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Radioastron (Spectr-R Project)—A Radio Telescope Much Larger than the Earth: Main Parameters and Prelaunch Tests

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Abstract—The Russian Academy of Sciences and the Russian Federal Space Agency are planning to launch *Radioastron* in 2011, which is a unique space observatory with a 10-meter reflector antenna. In conjunction with the largest ground-based radio telescopes and tracking stations, it forms the first system that will be able to carry out studies with a resolution millions of times greater than that of eyesight.

Keywords: space radio telescope, interferometer, angular resolution, sensitivity, atomic microwave oscillator, tests
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INTRODUCTION

The launch of the *Radioastron* space radio telescope (SRT) is scheduled for the year 2011. This radio telescope will form an Earth–space interferometer together with ground-based radio telescopes. The creation of the first space radio interferometer with a baseline that is much larger than the size of the Earth has a long and complicated history. Detailed information on the space radio observatory can be found on a special website [1] and in [2, 3].

The orbit of the *Radioastron* satellite [4] was chosen so as to evolve in a specific way under the influence of the Moon. The mean orbital period is 9.5 days (it changes between seven and ten days), the semi-major axis is 189000 km, the orbital inclination is 51 degrees. The radius of perigee is 10000–70000 km, and the radius of apogee is 310000–390000 km. The normal to the orbital plane circumscribes an ellipse on the celestial sphere over the course of three years; the major and minor axes of the ellipse are 150 and 40 degrees, respectively. Nearly 80% of the sources prove to be located close to the orbital plane at certain moments in time due to the evolution of the orbit; for these sources, images can be obtained with both high and moderate angular resolutions.

Table 1 presents the main parameters of the Earth–space interferometer. They were determined using the SRT parameters measured in ground tests and the characteristics of the 100-m ground-based radio telescope (Green Bank Observatory, NRAO, United States).

Figure 1 shows the schematic diagram of the SRT with the Navigator bus. The block-diagram of the SRT is given in Fig. 2. Figures 3–7 illustrate the general configuration of the SRT with the Navigator bus as well as the major components of the space radio telescope and some important stages of their ground tests.

Figure 8 shows the participants of the 29th International *Radioastron* Science Council Meeting at the NPO Lavochkin.

The general layout of the SRT in its covered (transportable) state is given in the paper of V.V. Khartov in this issue.

Table 1. Main parameters of the space interferometer

Main parameters of the Radioastron interferometer				
	P	L	C	K
Frequency bands [GHz]	0.320–0.328	1.636–1.692	4.804–4.860	18.372–25.132
Circ. polarization × bandwidth [MHz]	2 × 4	2 × 32	2 × 32	2 × 32
The fringe width for a baseline length of 350000 km [μs]	540	106	37	7–10
Formal 1σ sensitivity per polarization [mJy] (with GBT, for 5-min/3-hour integration)	42/7	4/0.7	4/0.7	10/1.7

TESTING THE SRT COMPONENTS

The multitask program at the experimental stage was aimed at testing the reflector, focal and equipment containers, hydrogen standards of frequency and time, the high-information radio complex (HIRC), and onboard cable system for maintaining the operation of the radio telescope together with the Navigator bus. The tests were completed in May, 2011, with positive results. The SRT construction and its components were repeatedly subjected to loads and influences arising in manufacturing, storing and transportation on Earth, during launch, and in orbital operations. Full-sized technological items were involved in static and vibration tests, radioastronomical instrumentation tests, and thermal vacuum tests.

The construction requirements were confirmed during the tests and the structure was authorized for

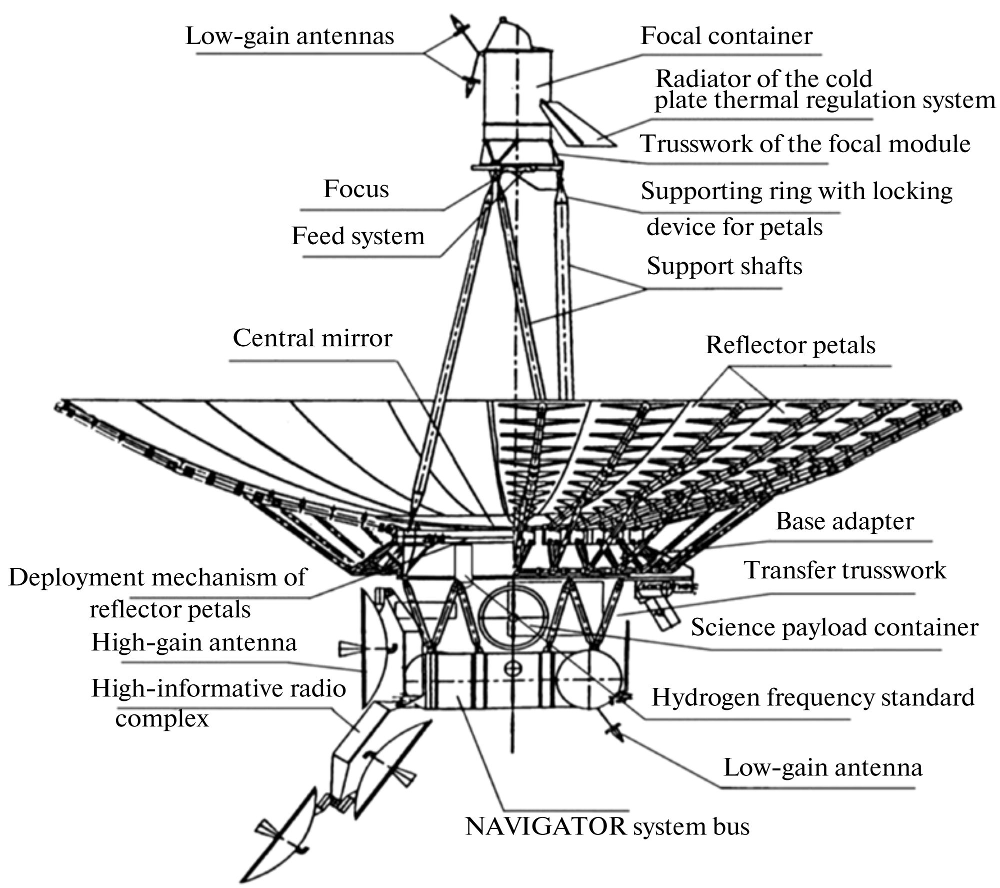


Fig. 1. Arrangement of the SRT and Navigator bus.

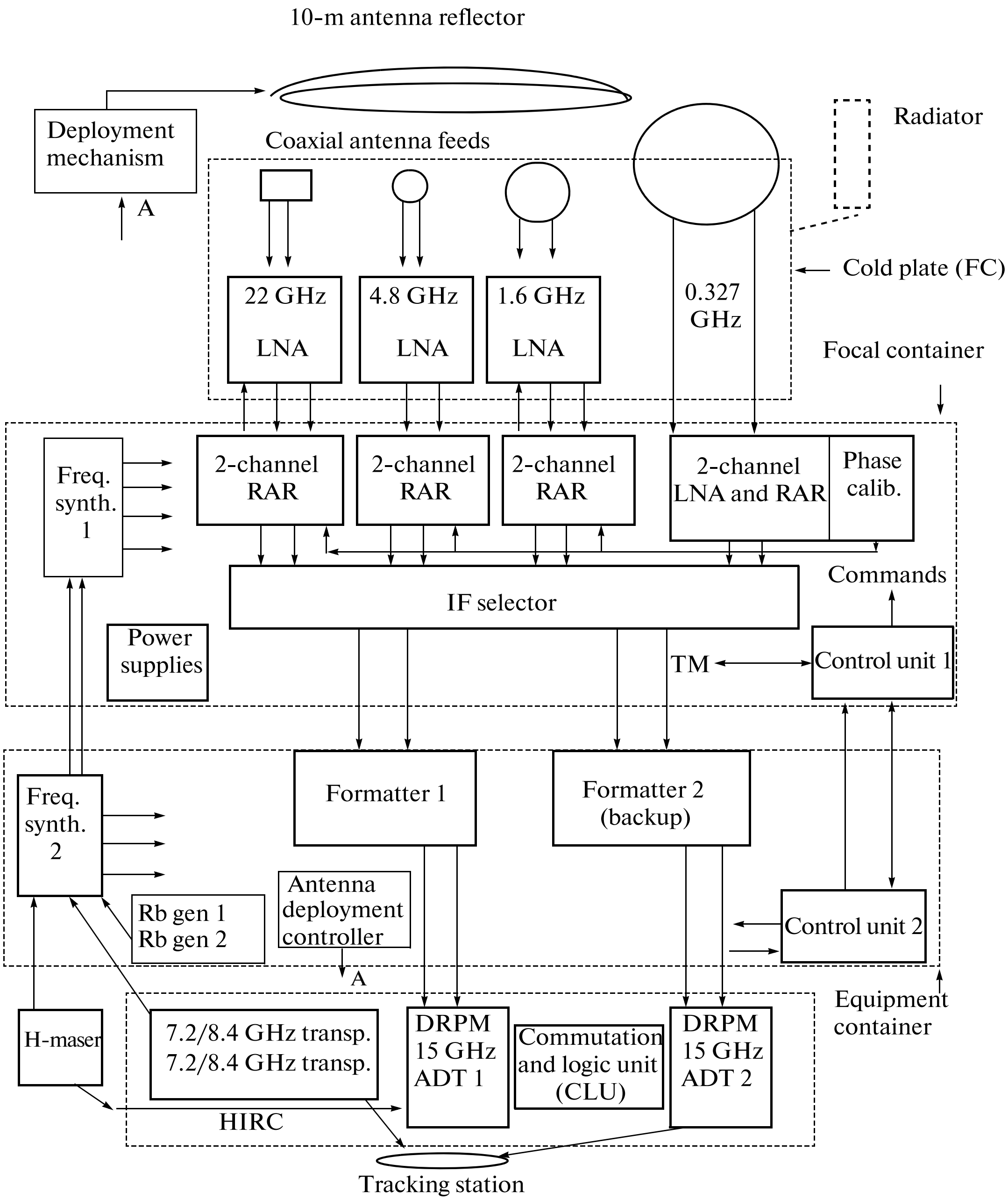


Fig. 2. The block-diagram of the SRT. LNA, low noise amplifier; FC, focal container with the feed system and LNA; RAR, radio astronomy receiver; IF, intermediate frequency; TM, telemetry information; Rb gen 1, 2; rubidium generators; H-maser, hydrogen generator (2 sets); HIRC, high-informative radio complex; 7.2/8.4 GHz transp., input-to-output (7.2 to 8.4 GHz) frequency transponder; DRPM, double phase manipulator; ADT 1, 2; Astronomical data transmitters with 15 GHz carrier frequency.

flight tests as part of the onboard scientific equipment. The major technical characteristics of the 10-m collapsible parabolic reflector of the telescope, after its unfurling, are as follows: the rms deviation of the reflecting surface from an ideal paraboloid is 0.7 mm, and the acceptable deviation of the center of the feed system from the paraboloid focus is ±1 mm. The characteristics of all systems supporting the thermal regime of the SRT were also confirmed.

THE SRT RECEIVERS

The goals of electrical and radio tests were to examine how steering signals were realized and telemetric parameters were recorded, to verify the operation of thermostats and temperature regimes of the instrumentation, and to confirm the final SRT parameters. The tests were performed in a display chamber of NPO Lavochkin (NPOL) according to regulations. A standard cable network was used in the complex. The

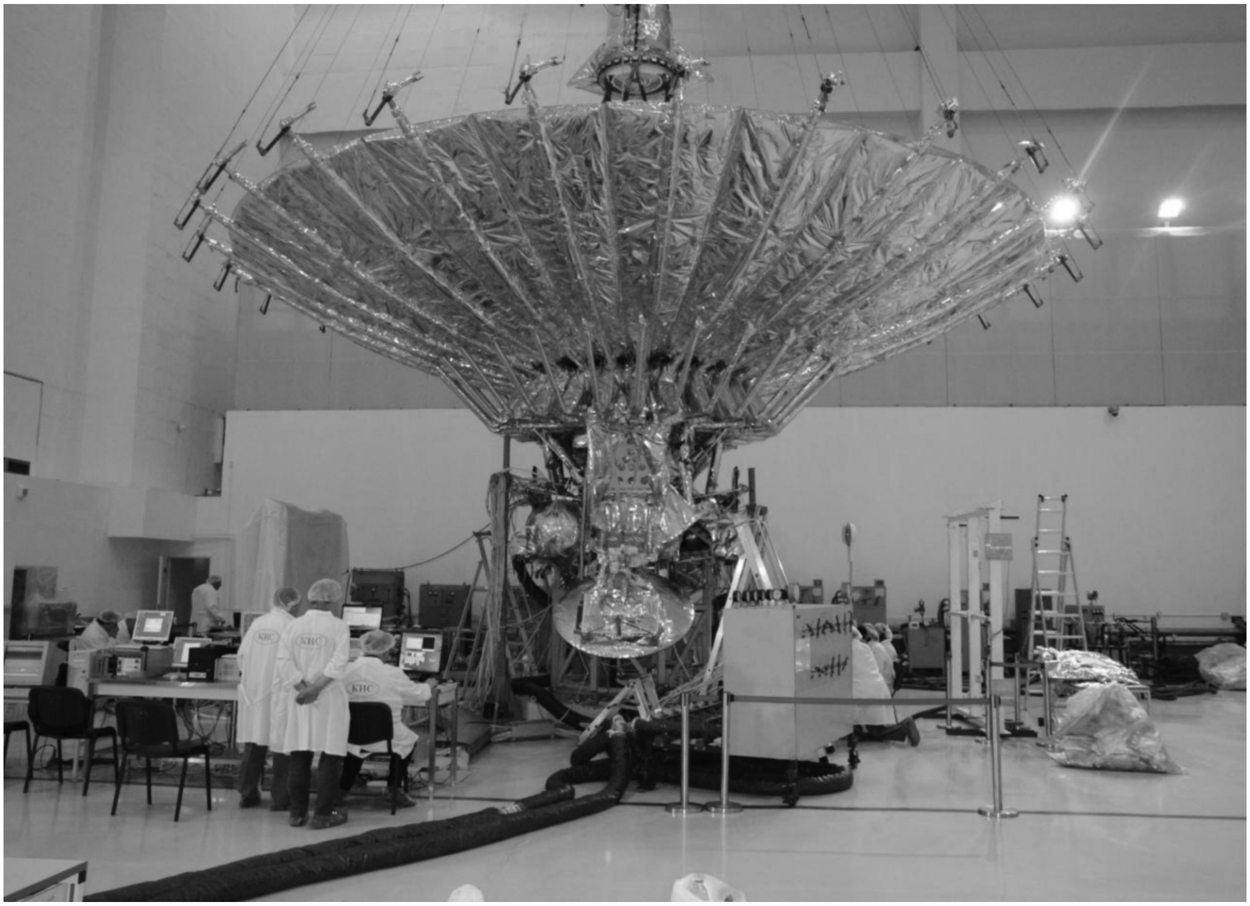


Fig. 3. Multitask tests of the SRT and the Navigator bus. The reflector is unfolded. (NPO Lavochkin, June 2011).

Fig. 4. The focal (left) and science payload (right) containers of the SRT.

Fig. 5. Hydrogen frequency standards (masers) developed for the Radioastron project at the ZAO Vremya-Ch (Nizhni Novgorod).

Fig. 6. Tests of individual carbon fiber petals of the SRT antenna (ESA, The Netherlands, Noordwijk, 1994).

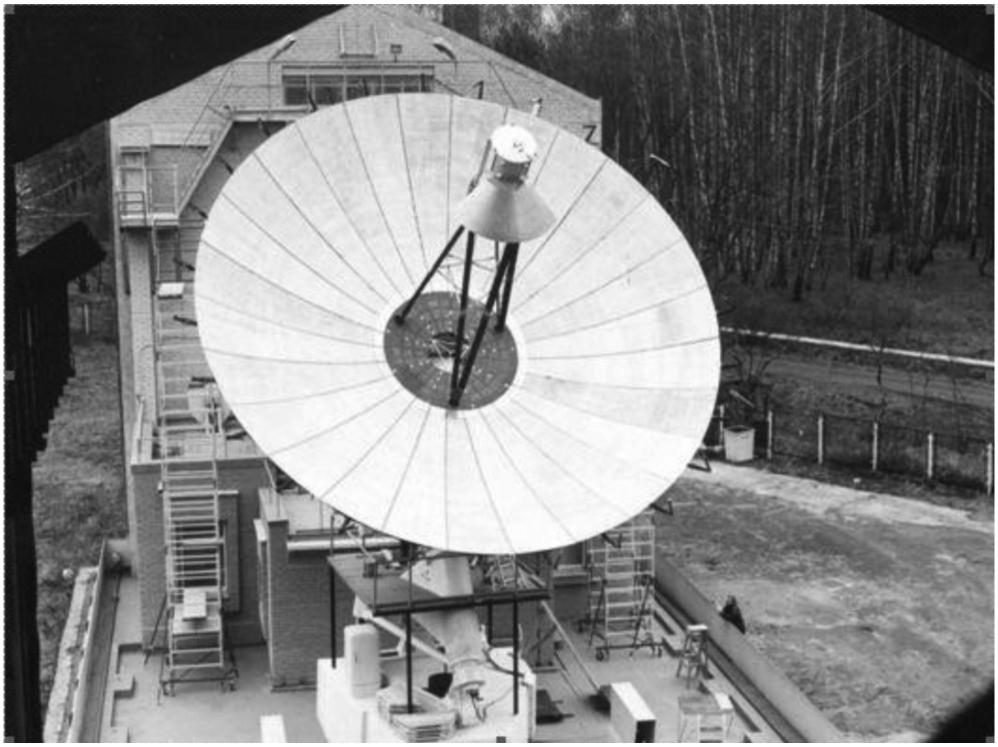


Fig. 7. Astronomical tests of the SRT using space objects (Pushchino Radio Astronomy Observatory, Astro Space Center, Lebedev Physics Institute, spring 2004).

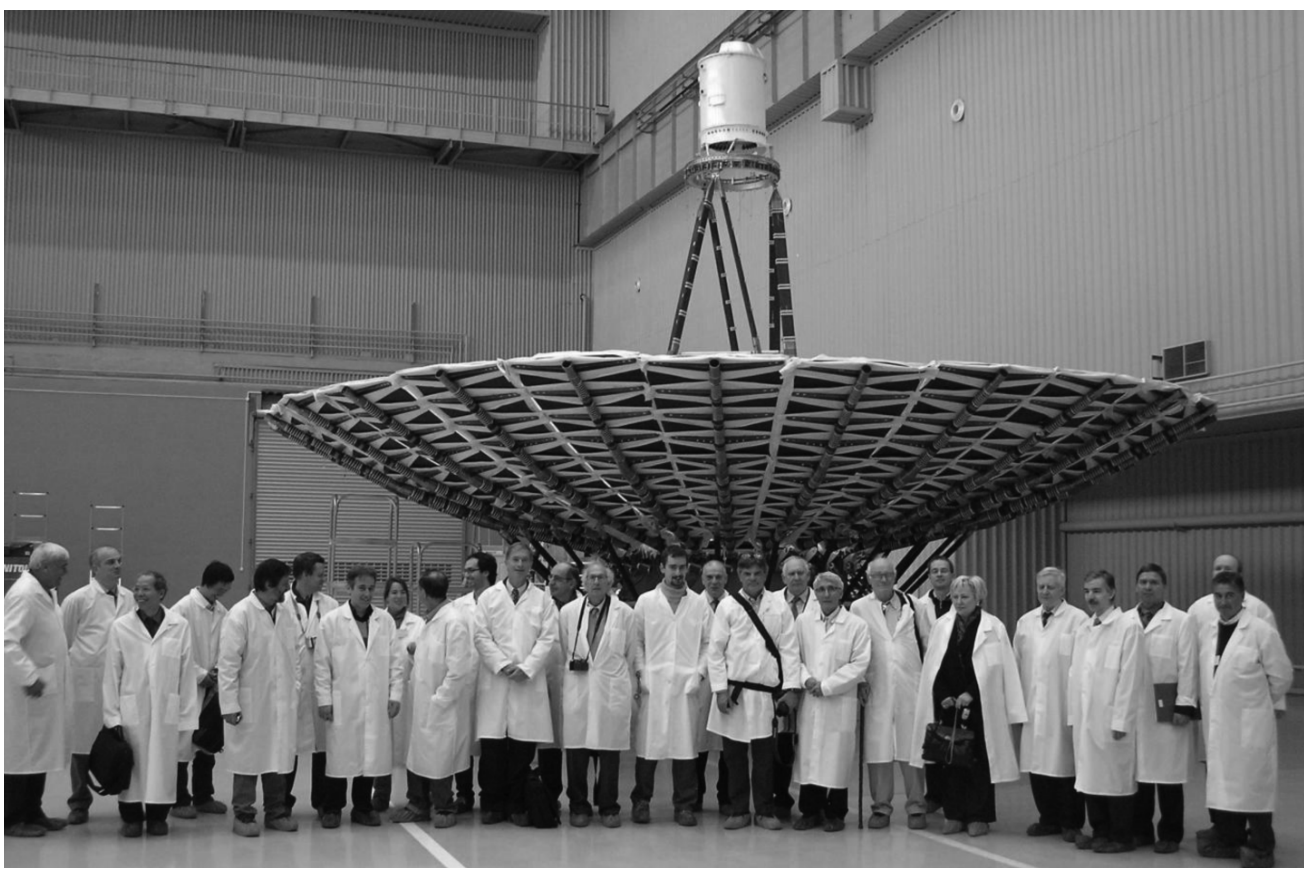


Fig. 8. The 29th International Radioastron Science Council Meeting (near the flight model of the SRT at the NPO Lavochkin, autumn 2008).

Table 2. The noise temperature of SRT channels

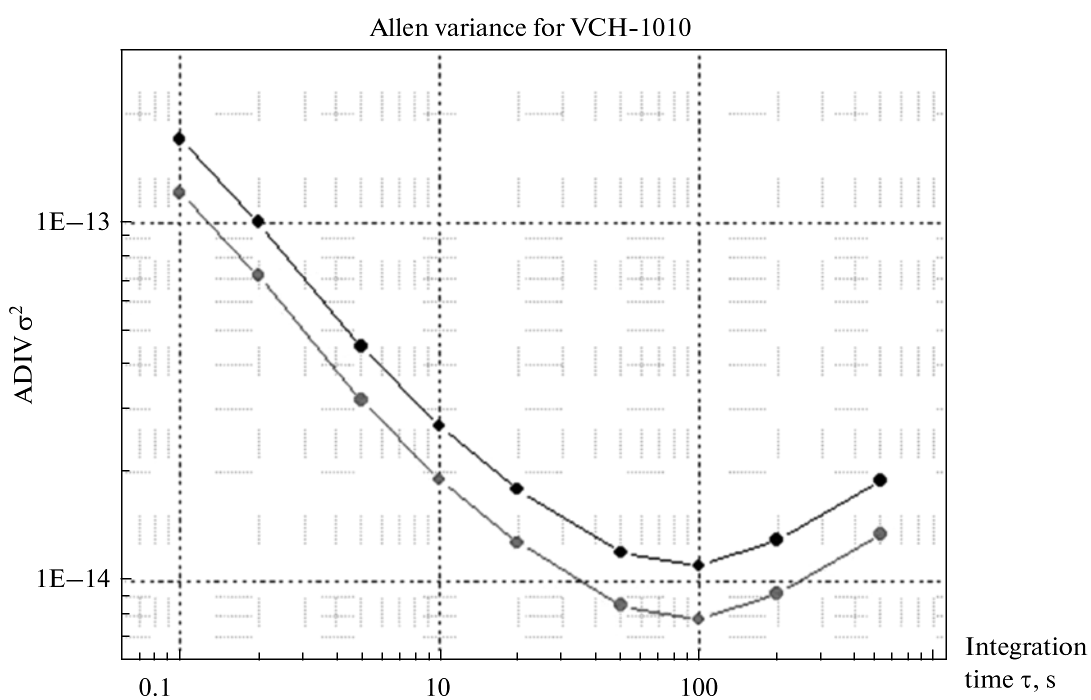
Range	92 cm	18 cm	6 cm	1.2–1.7 cm
T_{LNA}	35	15	25	40
T_{cable}	9	6	11	–
T_{feed}	54	5	22	20
T_{antenna}	6	4	5	7
T_{sky}	60	3	3	3
T_{system}	164	33	66	70

instruments were controlled using a standard system of interface conversion. A sequence of commands to steer the complex was performed according to controlling cyclograms with the first and second semipackages for the frequency generation system, formatter, and high-information radio complex (HIRC).

The telemetry data returned by detectors were registered by a standard telemetric system (TMS) to form a file with the tmi-extension. The state of the complex was monitored in the quasi-real time using the P_TMI_Extract.exe software specially developed at the Astro Space Center of the Lebedev Physics Institute (ASC LPI). The table data file was obtained from the registered telemetric tmi file using an automatic ASOVIST system specially developed for processing and visualization of the telemetry session data. The parameter visualization (e.g., for printing) was performed using the standard Excel Windows software. A solar cell simulator of the NPOL was used as a power supply. Table 2 presents the noise temperature distribution in onboard receivers and the summary noise temperature of the space telescope (in Kelvins) under on-orbit operating conditions.

THE ONBOARD HYDROGEN FREQUENCY–TIME STANDARD OF THE SRT

The *Radioastron* was the first project where a highly stable hydrogen frequency-time standard was installed on board the satellite. This standard makes it possible to improve the sensitivity of the Earth–space interferometer and to simplify the data processing. According to the requirements for development, the ZAO Vremya-Ch corporation designed, produced, and tested (in 2007) three sets of active onboard hydrogen frequency standard (OHFS) that attained the VCH-1010 index. The first set was used as a frequency standard on the ground for the prelaunch test and as a sample for the design development test; the second, for the flight; and the third, as an onboard spare in a cold standby



The measured relative function σ_2^2 of two identical devices (serial nos. 005 and 006) is shown in black. The function s_1^2 of one device ($s_2^2/\sqrt{2}$) is shown in red.

Fig. 9. Stability analysis of the frequency standard for the SRT.

mode. All the three sets were tested thoroughly according to programs for ensuring reliability and ground-based experimental data processing. The most important aspects in creating the onboard hydrogen frequency standard were:

(1) producing a reliable mechanical fastener for the storage chamber using carbon fiber materials to prevent its disintegration when it is subjected to significant loads during the launch of the spacecraft into orbit;

(2) vacuum degassing of the resonator cavity and thermostats using the space vacuum, with ground-based tests being conducted under normal climatic conditions (NCC);

(3) maintaining the characteristics achieved with ground samples of hydrogen standards.

Measurements carried out in autonomous tests at the ZAO Vremya-Ch, ASC, and NPOL confirmed the fulfillment of the technical specifications requirements.

One of the main parameters of the equipment, namely, the instability of the standard frequency, is plotted in Fig. 9. The behavior of the instability curve up to an integration time of $\tau = 100$ s corresponds to the technical specification. The specification requirements are exceeded for $\tau > 100$ s because destabilizing factors (temperature and pressure variations, etc.) cannot be compensated when testing equipment under NCC.

It is essential that the OHFS signals in orbit are controlled using a broad-band SRT–Earth channel to transmit scientific data (HIRC). The onboard and ground-based (reference) time scales are synchronized automatically provided that the digital data flow is synchronized with 1 ppS OHFS signals and a cross-correlation function for signals is produced in the ground-to-space interferometer using a strong radio source.

Multitask tests of the SRT and Navigator bus confirmed their compatibility and compliance with the technical specifications.

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