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Space VLBI mission RadioAstron: development, specifications, and early results

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RadioAstron collaboration

The 10-meter space radio telescope Spectrum-R was successfully launched on July 18, 2011, and unfurled several days later. The space element of the ground-space very long baseline interferometer RadioAstron covers four frequency bands from 92 to 1.3 cm and provides baselines up to 350,000 km. This allows to study space objects with a resolution as high as about 10 microarcsecond. The mission development, its current status after launch and test results are presented and discussed.

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1. RadioAstron development and specifications

On July 18, 1981 Roald Sagdeev then Director of the Soviet Space Research Institute in Moscow, authorized the development of the Spectrum-R space interferometer mission, also known as RadioAstron (Kardashev, 1997). RadioAstron was to be one of three missions; the others being Spectrum-X-Gamma and Spectrum-UV to operate at X/γ-rays and ultra-violet wavelengths respectively. However, the challenging technical goals of the three missions, combined with the political and economic difficulties following the fall of Soviet Union resulted in lengthy delays in the completion of RadioAstron which later was transferred to the Astro Space Center (ASC) of the P. N. Lebedev Physical Institute of the Russian Academy of Science. The Spectrum-X-Gamma and Spectrum-UV are currently under construction, the launch of the former is planned for 2014.

After 30 years of development of this ambitious Space VLBI project by scientists and engineers at the ASC, the 3660 kg RadioAstron spacecraft was finally launched from the Baykonur Cosmodrome on July 18, 2011, and a day later it was placed in a highly elliptical orbit extending out beyond 300,000 km with an eight to ten day period.

The 10-m space RadioAstron radio telescope was fabricated from 27 carbon fiber panels and has a F/D ratio of 0.43 (Figure 1). RadioAstron is equipped with feeds and receivers for four frequency bands as shown in Table 1. It also presents calculated system temperature $T_{\rm sys}$ values for the RadioAstron receiver systems and estimates of the expected sensitivity of space-ground interferometry with SRT and using the NRAO GBT telescope as an example ground station. Estimates of correlated flux density 1σ values are made for single polarization frequency channel (IF) with 16 MHz bandwidth for one bit sampling. The sensitivity for L, C, and K-bands channels is improved by a factor of $\sqrt{2}$ when both LSB/USB channels are combined.

The RadioAstron mission has enjoyed widespread international participation. The space radio telescope, the spacecraft bus, and instrumentation were designed and developed by the Astro Space Center, the Moscow S. A. Lavochkin Federal Research and Production Association Industries, and the Russian Space Agency, Roscosmos, while the specialized radio interferometry instrumentation was developed at the Astro Space Center. The low noise amplifier for the 330 MHz (92 cm) radiometer was built by the NCRA in India and the 1.6 GHz (18 cm) receiver was manufactured

Table 1: The sensitivity of the RadioAstron mission

RadioAstron	P-band	L-band	C-band	K-band
Frequency range (MHz)	316–332	1636–1692	4804–4860	18372–25132
Band width per polarization (MHz)	16	2×16	2×16	2×16
$T_{\rm sys}$ (K)	200	45	130	77
$A_{\rm e}$ (m^2)	30	41	35	7.5
SEFD (Jy)	19000	3400	10500	30000
RadioAstron-GBT baseline: 1σ (mJy)	16	3	5	13

Notes: The 1σ baseline sensitivity is shown for the 16 MHz bandwidth of a single polarization channel (IF) for 300 s integration time to be used for detection cutoff estimates. The actual coherence time is being discussed in § 3.

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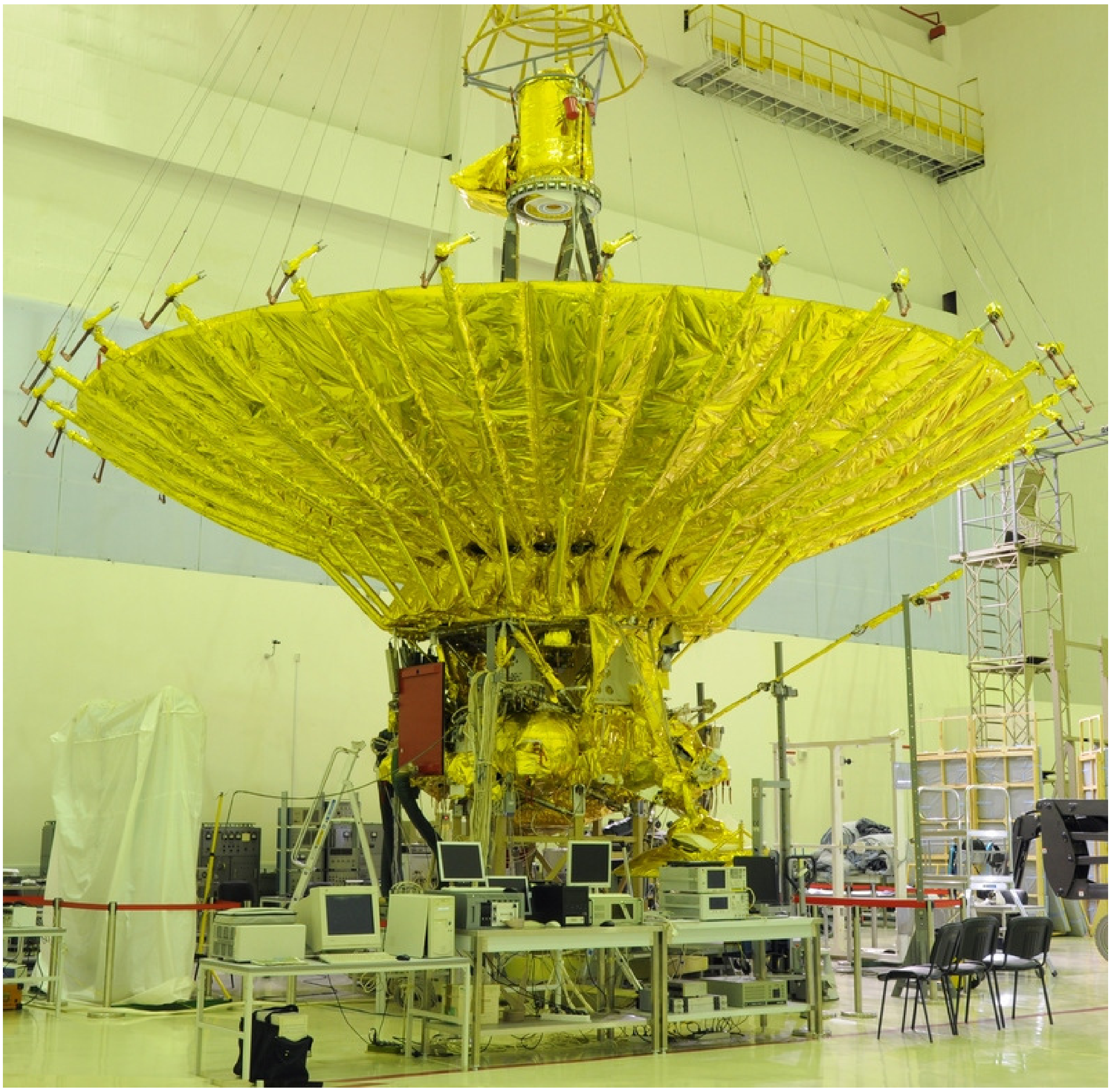

Figure 1: The space radio telescope Spectrum-R undergoing tests in Lavochkin Association.

by CSIRO in Australia. A 5 GHz (6 cm) receiver was constructed in the Netherlands on behalf of a consortium of European radio observatories. The 6 cm LNA was provided by the MPIfR in Germany, and the European Space Agency conducted thermal tests of the antenna panels in their vacuum chamber located in the Netherlands. The 22 GHz (1.3 cm) receiver was initially designed and built by the Helsinki Technical University. Due to the delays in the RadioAstron launch, both the original 5 and 22 GHz receivers were considered to have exceeded their shelf life and were replaced by newer units built by Russian industry. To obtain enhanced sensitivity and cover a wide frequency range from 18 to 25 GHz, the 22 GHz system uses low noise HEMT amplifiers constructed by the U.S. National Radio Astronomy Observatory. These are the same amplifier types as used for IF amplifiers in the WMAP spacecraft used to map the cosmic ray anisotropies. Each RadioAstron receiver operates in two (USB and LSB) 16 MHz wide channels (4 MHz wide at 330 MHz) in each of two orthogonal circular polarizations.

After conversion to baseband each 16 MHz intermediate frequency signal is digitized using one bit Nyquest sampling, and the 128 Mbps digital data stream is sent to the ground over a 15 GHz link. At the ground, the 128 Mbps data is recorded on RadioAstron Data Recorder discs (Belousov et al., 2006). The data is then played back and sent over fiber to Moscow or to the Max-Planck-Institute in Bonn, Germany, where they are correlated with data recorded at various ground radio telescopes throughout Russia, Ukraine, Europe, China, the United States, Japan, Australia, South Africa, and India. Correlation of the incoming data streams is performed in Moscow using a high performance computer cluster and specialized RadioAstron software correlator developed by the ASC team (Belousov et al., 2006) and in Germany using a modified version of the standard DiFX software correlator (Deller et al., 2007).

The RadioAstron spacecraft is equipped with two hydrogen masers, manufactured by the Russian company Vremya-Ch. The masers are used to stabilize the on board local oscillator system by generating a 5 MHz reference signal used to control a frequency synthesizer which provides the independent stable local oscillator signal. As a back-up, in case of failure of the masers, a closed loop system operates at 7.2/8.4 GHz which can synchronize the RadioAstron local oscillator with one at the ground tracking station.

Ground tracking support is currently provided using the 22-m antenna located at the radio observatory near Pushchino, outside of Moscow. Since the spacecraft is not always visible from Pushchino, an additional tracking station is under development at the U.S. National Radio Astronomy Observatory in Green Bank, as well as one in South Africa. The South African tracking station will provide critical tracking support when the spacecraft is near perigee in the Southern Hemisphere. These external tracking stations will use the same instrumentation as at Pushchino, thus insuring the uniformity of the data to facilitate the correlation. Precise orbit determination needed for radio interferometry is made utilizing five different methods including conventional radio delay and Doppler measurements, laser ranging, optical observations of the space craft sky position, VLBI tracking.

Data recorded simultaneously at the various radio telescopes on the Earth and from RadioAstron are being used to reconstruct crude but extremely high resolution images of celestial radio sources. Because of the very elliptical orbit of RadioAstron, the resolution of the earth-space interferometer is essentially one dimensional. Precession of the orbit resulting from gravitational perturbations by the Moon, will give some degree of two-dimensional coverage, although changes in the radio source structure during this period will make the detailed interpretation of the interferometer data more difficult. It should be noted that traditional imaging with a relatively good ground-space *uv*-coverage is also possible about once every nine days for specific sky positions which change with time due to evolving orbit and visibility contraints.

2. RadioAstron Scientific Goals

Probable targets of RadioAstron studies include pulsars, blazars, and cosmic masers. Previous ground based VLBI observations of blazars suggest the presence of structure on angular scales as small as 50 μarcseconds (e.g., Kovalev et al., 2005). These expected small scale structures are supported by observations of the radio spectra and rapid time variability. Of particular interest

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are the so called blazars, which are quasars whose relativistic outflow is directed toward the Earth. Because of the enhancement of the radio synchrotron emission which is beamed along the direction of motion due to relativistic boosting, the apparent brightness of blazars can appear boosted by factors of thousands. Also, since the radio emitting plasma is thought to be moving at nearly the speed of light along the line of sight, the radiating source is nearly keeping up with its own radiation, giving the appearance of faster than light motion. The high resolution observations made possible with RadioAstron, will allow unprecedentedly detailed observations of blazars, reaching an order of magnitude closer to the super massive black holes thought to lie at the base of the relativistic jets.

Also, clouds of hydroxyl (OH) ions and H_2O molecular gas are found in the regions surrounding highly evolved stars as well as regions where new stars are being formed. Excited by UV radiation from the associated star, these clouds can act as cosmic masers giving intense rapidly variable radio emission from very small regions.

Pulsar radio emission is formed within the highly organized strong magnetic fields surrounding rapidly rotating neutron starts. The pulsar radiation comes from such small regions that will remain unresolved, even by RadioAstron. However, the RadioAstron observations, especially at the longer wavelengths, will study the very small scale structures in the intervening intergalactic medium which scatters the radiation resulting in apparent angular dimensions greater than the intrinsic values.

Interferometer baselines between RadioAstron and ground based radio telescopes have an angular resolution more than an order of magnitude better than used in any previous astronomical observation. Specifically, at 22 GHz, the longest baselines are more than 2×10^9 wavelengths giving an angular resolution of only 7 μarcseconds to study the radio emission from quasars and cosmic masers. Early science observations have been in progress since February, 2012, and starting in mid 2013, access to RadioAstron and the supporting ground facilities is open to peer review proposals from any scientist, independent of their institutional or national affiliation.

3. Early Results

Following the launch of the spacecraft in July, 2011, the first four months in orbit were spent in checking and calibration of the various mechanical and electronic components and in calibrating the pointing of the antenna using the Moon and other strong cosmic radio sources. These observations confirmed the performance of the four radiometers each of which had a measured system temperature close to the design value.

Small uncertainties in the position and motion of the spacecraft at any time result in corresponding uncertainties in the interferometer fringe rate and in the path length delay between the RadioAstron and the ground antennas. A series of fringe-finding observations at each of the four observing frequencies was begun in November, 2011, to verify the performance in each of the four frequency bands and to determine the corresponding residual fringe rate and delay for a variety of cosmic sources. Since RadioAstron will observe primarily in a previously unexplored range of angular resolution, the early fringe finding observations were mostly made using strong sources with projected interferometer spacing that are comparable with previous earth based observations having sufficient fringe amplitude for detection with RadioAstron. These observations resulted in the successful detection of fringes in all four RadioAstron frequency bands. In three of them, 18 (see Figure 2), 6, and 1.3 cm first fringes were found on quasars while the 0.3 GHz band was successfully tested using a bright pulsar on a very long projected baseline. A coherence time analysis resulted in a very promising outcome. 18 and 6 cm coherence time is found to be about 10 min while 1.3 cm coherence time is about 3 min. This confirms the high stability of the on board hydrogen maser being used for the data synchronization.

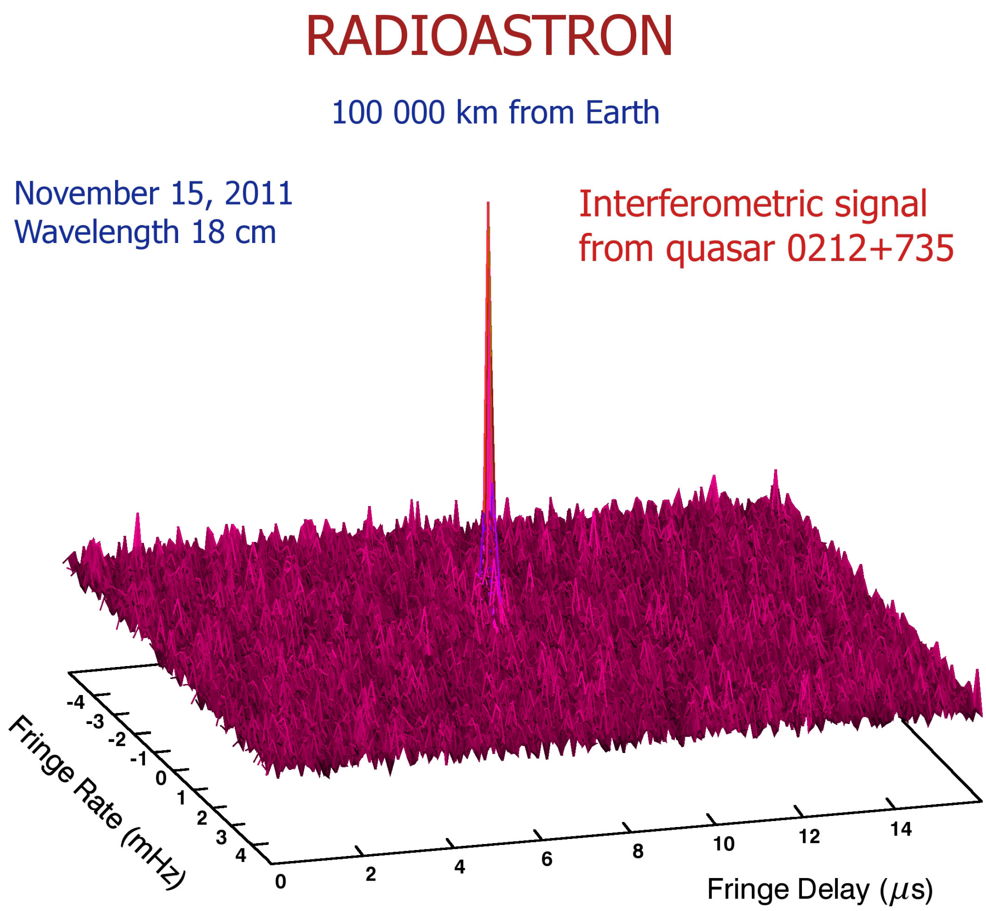

Figure 2: The first fringes found by the Space-VLB interferometer RadioAstron. Interference signal from the quasar 0212+735 on a 8,100 km projected baseline between RadioAstron and the 100-m MPIfR radio telescope near Effelsberg, Germany, observed on November 15, 2012. The wavelength of the observations was 18 cm. The plot shows the fringe amplitude versus residual delay and residual fringe rate in a single 16 MHz wide channel.

Regular scientific observations with RadioAstron are organized by three international RadioAstron early science program working groups being coordinated by Astro Space Center. They have been underway since February 2012 with 0.3 and 1.6 GHz observations of pulsars; 1.6 GHz observations of OH masers; 22 GHz observations H_2O masers; as well as 1.6, 5, and 22 GHz observations of quasars. By the mid 2012 important results were achieved by all the groups with quasar detection up to projected interferometer baseline of 92,000 km (7.2 Earth diameters), pulsar detection at up to 220,000 km (about 20 Earth diameters) and water maser detection at 1.3 cm just over 1 Earth diameter.

Acknowledgments

The ambitious RadioAstron program owes its success to the dedicated scientists and engineers at the Astro Space Center and Lavochkin Association, many of whom have worked for decades to bring the mission to fruition, as well as to the international observatories (Kvazar network, Russia; Evpatoria, Ukraine; Effelsberg, MPIfR, Germany; Medicina and Noto, Italy; Yebes, Spain; Westerbork, the Netherlands; other EVN telescopes; Arecibo and GBT, USA; Usuda, Japan; LBA telescopes and Tidbinbilla, Australia; etc.) and colleagues who have supported the development and early operations. This paper has used material from the RadioAstron user hand book, RadioAstron Newsletter, and papers by Kardashev et al. (2012, Astron. Rep. and URSI Bulletin, in press). Y.Y.K. was supported in part by the Dynasty Foundation and the Russian Foundation for Basic Research project 12-02-33101.

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