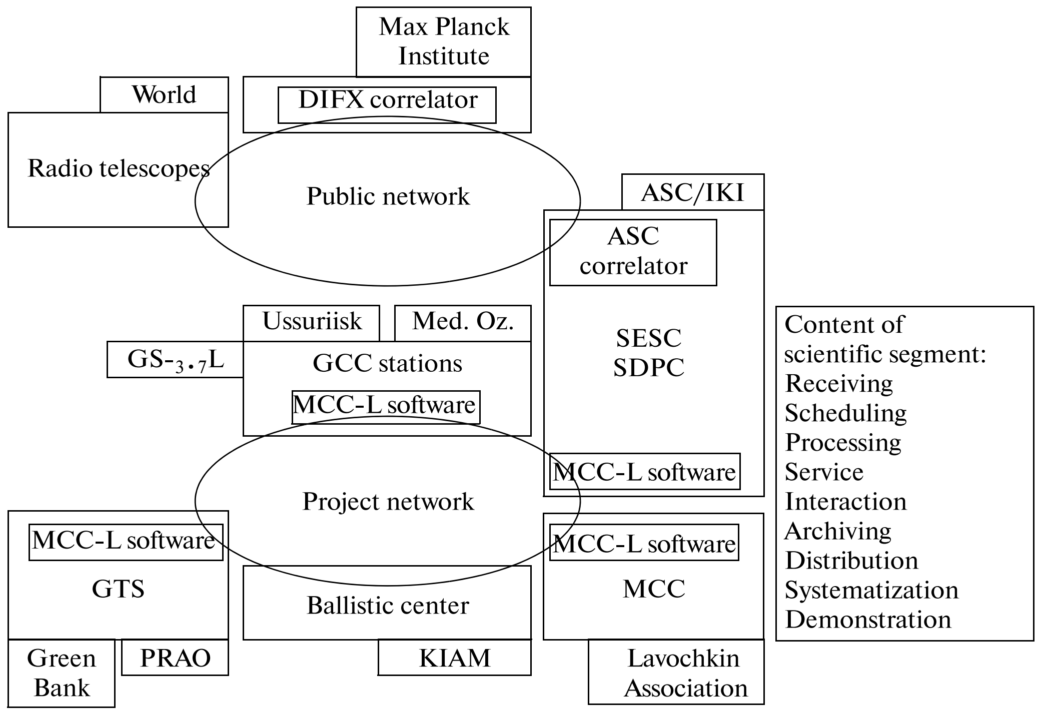

Fig. 2.

the spacecraft in an array of command and program information.

FLIGHT INFORMATION SUPPORT

Connecting technical elements of the ground segment are the transfer data network, specially designed and public, as well as technologies related with them. In this case, elements of unified software of MCC-L, which carry system-creating properties (Fig. 2), are at the intersection of the project network and objects of the ground segment.

The technological decision-making center, as well as a place of the acquisition and processing of the telemetry data from the spacecraft is the Mission Control Center *Spektr-R* (MCC-SR).

The scheme shown in Fig. 2 does not consider special cases of connecting remote researchers or test technologies of joint transfer via ground communication channels of scientific and technological information without sharing (the version of using the station in the United States). GTS stations can also have independent access to the public network to receive information about scheduling, as well as to receive scientific information in SESC/SDPC from the spacecraft. The gateway between the public and project network is provided with the means directly connected to a major hub of traffic exchange MSK-IX. The favorable geographical location of SDPC and SESC promotes to this.

Flexible use of special and public networks enables the presence of basic differentiation mechanisms for access and data protection, as well as ensures the mechanisms of the necessary quality of network services (QoS). The project has no direct transparent IP routing between networks for all users, and this scheme (access to project network resources from a public network) is used as a reserve to perform emergency operations or to use functions for IP telephony and video conferencing by MCC-L. The standard scheme of the information exchange is an excess at the application level to the special SDPC servers for the MCC applications, as well as unidirectional exchange with typified forms.

Using cloud technologies in the project network allows us to organize an access to the information by expanding the boundaries of the cloud according to common infrastructure rules without modifications of the software and agreement of any individual interaction protocols between organizations. The presence of this environment also improves the efficiency of the use in the framework of ground segment of systems for IP telephony with the numbering plan of MCC-L.

Scientific information obtained from the spacecraft by ground tracking stations during the observation sessions has autonomous timing and does not require the mode of real-time scale when transferring in SESC for correlation processing. In this case, the technological information, which is involved in making decisions for the spacecraft control, i.e., informationally forms the so-called control circuit, should be transferred and available for automated processing and an analysis as soon as possible in quasi-real time. Software elements of MCC-L on GTS and GCC stations are special user terminations that, as a rule, automatically provide the execution by the station of the standard service functions.

The Medvezhyi Ozera GCC station includes the Kobalt-R station type of SRB MEI developed specifically for the *Spektr-R* project and initially has the necessary MCC software components of UNIX system in its composition. At the Ussuriisk station, the typical station of the Klen family is used that was designed by OAO RSS (Russian Space Systems), which implements its own, less technological, set of exchange functions and MCC software that operates on a separate additional system.

When choosing a unified exchange protocol, we perform an analysis of the existing national solutions (including implemented in the same Klen systems, which is the most accepted), as well as foreign protocols of the CCSDS SLE families, for which Lavochkin Association has its own certified ESA implementation.

To ensure the exchange of information with the ground tracking stations, the high-tech solutions are implemented in it using in the automatic mode, the collection of information and service capabilities of GTS stations and including methods of receiving, decoding, and sharing streams of technological and scientific information from the radio line of high-data-rate radio complex (HDRRC); methods of filtering and routing traffic and organizing necessary tunnel interfaces and data encryption; methods for systemizing and local archiving the TM session data; subsystems for transferring a data stream using MCC IP protocols; and systems that ensure service functions, including the organization of running and diagnostics of abnormal situations, states, and statistics for the session; and methods of remote access to the functions using web interface.

In the project, the ballistic center is used according to traditional technology. It is assumed that all ballistic estimates and calculations needed to support the efficiency of the control circuit are carried out by the service of ballistic and navigation support located at MCC. Therefore, the data exchange with BC is performed by file-oriented forms of exchange with lower efficiency that carry out any software components from MCC, and BC is not provided. These forms are processed and imaged in the corresponding database record at MCC-SR.

An important point of the MCC software placement is SDPC IKI/SESC ASC. In the comfort mode, the server for applications specially installed in the territory of scientific organizations enables one to analyze and estimate the state of the target equipment. The server is included in the computing cloud of MCC-SR and has an access to all necessary information. Using the server is performed with the application of the XDMCP protocol from working places of the research group of ASC LPI and the group of the Plasma-F experiment in IKI RAS. On the server, a part of the standard MCC software is operated, which is associated with the presentation of the processing results of TM information (special software, SS-O). The SS-O components (the Tsytrus system) are capable to image the form in a graphic view on the real state of the instrument with lighting parameters, which exceed some given range.

For working specialists of the analysis group at MCC-SR, the program complex SS-O is fully implemented; the total number of available in MCC telemetry forms is about 500, in which the results of processing more than 3000 TM parameters from the spacecraft are used. Some of the forms represent the so-called “secondary parameters,” also known as “generalized judgments,” a powerful tool for integrated express estimates of the state of the spacecraft.

In this case, the process of sharing and processing of the TM parameters takes place online on special independent servers. TM information-processing servers also automatically prepare special slices of information ready for prompt transfer to third-party organizations, in particular to the complex bench of the developer of onboard control complex (OCC), MEDB Mars.

Servers for MCC-SR applications also have the possibility to run other set of software that performs the functions of scheduling and implementing communication sessions, as well as many service functions of control and diagnostics, acquisition and imaging of the statistical information implemented with web technologies.

A separate group of software is used visual representation. This software includes the so-called “main form” and means of 3D representation at all stages of spacecraft flight from the launching phase. These systems are performed in the same project manner and admit different versions of using from presentation assemblies and hall sets to complex reductions with automatic change of representation forms. Programs are not entertaining animation; they operate a large set of the data obtained online from the TM information processing servers, as well as visually represent certain sets in the automatic mode that accompany them via a three-dimensional scene of the spacecraft in the light of the Sun.

CONCLUSIONS

The operation of the RadioAstron ground-space system continues successfully. From November 2012 to December 2013, 257 control sessions, 885 observation sessions, and 28 sessions of the SRT adjustment were performed. The implementation of the planned program of the spacecraft control during this period was 98.9% [3].The system is complemented with new elements; the ground tracking station in Green Bank was introduced and already nominally used. The preparation of the station in Pretoria for operation has begun. There is an accumulation of statistical data on the operation of onboard spacecraft systems in the sessions of scientific observations that allows us to expand the boundaries in using the spacecraft for scientific research.

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