Precise stabilization in space—Spektr-R onboard control system (RadioAstron)

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Abstract. The report presents the outline of the Spektr-R onboard control system design
(RadioAstron) and describes the method for attitude determination and for achievement of the
pointing precision of the radio telescope during observing sessions. The required orientation
accuracy is provided by a complex of information from an otoscopic instrument and astro
sensors with filtering measurement noise. The achieved stabilization accuracy during the
operation of the spacecraft is presented.

1. Introduction
The launch of the Spektr-R satellite into a highly elliptical orbit on 18 July 2011 became the
beginning of a new era in Russian and international astrophysics research. Spektr-R contained
a radio telescope equipped with a 10-meter-diameter antenna (figure 1). This radio telescope
and several ground-based telescopes formed a radio interferometer having a very long baseline
(over 300 000 km), thereby the angular resolution of the Spektr-R telescope was 30 times better

Figure 1. Spacecraft Spektr-R.
than the angular resolution of its predecessors. The telescope was used by Russian and foreign astrophysicists over seven years.

Spektr-R and its satellite bus were created by Lavochkin Scientific and Production Association (shortly Lavochkin Association; Khimki, Moscow region, Russia) in cooperation with other enterprises. In particular, the satellite onboard control system (OCS) was designed, produced and maintained during its operation by Moscow Experimental Design Bureau “Mars” (shortly MEDB “Mars”; Moscow, Russia) [1]. The major challenges related to designing the Spektr-R OCS were to achieve high accuracy of attitude determination for pointing the radio telescope and to reach the required precision of stabilization during observing sessions. The requirements were as follows: actual attitude estimation error—no more than ±18 arcsec; stabilization angular drifts—no more than ±2.5 arcsec with respect to the mean value in the interval of 120 sec; errors during programmed angular velocity stabilization—no more than ±5 · 10⁻⁴ deg/sec along the x-axis in the fixed coordinate system and ±2 · 10⁻⁴ deg/sec along the y- and z-axes.

2. Spektr-R onboard control system design concept

The Spektr-R onboard control system was based on unique technological groundwork equal to the global development trends and laid by MEDB “Mars” at the beginning of 2000s. In the accordance with the Lavochkin Association requirements, the Spektr-R OCS was designed as a general model for the Navigator satellite bus. It was planned that the Navigator satellite bus would be used for other Spektr satellites (telescopes with various wavelength ranges) and for Elektro-L and Arktika-M series of satellites [2].

The Spektr-R OCS depicted on figure 2 was a redundant module system. It consisted of an onboard central computer, a control and switching unit and digital interfaces which formed an onboard computer network allowing to upgrade the onboard control system and, if necessary, to use different measuring equipment and execution devices [3]. In figure 2, OCC—onboard central computer (MEDB “Mars”); CSU—control and switching unit (MEDB “Mars”); PAU3–PAU7—power automation units (MEDB “Mars”); SPS1—sun position sensor (MEDB “Mars”); ST1—star tracker (MEDB “Mars”); G—gyroscope (Kuznetsov Research Institute of Applied Mechanics, Moscow, Russia); RWS—reaction wheel system (Research Institute of Control Units, Saint Petersburg); SDB—serial data bus (MIL-STD-1553); C—controller; TE—terminal equipment. The systems related to the OCS were as follows: OCMS—onboard command and measuring system (telecommand system); TMS—telemetry system; PL—payload (including the radio telescope); ECS—electrostatic control system; PT—pyrotechnics; TCS—thermal control system; PS—propulsion system; BACS—beam antenna control system; PSS—power supply system; SPCS—solar panel control system; SPOS—solar panel orientation system.

In order to ensure OCS reliable operation, together with the use of quality electronic components, additional methods of radiation protection, ESD hardening and assurance of EMC, different types of hardware redundancy were provided, viz. dual, triple and quadruple modular redundancy [3–5]. The OCS structure could be reconfigured either automatically (control processes onboard quickly and efficiently evaluated the situation) or manually by transmitting commands from the ground control station.

The approaches to the OCS redundancy described above compensated for the first failure of any equipment (according to the OCS technical specification) and extended the life span of the onboard control system and the satellite as a whole when the second (or even the third) failure occurred. E.g., OCC had quadruple modular redundancy (four identical computing parts) and therefore could work if three of these parts failed. Similarly, a CSU core was designed with four computing parts. Triple redundancy of the control boards was built in the power automation units. The gyroscope included four identical measuring channels forming a pyramid, and this structure automatically compensated for the first failure of one of the channels. In order to detect the second failure of the measuring channels, the OCS software activated star control by
Figure 2. The detailed-functioning diagram of the onboard control system in combination with the related onboard systems.

the gyroscope. The second failure of the measuring channels, i.e. the failure of the gyroscope, was compensated by star tracker data for the satellite attitude control (the star tracker attitude control mode). For star tracking, three identical star trackers were used, and OCS was functional even if only one star tracker worked. The solar attitude was provided by two SPS, as well as by inner redundancy of the SPS measuring channels. Each reaction wheel system had a duplicated electronic unit and four identical reaction wheels forming a pyramid. OCS automatically compensated for the first failure of one of the reaction wheels or the electronic channel in RWS. If there were failures of both RWS and control torques could not be created anymore, OCS would start using stabilization jet engines for the attitude control (accuracy would be lost).

For extending the life span of the onboard control system and the satellite as a whole, the OCS onboard software could be upgraded in flight. After an incident, Spektr-R operation could be recovered by changes in the OCS system logic and by new or updated algorithms sent from the ground control station to OCC (on-orbit servicing). Either OCC RPROM could be corrected or RAM patches could be introduced. Besides, the ground control station could change so-called adjustable parameters of the OCS onboard software, i.e. algorithm constants (for example, ratios of the regulators).

OCC RPROM was divided into two parts (two banks). Therefore, in flight, the software could be corrected (rewritten) in one of the banks without the interruption of control operations in the other bank. Copying the corrections to the other bank took place after testing these corrections and receiving positive results of the tests.

In order to determine Spektr-R attitude, an algorithm working with the gyroscope data was used. The algorithm represented a recurrent procedure of finding a quaternion with the step of 0.1 sec for the satellite current attitude. The algorithm allowed for current quaternion corrections based on star tracking and for gyroscope drift corrections defined by star calibration [3, 6]. The angular velocity was evaluated on the basis of the gyroscope data with the use of a second order Luenberger observer [5–7]. If the gyroscope failed, a redundant control mode was activated, viz. star tracker attitude control. In this mode the frequency of 0.5 Hz was used, as well
as star pattern recognition algorithms and star orientation calculation using the onboard star catalogue (2500 5.5–6-magnitude stars).

The satellite attitude control was carried out by the Spektr-R attitude control system, which was an OCS subsystem. The algorithms of the Spektr-R attitude control system were performed by the onboard central computer. When the radio telescope was on, the reaction wheels (reaction wheels “Koler-E”) worked as execution devices. The required precision of angular stabilization during the radio telescope performance was achieved by implementing integral components into the attitude control laws. The integral components eliminated static errors produced by external disturbance torques, including those of the reaction wheels.

The developed algorithms and the OCS software were tested multiple times with MEDB “Mars” test equipment. The final report on the Spektr-R onboard control system confirmed that the system meets the requirements for accuracy of attitude control and for the precision of stabilization during observing sessions.

3. Conclusion
The telemetry data received during the flight tests and further Spektr-R operation showed the following results [8]: angular oscillation amplitude was no more than $\pm 1.4$ arcsec; angular velocity oscillation amplitude was no more than $\pm 0.00012$ deg/sec; gyroscope residual drifts were no more than 0.005 deg/h; radio telescope pointing precision was about 0.7 arcsec.

![Figure 3. Angular deviations (deg).](image-url)

![Figure 4. Angular velocity (deg/sec).](image-url)
The graphs in figure 3 and 4 show changes of Spektr-R angular deviations and angular velocity when the radio telescope was on. The graphs are based on telemetry data received during the satellite operation.

The experience of the Spektr-R operation over 7 years demonstrated the consistency of the approach chosen by MEDB “Mars” for the OCS design in order to achieve the required precision of stabilization to assure the high pointing precision of the radio telescope. The confirmed pointing precision of the radio telescope was highly appreciated by Russian astrophysicists [1, 2].

References
[1] Babakin N G 2020 About the history of the Spectrum-R complex Vestnik NPO im. S. A. Lavochkina 2 34–40
[2] Shirshakov A E, Karchaev H Z, Moisheev A A and Lokhanov I V 2019 One step ahead Vestnik NPO im. S. A. Lavochkina 2 3–18
[3] Brovkin A G et al 2010 Spacecraft Onboard Control Systems ed A S Syrov (Moscow: MAI-PRINT)
[4] Andreyev V P et al 2011 Design and testing of on-board control systems ed A S Syrov (Moscow: MAI-PRINT)
[5] Cyrillin A N, Akhmetov P N, Sologub A V and Makarov V P 2010 Methods for ensuring durability of low-orbit automatic Earth sensing spacecraft: mathematical models, computer technologies (Moscow: Mashinostroenie)
[6] Efano V V 2014 Design of automatic spacecraft for fundamental researches vol 3, ed V V Khartova and K M Pichhadze (Moscow: MAI-PRINT)
[7] Burdygov B G et al 2017 On-boarding control system Multifunctional Space platform Navigator ed S A Lemeshevskyi (Himki: Lavochkin Scientific and Production Association) pp 93–125
[8] Lisakov M M et al 2014 Operation of the Spektr-R orientation system Cosmic Research 52 399–407