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Space–Ground Radio Interferometer RadioAstron

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Abstract—The paper considers the design, features, and characteristics of the Russian space–ground very long baseline radio interferometer (VLBRI) RadioAstron.

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INTRODUCTION

In the 20th century, the exploration of the Universe spread to all ranges of electromagnetic radiation. In addition to optical astronomy, gamma, X-ray, infrared, and radio astronomy appeared. This led to the extraordinary expansion of knowledge of the Universe up to the development of the model of the Universe as a whole and understanding of the laws of the origin and evolution of most astronomical objects. However, many of the key questions in astronomy remain unsolved and new major challenges have arisen including the possible existence of the multicomponent Universe.

The progress in astronomy is closely connected both with the ability to conduct research from space and with the advent of new technologies for developing telescopes and techniques of radiation analysis in all ranges.

The main parameters that limit research in radio astronomy are the sensitivity and angular resolution. Both of these parameters only have great prospects in space. Radio telescope sensitivity is mostly determined by the area of its antenna and receiver noise. Initially, the angular resolution was also limited by the antenna size; however, using the interferometric method, this relationship has been excluded. Thus, the resolution came to be determined by the distance between the antennas. With the advent of the possibility of signal detection in a digital form and their subsequent computer processing, as well as the use of very stable oscillators that make it possible to bind signals recorded at different telescopes by frequency and time, very long baseline interferometers (VLBI) appeared. By the end of the 20th century, bases of these systems have reached 10000 km (about the Earth diameter). As a result of VLBI studies, it was revealed that many of the most interesting astronomical objects (active galactic nuclei, quasars; neutron stars, pulsars; star forming regions, cosmic masers) are very compact and cannot be efficiently studied by ground base interferometers. In this regard, in the 1970s–1980s, the development of space–ground interferometers began [1]. These projects were widely discussed at international conferences. In order to prepare for the implementation of the first space–ground interferometer aboard the manned space station, *Salyut-6* astronauts V. A. Lyakhov and V. V. Ryumin deployed a prototype of the parabolic antenna of the radio telescope SRT-10 (with a diameter of 10 m) with a mesh reflective surface [2]. The telescope operated in bands of 12 and 72 cm at a height of 400 km from July to August 1979.

Based on the results of measurements by cosmic radio sources it was decided to design a telescope with greater surface accuracy since it was necessary to carry out research for the shortest waves in the centimeter range or at even shorter wavelengths (greater transparency of investigated sources themselves and higher resolution).

In April 1979, the Institute of Space Research and NPO Lavochkin began to develop technical proposals on the creation of a space–ground interferometer with a base much larger than the diameter of the Earth for radio astronomy observations in the range of 1 cm to 1 m [3, 4].

In May 1980 the Government of the Soviet Union issued a decree on the development of six unmanned space observatories by the NPO Lavochkin together with the USSR Academy of Sciences in the subsequent ten years. In 1983, the plan of launches was updated. In particular, *Astron-R* (the shortest wavelengths in the centimeter range) was to be launched in 1987–1988 and *Astron-M* (shorter wavelengths) was due to be launched in 1990.

The first international meeting on the space–ground interferometer RadioAstron was held in Moscow on December 17–18, 1985. Major bands (1.35, 6.2, 18, and 92 cm) of the space radio telescope were determined. Other parameters of the interferometer were discussed, in particular those related to the choice of its orbit. By the time of radical changes in the

Table 1

f_m	22.232 GHz	4.832 MHz	1664 MHz	324 MHz
Δf	8 bands within 7 GHz	100 MHz	100 MHz	16 MHz
ΔF_c	32 MHz × 2	32 MHz × 2	32 MHz × 2	16 MHz × 2

country several, these meetings had been held. On October 21, 1991, in Pushchino near Moscow (Radio Observatory of the Astro Space Center of FIAN) the 13th international meeting took place. In 2003–2004, in Pushchino, the already assembled space radiotelescope was tested on all bands, and the prototype was presented for joint tests with the *Spektr-R* spacecraft [5–7].

On July 18, 2011, the space radio telescope was successfully launched by the rocket *Zenit-3F* with the upper stage *Fregat–SB* from the Baikonur Cosmodrome. The deployment of a parabolic antenna and first tests including the single radio telescope and interferometer mode were also successfully carried out in 2011. Then, there were successful tests on all bands of the space radio telescope, which confirmed that its efficiency as the largest fixed space antenna with a diameter of 10 m and the largest interferometer with a base of up to 350000 km. For systematic radio astronomy studies, international cooperation has been organized, which includes more than 30 ground-based telescopes and two data collection stations (in Pushchino, Russia, and in Green Bank, United States) [8], http://www.asc.rssi.ru/radioastron/index.html. The International Program Committee selects applications for research.

The on-orbit operation of this radio telescope is provided by the multifunction space platform Navigator, on which it is installed.

The preparation and conduction of research with space–ground interferometer RadioAstron described in the later papers are of interest for further development in this direction (creation of the Earth–Space interferometer at shorter wavelengths and with larger bases, the Millimetron project of the Federal Space Program of Russia) [9], http://asc-lebedev.ru/index.php. The prospects of creating fixed parabolic antennas of higher accuracy in space for operation at shorter wavelengths down to the infrared range is also quite important. The creation of very large antennas and multiple-element interferometers with space-only bases is also a prospect [10, 11].

1. FUNDAMENTAL DIFFERENCES BETWEEN VLBRI AND VLBI

For a single telescope, the angular resolution $\theta = \lambda/D$, where D is the telescope effective diameter. For VLBRI, $\theta = \lambda/B_1$, where B_1 is the projection of the base B of a pair of radio telescopes (a space radio telescope, SRT, and a ground radio telescope, GRT) on the plane perpendicular to the direction to the source S (Fig. 1). The configuration and composition of the VLBRI RadioAstron is shown in Fig. 1. It can be seen that its distinctive feature is the VLBRI arm from the space radio telescope to outputs of the tracking station (TS). The SRT, as well as the GRT, receives the source radiation in radioastronomical bands from the direction of S, converts it into a desired form, and transmits it in real time over a radio link in the direction of R to the Earth, where it is reconstructed and stored in the data logger on the TS (Fig. 2). Therefore, all of the factors that change the input phase of the source on the way to the TS output (by time delays and frequency shifts) should be considered in the correlation with data from the GRT. Table 1 shows medium frequencies f_m of the SRT receiver tuning, bands of receiving frequencies by input Δf and used for the correlation processing of the video ΔF_c. Factor 2 in the third row means that the radio emission can be received simultaneously in two circular polarizations (left and right). As can be seen, VLBRI is a super system of synchronously operating telescopes (SRT and GRT), means of data transmission from SRT to Earth (to the TS) and as fast as possible data delivery for the correlation processing. The task of the interferometer as the phase system is to achieve the best resolution $\theta = \lambda/B_1$ in the study of celestial objects at the selected wavelength λ. The measured difference between radiation source phases reaching telescopes at the same time can be different from the purely geometrical (in vacuum) $\Delta\varphi_c$ by the presence of bad constituents $\Sigma\Delta\varphi_i$. In terrestrial VLBIs, the base B between GRTs does not change during observation, and the projection of the base B_1 changes slowly because of the rotation of the Earth and according to an established law. The clock on the GRT (usually a hydrogen clock) is periodically compared using *GPS* or *UT* systems; therefore, the synchronization error of these clocks does not usually exceed 10–100 ns. Data received by telescopes taken together with the current time t_{GRT} are recorded to the loggers for delivery to the correlator and, in the *VLBA* system, data are transmitted over communication lines [12]. Thus, the measured phase difference can be different from a geometrical difference only because of the clock synchronization error and the possible difference of the effect on the phase of the Earth's atmosphere at GRT locations. In the VLBRI, the base between SRT and GRT telescopes and its projection B_1 is continuously and rapidly changing because of the SRT orbital motion and the Earth's rotation. SRT data are specially converted to noise-resistant digital data streams and are transmitted in real time to the TS

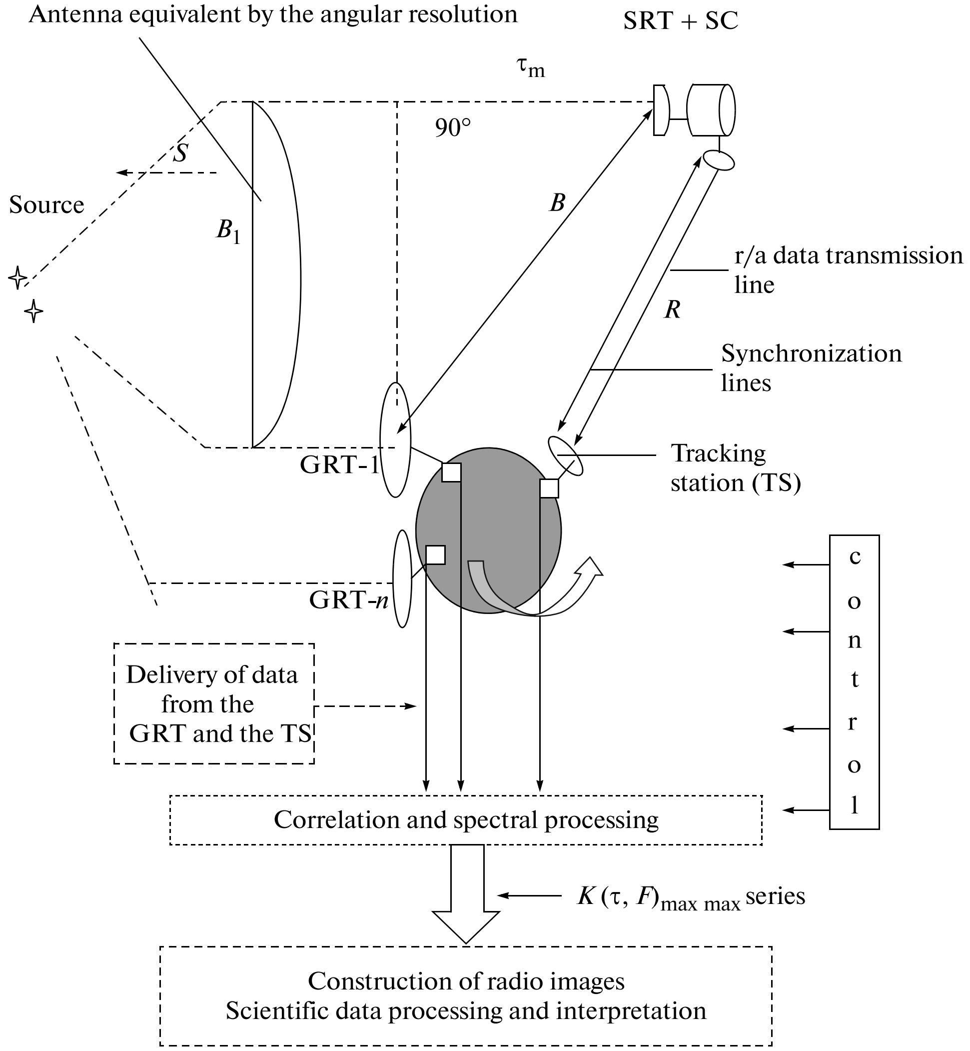

Fig. 1. Configuration and basic segments of the VLBRI. τ_m is the difference of geometric (in vacuum) delays from the source to the SRT and GRT, $K(\tau, F)_{\max\max}$ are maximum correlation values for delay and frequency interference.

via radio-link f_0 over the carrier of 15GHz. There, they are decoded, reconstructed, and recorded together with the current time t_{TS} by the clock of the TS (Fig. 2). The TS clock is synchronized with the GRT clock, but the SRT time $t_{SRT} = t_{TS} - \Delta t_{SRT\text{-}TS}$ remains undefined because of the changing delay $\Delta t_{SRT\text{-}TS}$ in the radio channel SRT-TS. A two-way coherent synchronization line (the TS-SRT-TS phase loop) makes it possible to determine the current values of $\Delta t_{SRT\text{-}TS}$ more accurately and significantly more often than by the ballistic prediction [13]. All communication frequencies of the SRT with the TS are selected according to the Regulation of the International Radio Consultative Committee. The data delivery from the TS and GRT for the correlation processing is conducted on carriers of their Registrars or over the Internet. For the correlation data, the SRT and all GRTs should also be identical functionally and by a number of parameters, i.e., to operate in the same frequency bands and polarizations and to have the same recorded frequency bands and positions of the local oscillator frequencies, as well as known instrumental delays. The sum of phase errors added to the geometric phase difference $\Delta\varphi_{geom}$ is determined by bad time delays and frequency shifts on the way to the correlator.

2. SPACE RADIO TELESCOPE

A key new segment of the radiointerferometer is the space radio telescope (SRT), which is a radio receiving electronic complex with a 10 m parabolic antenna with 27 rigid carbon fiber petals that unfurl in space. A space telescope is the payload of the far-orbit satellite Spektr-R. It was launched into a high elliptical satellite orbit with an apogee of about 350000 km for observations of celestial sources synchronously with a network of terrestrial telescopes. The SRT is connected to the tracking station via airborne means of

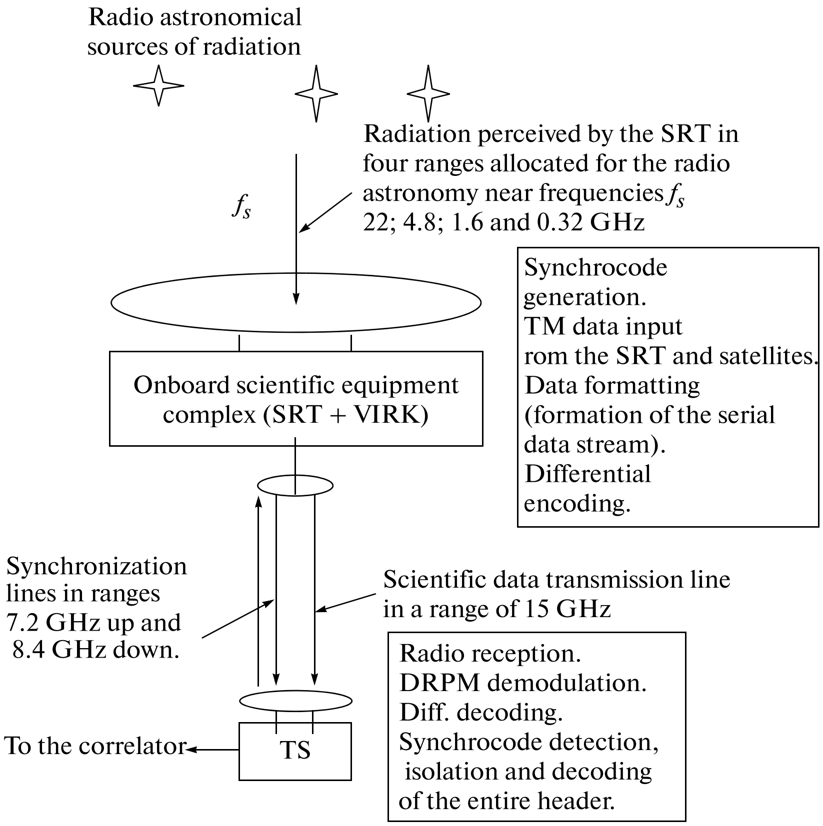

Fig. 2. Space arm of VLBRI RadioAstron. In the box in the right part of the diagram actions are listed that are performed on the SRT and the TS for data transmission from the SRT via radio.

the high-capacity radio complex (VIRK). With such bases the interferometer provides information with a record angular resolution up to 10 μs of arc (for the shortest wavelength $\lambda = 1.35$ cm). For comparison, the most powerful ground-based optical systems have a resolution of 0.1–0.01 arcsec.

SRT systems perform the following functions (Fig. 3): the reception and amplification of radio emission of both polarizations for the investigated galactic or extragalactic source (an antenna and devices of the cold plate), the transfer of the frequency spectrum of received signals in the video area without losing the phase of the received signals (instruments of focal and instrument containers), the conversion of these signals together with the SRT intrinsic noise in binary form, the formation of digital data streams (instrument container), and their transfer to a ground tracking station over the air with the carrier $f_0 =$ 15 GHz, as well as the formation of a phase loop on tone signals 7.2075/8.4 GHz (the VIRK with the tracer for the TS antenna).

As can be seen from the SRT diagram in Fig. 3, the main interferometric mode involves all subsystems and devices, excluding reserve systems, and the two or three receivers not included in the range of current observations.

Heterodyne and clock signals are required for the operation of the receivers in the FC and the formatter in the IC. Their formation in frequency synthesizers 1 and 2 (VHFFB and HCFFB) can occur either from the reference signal from the output of the loop phase transponder (15 MHz) received from the TS or from the onboard autonomous rubidic oscillator, or from an autonomous airborne H-maser (15 MHz). Synthesizer 2 forms clock frequencies of 64 and 72 MHz and 4 heterodyne frequencies of 250, 254, 258, and 262 MHz for the formatter, as well as frequencies of 64 and 160 MHz for further formation of frequencies for heterodyne receivers in the synthesizer 1 (200, 1152, and 4320 MHz). Thus, the SRT signal path is ready to receive signals from the onboard antenna feed (OAF) elements. Signals from each of the variously polarized outputs of the OAF are amplified by low noise amplifiers (LNA) and fed through FC pressure-seal connectors to the inputs of two-channel receivers; in the range of 324 MHz the LNA is not cooled and is placed directly in the receiver of this FC range. Spectra of the received signals transferred to an intermediate frequency (about 512 MHz) together with the SRT intrinsic noise are fed from a pair of outputs of each receiver to the selector (IF selector on the scheme). Depending on the chosen observation mode the selec-

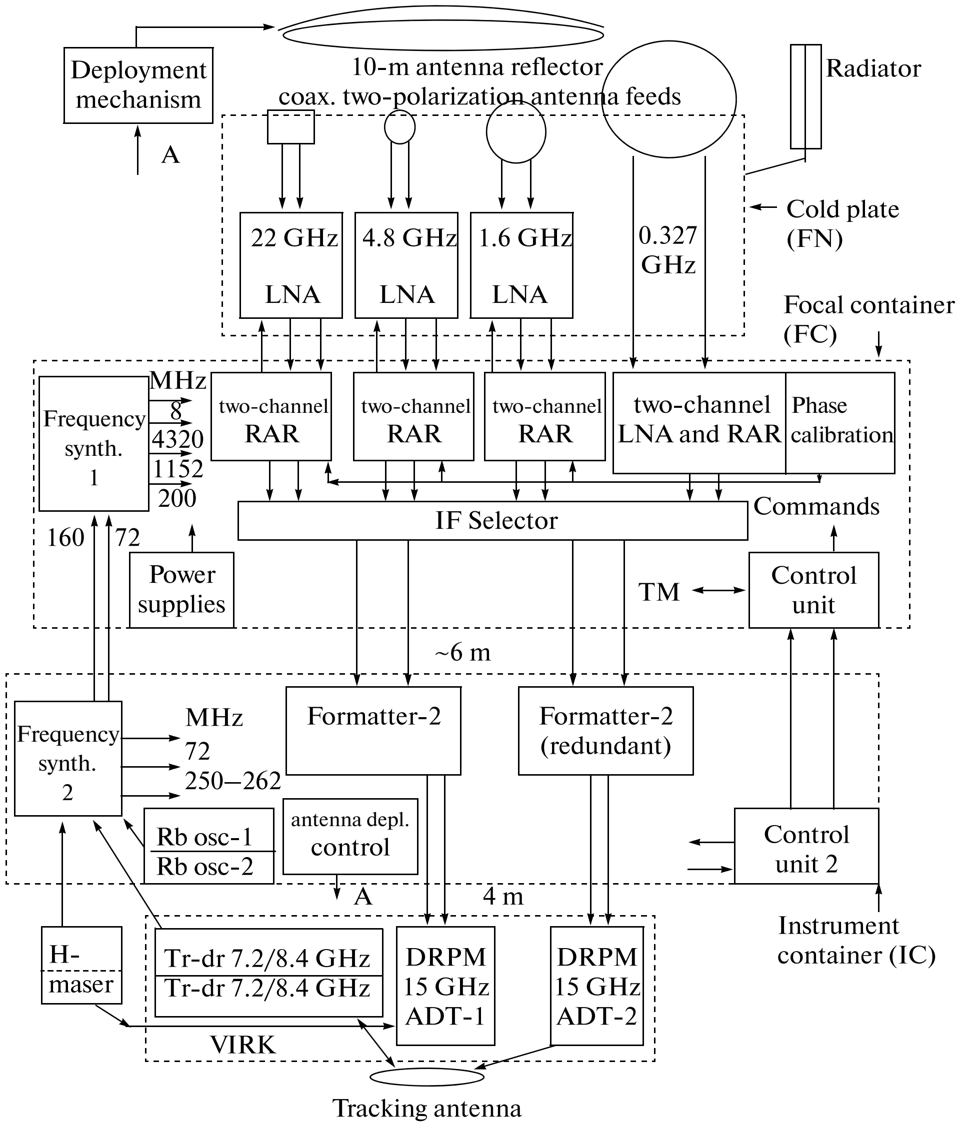

Fig. 3. SRT and VIRK block diagram. Key: LNA is the low-noise amplifier, FN is the focal node containing a block of antenna feeds and LNA, RAR is the radio astronomy receiver, IF is the intermediate frequency, TM is the telemetry, Rb osc-1, 2 are rubidic oscillators, H-maser is the hydrogen oscillator (two copies), VIRK is the high capacty radio system, Tr-dr 7.2/8.4 is the transponder of the input frequency of 7.2 GHz in to the output frequency of 8.4 GHz, ADT-1, 2 are transmitters of astronomical data of the carrier frequency of 15 GHz.

tor chooses any two channels by commands (two from any radioastronomic receiver (RAR) or by one from any two RAR, or any one RAR output is fed to the two Selector outputs) and feeds them to the FC output connectors. Then, these signals are inputted to the IC by rigid coaxial cables extending along rods and are fed to the formatter (the second one is on cold standby). There, they are converted into a video range and a digital form. Next, they are compacted in two consecutive binary data streams where antijamming synchrocode and other data that form a data format of the SRT are also added [13]. Both streams (*I* and *Q*) are derived from the IC by the paraphase circuit and fed to inputs of the modulator of astronomic data transmitters (ADT) of 15 GHz of the VIRK by cables of equal length. Next, modulated double relative phase modulation (DRPM) signals are transmitted to Earth via the VIRK antenna tracking the TS. The described modulation makes it possible to transmit two data streams simultaneously in a single frequency band at a speed of 72 Mbit/s each. The antenna tracking for the selected TS and its refocusing on another TS should be initiated by software commands from the SC onboard computer. The first two years of the mission only used one tracking station located in Pushchino, Russia. At the end of 2013, the US TS (Green Bank) was put into operation.

Table 2

1	Pointing to the source (provided by the SC)	Triaxial stabilization, pointing accuracy: ±2 arcmin, stabilization error: ±32 arcsec, max reorientation rate 0.1 deg/s
2	SRT antenna	10 m diameter, unfurlable, parabolic. Coaxial feeders, in the primary focus, with outputs of the right and left circular polarization. Max deviation from the parabolic shape is ~2 mm
3	Input frequency range and used bands	324 ± 8, 1664 ± 32, 4832 ± 32, 22232 ± 32 MHz (18–25 GHz—for the multifrequency synthesis mode)
4	Noise temperatures of the SRT system in the specified ranges	<200, <45, <130, <80 K
5	Effective antenna areas in the specified ranges	>30 m^2, >41 m^2, >35 m^2, >7.5 m^2
6	Frequencies of heterodynes for both receiver channels in the specified ranges	200, 1152, 4320, 21720 (4320) MHz
7	Heterodyne frequencies of video converters of the Formatter	500 (250 × 2); 508 (254 × 2); 516 (258 × 2); 524 (262 × 2) MHz
8	Sources of reference frequencies for all frequency transformations and their stability	Rubidic oscillator 5 MHz: 10^{-12} per 100 s; Hydrogen oscillator of 5 and 15 MHz: 5×10^{-15} per 1000 s; Reference signal from TS (on the output of the VIRK transponder): 15 MHz with the Doppler residual error
9	VIRK parameters	Frequencies of TS synchronization lines: 7.2075 GHz up, 8.4 GHz down, 1–4 W (carrier). Scientific data transmitter: DRPM modulation of 15 GHz, 40 (4) W; transfer rate of 2 × 72 Mbaud, or 2 × 18 Mbaud, the tracking antenna, diameter of 1.5 m
10	Number of control commands —CCW —functional	 300 124
11	Power consumption is 27 V from the onboard network	<1150 W (depending on mode)
12	SRT weight (with VIRK)	<2500 kg
13	Folded dimensions (without VIRK)	Length of 7460 mm, diameter of 3550 mm
14	Orbit	Apogee of about 350000 km, the inclination of 79.70 (April 2012), period of 8.5 days, and initial perigee of 500 km
15	Best angular resolution of the interferometer	8 arcμsec (in the range of 1.35 cm)
16	Best sensitivity of the SRT - GRT interferometer (VLA)	10 mJy

Table 2 gives the values of the parameters in the draft of SRT and VLBRI that make it possible to achieve scientific goals of the mission, i.e., to obtain images, coordinates, and the evolution of the angular structure of celestial radio sources in the Universe with ultra-high angular resolution, as well as to conduct gravity experiments.

3. RESULTS

(1) An ultra-high angular resolution of radio astronomicalal sources is achieved based on fundamental differences between VLBRI and ground VLBI, i.e., the placement of the SRT in the satellite orbit, the establishment of the radio communication complex with the Earth (with TS), and a special conversion of signals from the SRT for further transmission to TS and restoration for correlation with data from the GRT.

(2) A four-band SRT (from 1.35 to 92 cm) is created on the basis of the 27-petal antenna unfurling in space and radiation cooled LNA.

(3) The energy potential of the communication with the Earth is capable of transmitting data from the SRT at a speed of up to (72 × 2) Mbit/s in two elliptical polarizations.

(4) The SRT (and airborne transmitters) synchronization is possible through the phase loop of hydrogen clocks of the TS, which are in turn synchronized with the GRT clock. Synchronization with an autonomous onboard H-maser or rubidic oscillator is also provided, which potentially makes it possible to conduct gravity experiments.

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