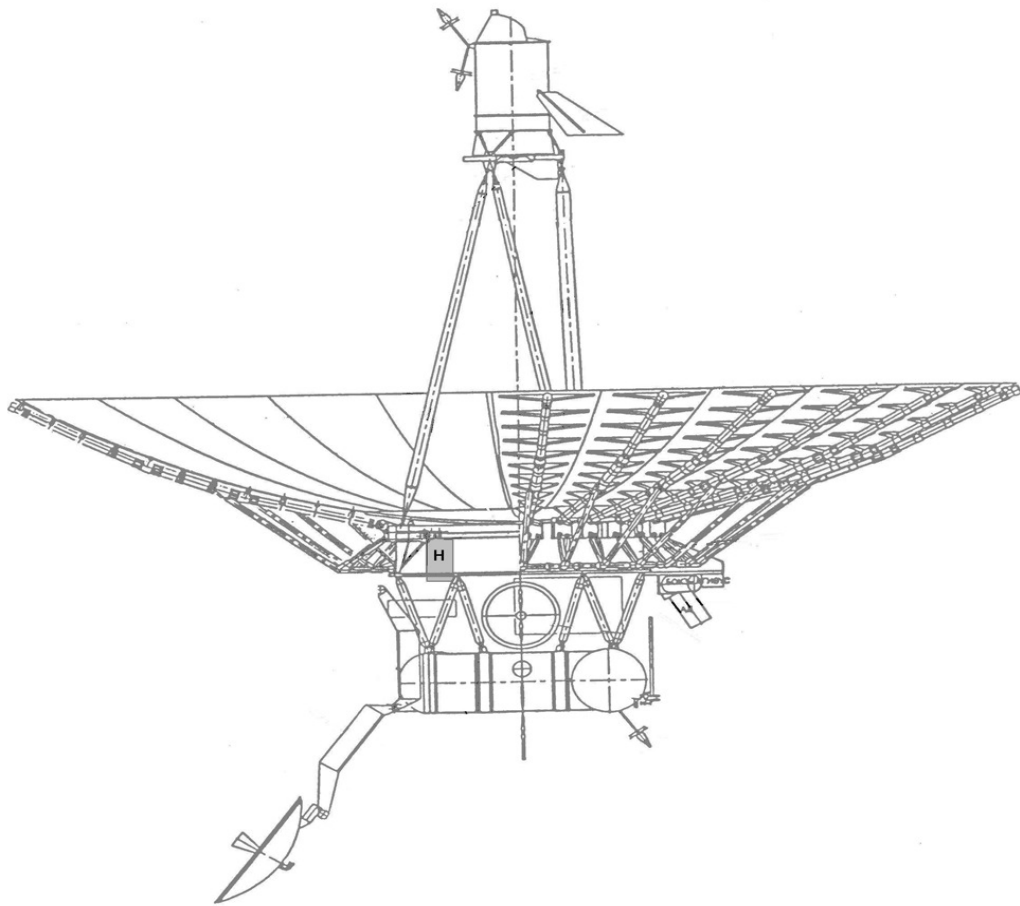


RADIOASTRON USER HANDBOOK



Prepared by the RadioAstron Science Operation Group
Version 1.1; July 2, 2010

Contents

1	Introduction	3
1.1	Basic information	3
1.2	Main performance parameters of RadioAstron	4
2	RadioAstron Space Segment	4
2.1	Spacecraft design	4
2.1.1	The Main Radio Complex (MRC)	5
2.1.2	The Spacecraft Attitude Control System (ACS)	9
2.2	Scientific payload	10
2.2.1	Space Radio Telescope (antenna)	10
2.2.2	The Feed System	10
2.2.3	The Receivers	11
2.2.4	The Formatter	11
2.2.5	High-Data-Rate Communication radio links (HDRC)	12
2.2.6	The System of Frequency Synthesis (SFS)	12
2.2.7	The Control System (CS)	12
2.3	RadioAstron orbit	13
2.3.1	Initial orbit elements and their evolution	13
2.3.2	Orbit Measurement (OM), prediction, and reconstruction	13
2.4	Operational constraints	17
2.4.1	Constraints connected with SC service systems	17
2.4.2	Constraints connected with the science payload	18
2.5	Pointing offsets and gain measurements	18
2.6	Calibration	19
2.6.1	Noise calibration	19
2.6.2	Pulse calibration	19
3	RadioAstron Ground Segment and Operations	19
3.1	Tracking stations	20
3.2	Ground radio telescopes	20
3.3	Data recording	20
3.4	Data correlation	21
3.5	Satellite operations and experiment scheduling	21
3.6	Observational modes and procedures	22

<i>CONTENTS</i>	2
3.7 Science access	22
4 Observations with RadioAstron	23
4.1 The Frequency setup	23
4.1.1 K-band observing and MFS	24
4.2 Observing strategy and imaging	24
4.2.1 All-sky UV-plots	24
4.2.2 Examples of observing strategies	28
4.2.3 Imaging capabilities	28
4.3 Resolution	29
4.4 System sensitivity	29
4.5 Experiment preparation	32
4.6 Data reduction	33
A Document abbreviations	34
B Abbreviations used in the Diagrams	35

1 Introduction

This Handbook establishes the design guidelines and the constraints that govern the use of all systems of the RadioAstron mission. This document provides description of the spacecraft systems and the access to the mission for scientific use.

This Handbook serves primarily as an observer aid on technical and operational issues related to generating an observing proposal.

The Handbook will be updated as needed and is available at the RadioAstron web site. We encourage all readers and users to provide comments.

1.1 Basic information

The RadioAstron Project was initiated by the Astro Space Center (ASC) of the P.N. Lebedev Physical Institute of the Russian Academy of Science.

The RadioAstron project is an international collaborative mission to launch a free-flying satellite carrying a 10-m space radio telescope (SRT) into an elliptical orbit around the Earth. The aim of the mission is to use the space telescope for radio astronomical observations using VLBI (Very Long Baseline Interferometry) techniques in conjunction with ground-based VLBI networks located in Australia, Chile, China, Europe, India, Japan, Korea, Mexico, Russia, South Africa, Ukraine, and USA. The expected orbit of the RadioAstron satellite is evolving with time and has an apogee between 310,000 and 390,000 km, a perigee between 10,000 and 70,000 km, a period of 8 to 9 days, and an initial inclination of 51° . RadioAstron will operate at the standard radio astronomical wavelengths of 1.19-1.63, 6.2, 18, and 92 cm. Space-Ground VLBI observations using RadioAstron will provide morphological information on galactic and extragalactic radio sources with fringe size of $7 \mu\text{as}$ at the highest frequency and the longest baselines. The guaranteed spacecraft's operational lifetime is five years.

International contributions: During the long period of project development, institutes from other countries have made notable contributions to the RadioAstron Project. The low-noise amplifier (LNA) for the 92-cm (P-band) receiver operating at 327 MHz has been built in India by NCRA. The 18-cm (L-band) receiver operating at 1665 MHz has been developed and manufactured in Australia by CSIRO. The initial 6.2-cm (C-band) receiver operating at 4830 MHz has been developed at ASTRON, the Netherlands, and MPIfR, Germany, on behalf of the European VLBI Consortium (EVN). Finally, the initial 1.35-cm (K-band) receiver operating at 22 GHz has been provided by the Helsinki University of Technology in Finland. Because of aging issues, the last two receivers (the C- and K-band) have been replaced by new models developed in Russia. The new K-band receiver contains an LNA provided by the NRAO, USA, and can operate in frequency switching mode in the range of 18.392-25.112 GHz. Both initial receivers have been extensively used in system development tests, and particularly in the astronomical tests of the complete engineering complex of the SRT in Pushchino in 2004. In addition, the European Space Agency (ESA) conducted complicated tests of the SRT antenna petals in the vacuum chamber in Noordwijk. These tests were essential for the final development of the RadioAstron project. ESA has also provided funding for the development of the on-board Rubidium frequency standard, which has been manufactured by the Neuchâtel Astronomical Observatory in Switzerland. The recording and playback facility, S2, which helped in the development of the RDR recorders and ASC software correlator, were provided by the Canadian Space Agency and York University in Toronto, Canada.

1.2 Main performance parameters of RadioAstron

Main performance metrics of RadioAstron are shown in Table 1. See section 4 for details.

Table 1: Basic performance of RadioAstron

Observing Bands (cm)	Frequency range (MHz)	Bandwidth per polarization (MHz)	Smallest fringe spacing (μ as)	SEFD (Jy)	Gain (K Jy ⁻¹)	Baseline sensitivity (mJy)
92 (P)	320 – 328	2×4	530	15400	0.011	42
18 (L)	1636 – 1692	2×16	100	2300	0.015	4
6 (C)	4804 – 4860	2×16	35	4400	0.015	4
1.3 (K)	18372 – 25132	2×16	7	6500	0.011	10

K-band observing can be done at one of the eight central frequencies: 18392, 19352, 20312, 21272, 22232, 23192, 24152, 25112 MHz. Fringe spacing is calculated for the longest possible baseline. The one-sigma baseline sensitivity is estimated for the RadioAstron-GBT pair for 300 s integration time and 16 MHz (4 MHz for the P-band) bandwidth of a single polarization single frequency channel (IF). Image sensitivity is discussed in section 4.2.3.

2 RadioAstron Space Segment

The space segment of the mission comprised of the RadioAstron satellite hosting a 10-meter parabolic antenna, scientific payload, communication system, and a spacecraft bus. Detailed description of these elements of the satellite is given below.

2.1 Spacecraft design

The RadioAstron satellite consists of a parabolic reflector, a scientific payload located in two containers, the focal container and the instrumentation module, and a “Navigator” service module (bus), which is a standard module used in several other scientific missions. An on-board Hydrogen frequency standard is installed separately. The space radio telescope (SRT) is a deployable parabolic reflector (10-m diameter) made of 27 carbon fiber petals. It has a focus to diameter ratio $F/D = 0.43$, and an overall RMS surface accuracy ± 0.5 mm. The prime focus concentric feed arrangement provides the possibility of observing at two frequencies, or two circular polarizations simultaneously. Observing frequencies are: 0.327, 1.665, 4.830 and 18.392-25.112 GHz. The total satellite mass is 3660 kg, with 2500 kg belonging to the scientific payload including the SRT, and with 1160 kg for the service module Navigator. The satellite will be launched from Baikanur by the Zenit-2SB launcher manufactured by the Ukrainian KB-Yuzhnoe company. An elliptical orbit of the satellite with an apogee height of about 320000 km will be achieved by a Fregat-SB rocket upper stage.

A general overview of the systems of the RadioAstron spacecraft is shown in Figure 1, while Figure 2 presents the general diagram of the on-board scientific complex and Figure 3 — the detailed functional diagram. The service module Navigator consists of the following basic spacecraft subsystems:

- main radio complex (MRC)
- attitude control system (ACS)

- power supply system (PSS)
- thermal control system (TCS)
- autonomous electronics module (AE)
- low gain telemetry (TM) antenna and feed system (TMAFS)
- high data rate communication radio link (HDRC)
- up-down phase transfer radio link (UDPTR)
- solar panel attitude control system (SPAS)
- orbit correction engines (OCE)

These systems are responsible for keeping the spacecraft operable during periods with radio contact with a ground station and during autonomous operation without direct radio contact.

Operational commands are generated in the Main Radio Complex (MRC) during GT contact and the Attitude Control System (ACS) for periods without GT contact, which can be programmed during flight. System performance is monitored using a comparison of the operational status generated by some external controlling actions with the response of internal (checking) logic in response to the status as monitored by the system. The information on ACS commands is entered into ACS storage during GT radio contact, in order to execute an ACS command for a required operation, such as setting spacecraft attitude angles at a certain point in time. As an example, under ACS control the solar panel attitude control system may autonomously rotate the solar panels in accordance with information from the solar sensors. On the other hand, direct MRC commands may override earlier ACS operational commands by putting them in a certain fixed positions.

Operational (observational) programs can be carried out in real-time during a radio contact by means of instructions transmitted from the ground, and in the autonomous mode by instructions stored in the Time-Program System (TPS) that is also part of the MRC. The basic function of the TPS is that of command-dispatcher for spacecraft systems that are controlled by corresponding TPS-programs. TPS programs are a sequence of macro-instructions and information codes, which produce transmissions of timed CCW-sequences addressed to any device. The entire memory of the TPS comprises 10K 16-bit words. This software-hardware complex of TPS is designed for:

- generating and transmitting clock frequencies for the vehicle service systems;
- providing the exchange of controlling code words (CCW) between the vehicle systems;
- executing fixed (stored in ROM) or flexible (stored in RAM) time-sequence using Control Code Words (CCW) for the vehicle systems;
- keeping vehicle time and transmitting time codes to the vehicle service systems;
- recording and storing CCW settings and transmitting them to the vehicle systems.

2.1.1 The Main Radio Complex (MRC)

The Main Radio Complex (MRC) also includes the low-rate Telemetry System (TMS). The TMS is a software-hardware package that is used for the acquisition, conversion and storage of telemetric information. TMS parameters are sequentially scanned by the telemetry system in accordance with

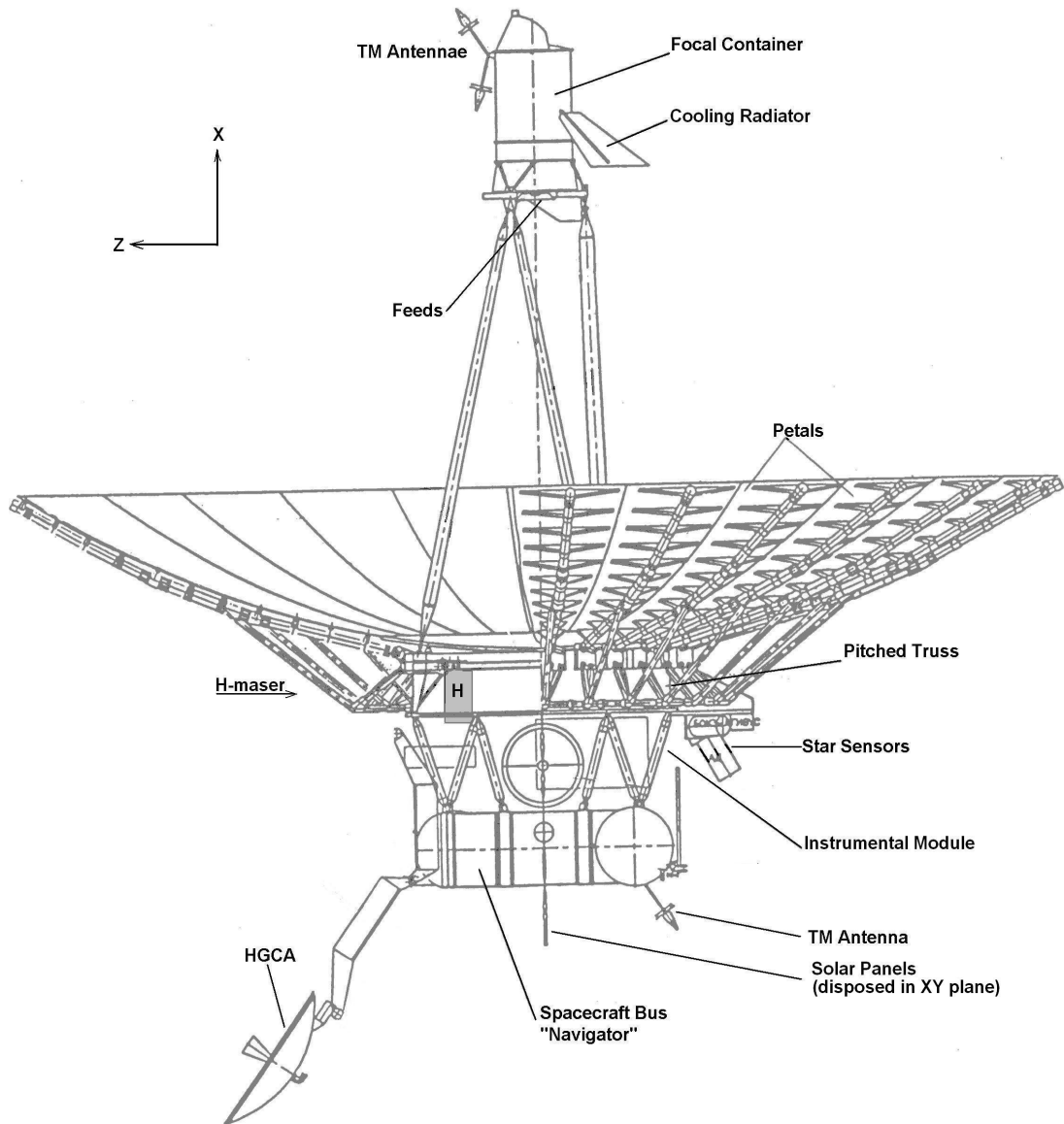


Figure 1: The sketch view of the RadioAstron Space Observatory. The Space Radio Telescope (SRT) is serviced by the Navigator spacecraft bus. The solar panels are exposed in the Y-direction, i.e. perpendicular to the sketch plane. Component H is the high precision Hydrogen frequency standard (H-maser).

RADIOASTRON PAYLOAD GENERAL SCHEME

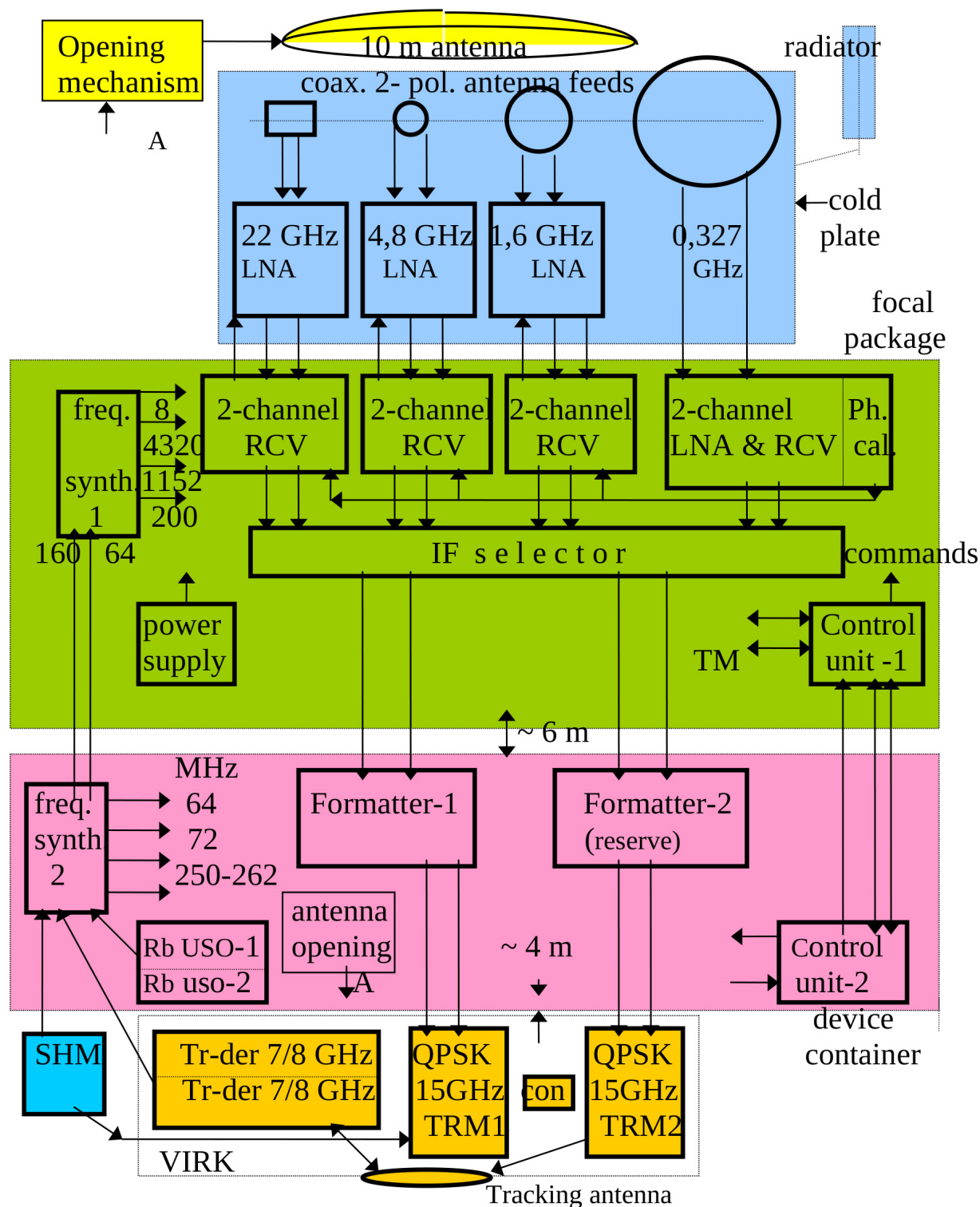


Figure 2: The general diagram of the on-board scientific complex. Explanation of abbreviations in use see in appendix B.

On-board Scientific Complex – OBSC-SRT Functional Diagram

A.V. Biriukov, ASC, august 2008

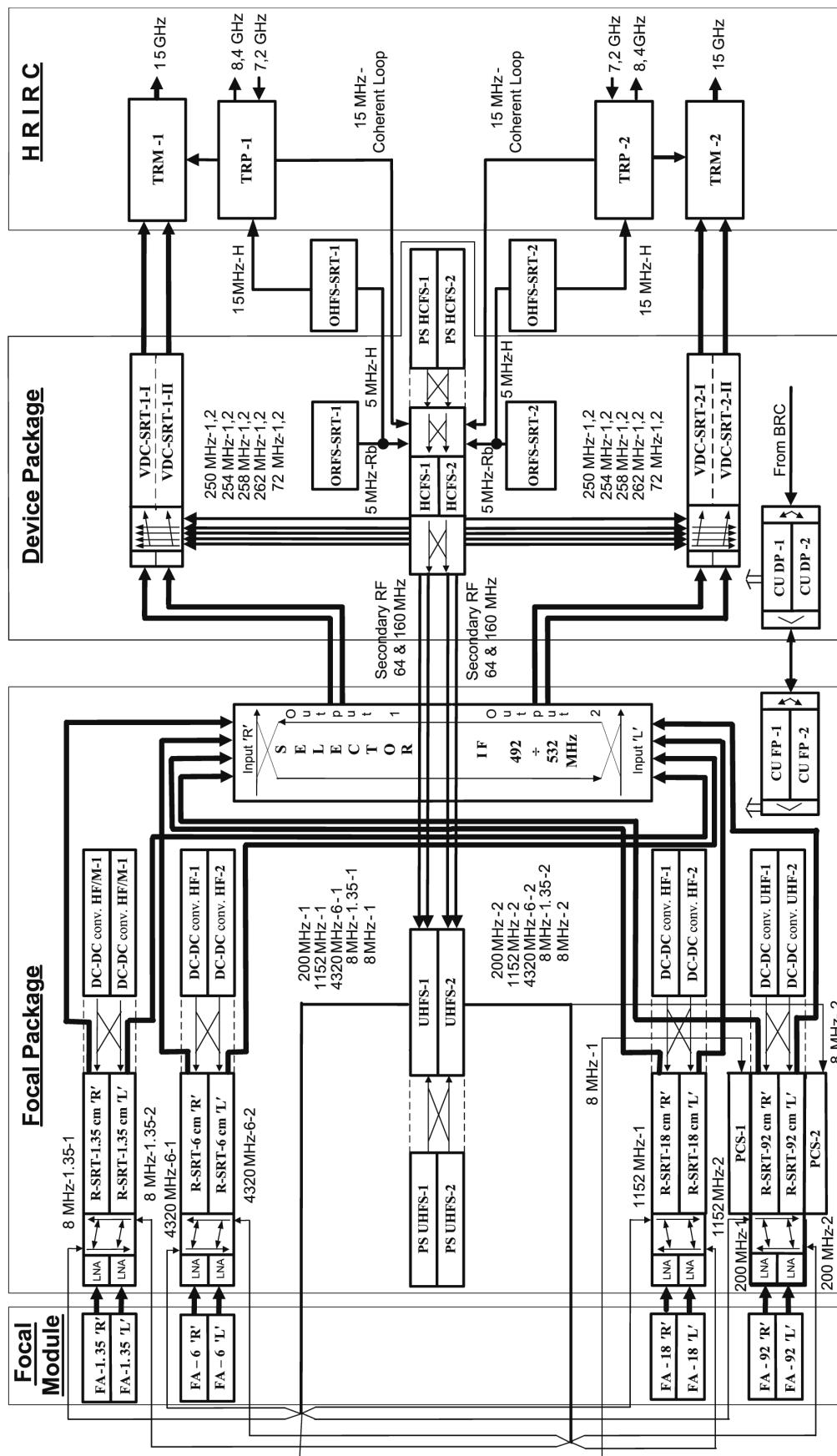


Figure 3: The detailed functional diagram of the on-board scientific complex. Explanation of abbreviations in use see in appendix B.

TMS frame descriptions stored in the TMS-computer. There are three different TMS streams with different TMS programs, which may be generated separately or simultaneously. The first TMS stream may be sent to the MRC for direct transmission to the ground and simultaneous recording in the memory. The second stream is intended solely for recording in the on-board memory. The third (digital) stream may be sent to the TMS for direct transmission to the ground and simultaneous recording in the memory. During the mission, the TMS computer can be partly reprogrammed.

Spacecraft radio support is provided in the C-band and includes:

- two command receivers,
- two receiver-transponders to receive commands and retransmit a signal to the Earth for trajectory measurements,

The spacecraft radio system can operate in the following main modes using omni-directional antennas:

- reception of commands from the ground,
- measurements of range and range rates,
- transmission of telemetry information in a direct transmission mode (in real-time) or in a memory playback mode at a rate up to 32 Kbps.

2.1.2 The Spacecraft Attitude Control System (ACS)

The Spacecraft Attitude Control System (ACS) has the following major functions:

- setup of base three-axis orientation from an arbitrary initial position;
- orientation of the axes of the SC in a given direction and stabilization relative to this direction;
- controlling operation of orbital correction engines;
- pointing the HDRC high-gain antenna to the Earth tracking stations.

The following components are incorporated into the ACS to carry out the aforementioned functions:

- sensor elements;
- on-board computer;
- interface instruments;
- movement execution devices.

The three star sensors are combined in an astro-system mounted on the pitched truss of the SRT. Mutual directions of the optical axes of these star sensors will be described in paragraph 2.4.1. Each star sensor has an objective lens with a diameter of 25 mm and a focal distance of 52 mm, and a field of view of 12° . The ACS can be used for stars down to 6^m .

The on-board computer contains a star catalog and the ACS can identify the SC orientation without any preliminary information. For precise pointing and stabilization, two star sensors are used

simultaneously. The ACS provides an accuracy of $\pm 18''$ as the maximum random error. Systematic errors connected with thermal deformations are determined by bore-sighting measurements (see paragraph 2.5).

Inertial devices and a jet systems are used as movement execution devices for the spacecraft. A total of eight reaction wheels are used for maintaining of the "fine" mode of the SC orientation and for re-pointing. The hydrazine thruster jet system is intended as first order system for the SC orientation, the unloading the reaction wheels, and for orbit corrections. There are 12 thrusters in total: 4 for coarse traction, and 8 for fine traction. The control system can provide as many as 15 automatic re-pointing operations during a scientific observation session. The settling time after each re-pointing is about 5 minutes. The slew rate is 0.1 deg/s.

2.2 Scientific payload

The science payload consists of a space radio telescope, feed arms, a focal container, an instrumentation module, a high data rate communication system with a high-gain antenna, and two separate Hydrogen maser frequency standards located in open space.

2.2.1 Space Radio Telescope (antenna)

The Space Radio Telescope (SRT) with a diameter of 10 m and a focal distance of 4.22 m operates in four frequency ranges: 0.327(P band), 1.665(L band), 4.830(C band), and 18.392-25.112 GHz (K band). In order to achieve a high surface accuracy, the SRT consists of a solid central mirror of 3-m in diameter surrounded by 27 solid petals ($34 \times 115 \times 372$ cm) made of carbon-fiber. The maximum deviation for the surface from a paraboloid must not exceed ± 2 mm. In the initial folded configuration, the whole construction occupies a cylindrical volume of 3.6×7.6 m. The process of unfolding the SRT in orbit is achieved by a single motor, which causes the synchronous rotation of each petal over its own specially inclined axis and a cylindrical hinge. The process of unfolding takes less than 2 hours. Finally, the whole construction is fixed by pins at the very edge of each petal fastening them altogether. Each petal is also fixed in position with a cross brace. The petal framework is made of carbon-fiber tubes, which is covered by a surface with a three-layer composition including carbon-fiber trimmings combined with aluminum honeycomb. The surface of a petal can be adjusted before launch by means of 45 special screws over a range of ± 7 mm. The solid central mirror of the dish is fixed to a pitched truss by nine connecting bolts that eliminate the influence of thermal deformation of the pitched truss. The pitched truss itself is a cylindrical ribbed construction made of aluminum alloy. The truss serves as basic structural element for the SRT; it carries all petals, the central mirror, six supporting legs of the focal container, and all unfolding devices. In addition, the star sensors are placed at the pitched truss to reduce the effects of thermal deformations in operating the ACS.

The required high reflectivity of the SRT surface (98%) is provided by an aluminum coating of $100\mu\text{m}$ thick. To reduce thermal deformations of the SRT, the tubes of the petal framework are thermo-stabilized by special heating elements keeping the temperature within $\pm 50^\circ\text{C}$. At the rear, the petals also are shielded by multi-layer thermal isolation. According to the functional constraints (see paragraph 2.2.7), the Sun is not supposed to illuminate the SRT dish surface.

2.2.2 The Feed System

The feed system is located at the prime focus of the paraboloid and is attached to the bottom of the focal container. Fine-tuning of the position of the whole system is possible over a range of ± 7 mm during its assembling before launch. The feeds for 92, 18 and 6.2 cm wavelengths are ring resonators,

while the 1.19-1.63 cm feed is a conical horn. The concentric design provides the possibility of observing at two different frequencies, or, alternatively, at two circular polarizations simultaneously.

2.2.3 The Receivers

Radio astronomical receivers at each frequency range have two independent channels to accept signals with right-hand and left-hand circular polarization (RCP and LCP) from the feed system. All receivers are located in the focal container. The low noise amplifiers (LNA) utilize high electron mobility transistors (HEMTs). The LNAs for 1.665, 4.830 and 18.392-25.112 GHz are located on a "cold plate" with a passive cooling system, which is expected to keep a temperature of about 130 ± 20 K. The LNA for a 92-cm receiver operates at a physical temperature of 303 ± 3 K. Noise temperatures for all LNAs are indicated in Table 7. The first stage of each receiver is kept at a constant temperature of 43 ± 1.5 C by a thermo stabilization device, while the temperature in the focal container itself is kept within a 5-35 C range.

The LNAs are connected to the receiver units using semi-rigid coaxial cables. The P-, L-, and C-band receivers are designed with the single frequency conversion to 512 MHz (L- and C-band), and to the 524 MHz (P-band) central IF frequency. The conversion for K-band Multi Frequency Synthesis is more complicated and will be described later. The IF output signal of each receiver can be attenuated by 0-31 dB with steps of 1 dB, in order to adjust the input level for the Formatter. The operating bandwidth of the IF output signal is 16, 64, 64, and 320 MHz, respectively for the P-, L-, C-, and K-band receivers.

The microwave selector provides channeling of two IF signals (two polarizations or two frequency bands with different polarization) by cables, running along the support legs of the focal container, to the formatter located in the instrumentation module. In addition to the IF output, each receiver provides power levels detected with a 1 sec time constant in the bandwidths mentioned above. These power levels are digitized with a 12-bit ADC, and stored in on-board memory to be used for calibration and bore-sighting.

2.2.4 The Formatter

The Formatter receives two IF signals and converts them to a video band, where they are digitized with 10-bit at the 64 MHz sampling rate. Subsequent digital filtering is used to form the upper and low side bands of 4 or 16 MHz wide. The Formatter operates with one-bit sampling at Nyquist frequency. Finally, the Formatter forms two binary data streams corresponding to two polarization or two frequency channels (parity bit being added to every byte). These data streams are transmitted to the ground tracking station using a QPSK modulation at a rate of 18×2 or 72×2 Mbit/s. Each stream consists of a sequence of data frames each containing 20,000 bytes: 30 bytes of data header and 19,970 bytes of science data. The header replaces the science data.

The header contains a synchro-code (7 bytes) and a frame counter (2 bytes) in the range of 1-400, which covers the recording time of 1 or 4 seconds as required by the above data rate. The header contains information about the current configuration of the science complex. The first 10 bytes of the header are given for the spacecraft telemetry system, which uses these bytes to form standard telemetry frames by inputting data into successive headers. At the tracking station these TM-bytes will be identified, selected, and transferred to the Flight Control Center for near-real time analysis.

The frequency plan of the different configurations of the Formatter will be presented in section 4.1.

2.2.5 High-Data-Rate Communication radio links (HDRC)

The high-data-rate communication radio link system provides:

- Transmission of science data to the ground tracking station. The central frequency is 15 GHz, the modulation mode is QPSK, the maximum data rate is 2×72 Mbps, and the transmitted power is 40 W. There is also a low power 4 W mode.
- Receiving from the TS the reference tone signal with a nominal frequency of 7.2075 GHz, and transmitting a response at 8.4 GHz (2W), thus providing an up-down link loop.
- Coherent conversion of the received tone to a 15 MHz reference frequency to be used in the operational mode with external synchronization (alternative to synchronization of the on-board Hydrogen maser).

To provide the required power for communication at the longest distances (near apogee), the HDRC system utilizes a 1.5-m diameter high-gain communication antenna (HGCA) made of carbon-fiber. The bi-axial drive of the HGCA allows pointing at selected ground tracking stations (for more details see Section 2.4.1).

2.2.6 The System of Frequency Synthesis (SFS)

The system of frequency synthesis includes frequency standards and frequency synthesizers. In the external SFS mode, a reference frequency of 15 MHz is formed from the coherent tone signal, received from the ground TS at a frequency of 7.2 GHz. In the internal SFS mode, the H-maser frequency standard provides a reference frequency of 5 MHz for science complex. The H-maser can also provide 15 MHz reference signal for the HDRC operation, or the HDRC may utilize 15 MHz reference signal obtained from up-down link loop, while all frequency synthesizers are being feed with the H-maser output (5 MHz, or 15 MHz). In other words, operations without up-down link loop is possible, and combined modes up-down link and internal H-maser synchronizations are also allowed. An additional on-board Rubidium frequency standard (RFS) to be used for equipment testing and antenna measurements.

All local oscillator frequencies are generated by the high-frequency synthesizer (HFS) located in the focal container, while secondary LO-frequencies used by the Formatter are generated by the low-frequency synthesizer (LFS) installed in the instrumentation module. The LFS also provides a sampling frequency. All SFS devices, including the H-maser standard, have a secondary unit for redundancy. The on-board Hydrogen maser (VCH-1010) weighs 60 kg and has a size of 460x729 mm (diameter and height). It has a relative frequency uncertainty of 3×10^{-13} for 1 s, 3×10^{-14} for 10 s, 7×10^{-15} for 100 s, and 3×10^{-15} for 1000 s. A separate frequency synthesizer, as part of the receiver, is used for multi-frequency operation at 18.392-25.112 GHz.

The frequency plan for all observable frequencies is described in Section 4.1.

2.2.7 The Control System (CS)

The Control System (CS) receives commands from the TMS or the TPS spacecraft systems and distributes these commands among the different devices of the science payload. The CS consists of two units: a Control Unit located in the focal container (CUFC) and a Control Unit in the Instrumentation Module (CUIM), which are responsible for the science equipment located in the respective container.

There are two types of commands: operational commands and digital commands. An operational command represents a pulse issued by the TMS/TPS to the CS using the selected electric bus line. In response to this pulse, the CS switches voltage to the necessary relay in order to turn on the power for a receiver, for example. Digital commands are issued by the TMS/TPS to the CS or directly to the selected device, where they will be decoded and result in the required action.

2.3 RadioAstron orbit

RadioAstron will be flying in a moon-perturbed orbit, where the orbital elements have been chosen to maximize their evolution by weak gravitational perturbations from the Moon and the Sun.

2.3.1 Initial orbit elements and their evolution

The initial orbit elements and the date of launch have been selected by numerical simulations. The orbit must have ballistic lifetime greater than 9 years, and the orbiting SC may not be in the Earth's shadow for longer than 2 hours. The initial orbital elements for the planned date of launch (June 21, 2010) are the following:

- semimajor axis = 171571.612 km
- ascending node-perigee angle $\omega = 303^\circ$;
- inclination of the orbit $i = 51.4^\circ$;
- longitude of ascending node $\Omega = 304^\circ$;
- time of perigee transit 04:48:43.49 UTC on June 21 2010.

The initial rotation period is about 8.5 days and the state vector for 04:48:43.49 UTC on June 21, 2010 is expressed as:

$$X = -876.224 \text{ km}, Y = -5039.251 \text{ km}, Z = -4436.735 \text{ km}$$

$$V_x = 8.065921 \text{ km/s}, V_y = -5.427403 \text{ km/s}, V_z = 4.571491 \text{ km/s}$$

The evolution of this orbit is illustrated in Figures 4, 5, 6, 7, 8. The perigee will vary from 400 to 65,000 km, the apogee will vary from 265,000 to 360,000 km, and the eccentricity of the orbit changes from 0.59 to 0.96. The characteristic period of these variations is about three years. Figure 8 shows the equatorial coordinates for the evolving taken normal to its evolution with time. The evolutionary time scale is indicated by numbers of years, starting with zero for the planned launch date. The vector circumscribes an ellipse of 150° by 45° in about 4-5 years. Such evolution provides a possibility to observe radio sources close to the orbital plane with moderate angular resolution.

2.3.2 Orbit Measurement (OM), prediction, and reconstruction

From a ballistic point of view the SRT is a difficult object because the pressure of the solar radiation affects the elements of the spacecraft construction differently. As a result, a force-moment appears around the spacecraft center of mass. The reaction-wheel system (RWS) will be used to maintain the spacecraft orientation. Long-term effects of these force-moments lead to a permanent increase of angular momentum that requires unloading of the spinning reaction wheels by switching the gas

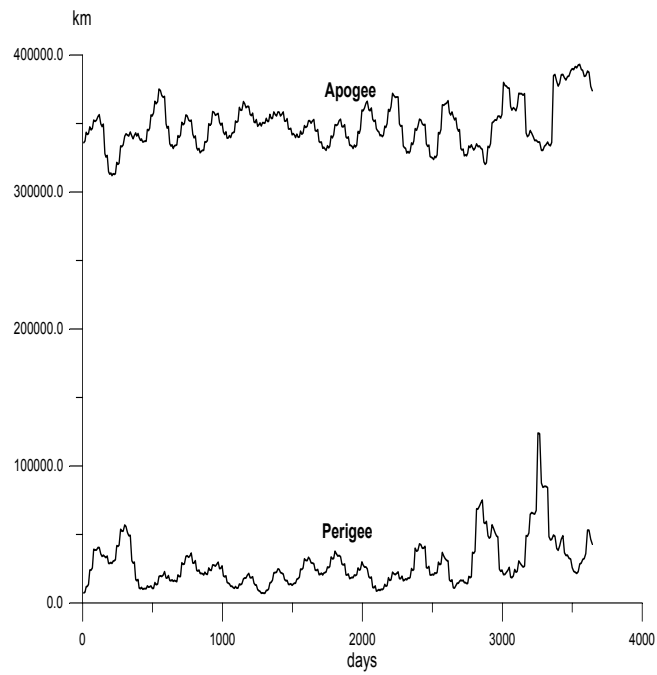


Figure 4: The variations of the perigee and the apogee heights during ten years.

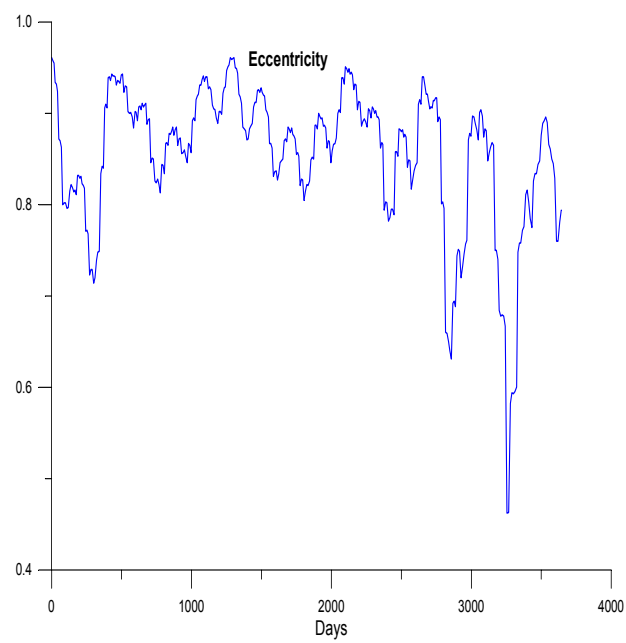


Figure 5: The variations of the orbit eccentricity during ten years.

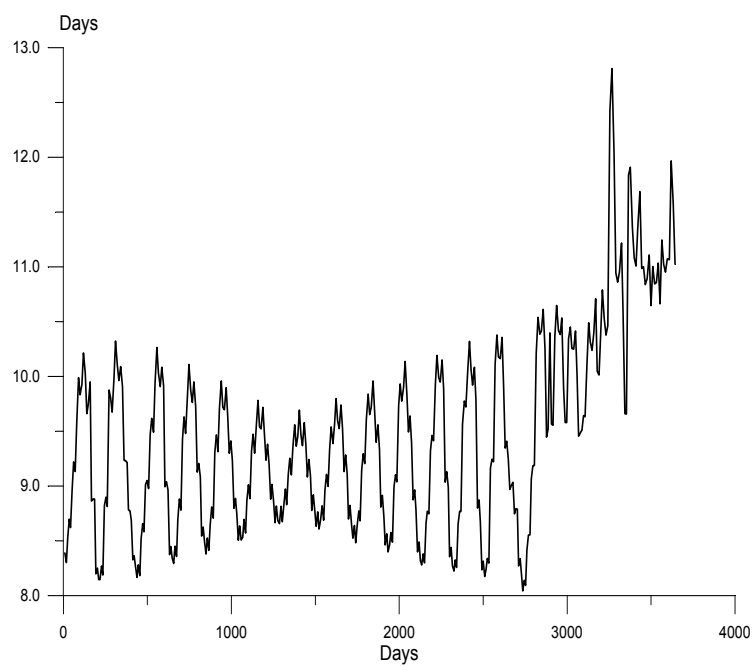


Figure 6: The variation of the orbital period during ten years.

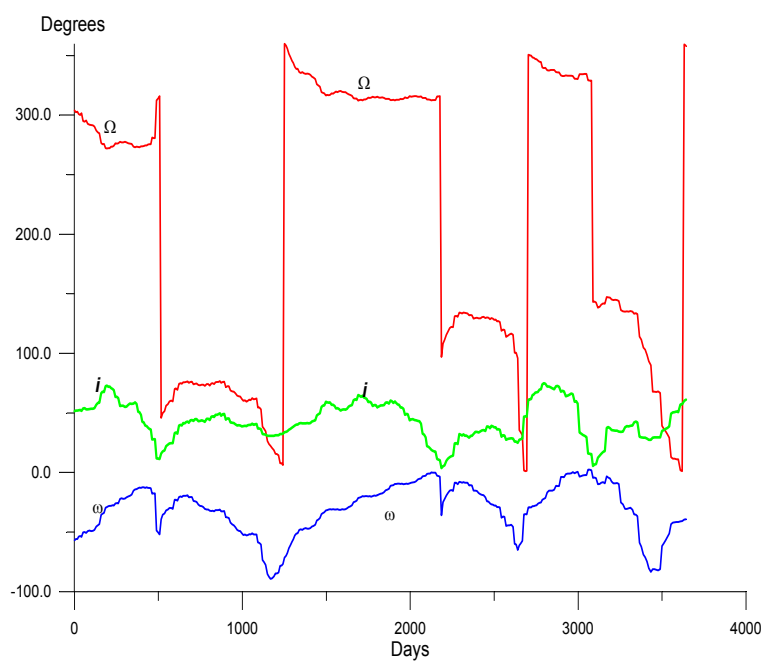


Figure 7: The variation of orbital elements (i, ω, Ω) during ten years.

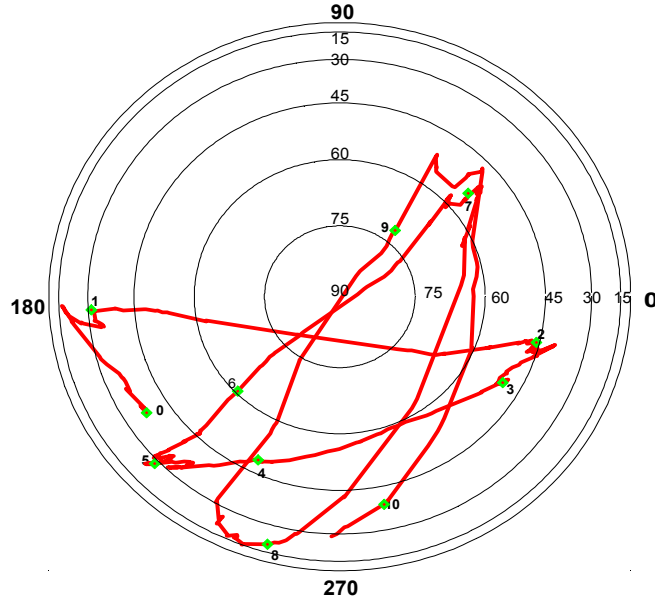


Figure 8: The evolution of the direction of orbital normal during ten years (equatorial coordinates).

engines on. Such operations result in perturbations of the motion of the SC center of mass. Estimates show that the velocity changes caused by such perturbations can reach values of 1-5 mm/s. There are three sources of OM data:

- orbit measurements made in the C-band (telemetry and commanding radio link),
- orbit measurements made in "X" band during science data transmission using the up-down link loop of the HDRC (radial velocity only),
- specific measurements using laser ranging stations.

The first kind of OM includes range and range-rate measurements made by the control station facilities located at Bear Lake (near Moscow) and at Ussuriisk. The range-rate (\dot{R}) is measured by a Doppler method using a carrier frequency in the C-band in coherent two-way mode using a 10 s integration interval. Systematic and RMS equipment errors of the \dot{R} measurements are $\sigma(\dot{R}) = 0.2$ mm/s. The range R is measured using a phase measurement with sub-carriers at 0.03, 0.3 and 1.2 MHz. Systematic and random RMS errors of the range measurements are $\sigma(R) = 20$ m. The duration of trajectory measurements in the C-band will generally not exceed 8-10 minutes.

Orbit measurements using the HDRC radio channel only give the radial components of the SC velocity, but such measurements can be done continuously during observing sessions using any tracking station that receives the scientific data. The RMS errors of these measurements are $\sigma(\dot{R}) = 0.1$ mm/s. Orbit measurements by laser ranging techniques can only be done after reorientation of the SC but would provide an accuracy of $\sigma(R) = 10$ cm.

Ballistic navigation information of the RadioAstron SC will be made available to other parties (agencies) in order to perform orbit reconstruction and other control activities and will include:

- the state vector of the spacecraft at the time of definition of the orbit with respect to the trajectory measurements,
- the radial velocity measured by ground tracking stations,
- the information about the attitude of the space radio telescope (SRT) antenna and the solar battery panels,
- the information about SC maneuvers,
- the ephemeris of the spacecraft.

The accuracy of the orbit prediction depends on the kind of trajectory measurements that were used for the orbit reconstruction. The anticipated RMS accuracy in position and velocity are (maximum errors):

- for planning the orbit (for spacecraft operations, 30 days in advance): 3000 m and 0.50 m/s,
- for predicting the orbit (for tracking stations, 3-7 days in advance): 1500 m and 0.2 m/s,
- for reconstructing the orbit (for scientific observation and correlation): 600 m and 0.02 m/s. A reconstructed orbit will be available about 2-3 weeks after the science observations.

2.4 Operational constraints

A number of physical and operational constraints affect the pointing of the on-board radio astronomy antenna SRT. A frame of reference with a right-handed rectangular coordinate system would have the X-axis directed along the electrical axis of the SRT (see Figure 1), the Y-axis falling parallel to the rotation axis of solar panels, and the origin O located at the mass center of the spacecraft. Using spherical coordinates, the angle θ may be counted from the +X-axis (0–180°), and the angle ϕ may be counted from the +Z direction counterclockwise as seen from the +X direction (0–360°).

A general condition for the SC operation is that the SC can only be illuminated by the Sun from the +Z and -X directions. In this manner, the -Z hemisphere (rhs of SC in the figure) will mainly be in the shadow.

2.4.1 Constraints connected with SC service systems

1. **Thermal Control System (TCS):** The angle between the +X-axis and the direction to the Sun must be in the range of 90–165°. In Fig. 1 the Sun will shine from the left and underneath the antenna surface). The deflection of the vector to the Sun from the XOZ-plane must not exceed $\pm 10^\circ$.
2. **Solar battery panels:** The angle between the normal to the solar panels plane and the direction to the Sun must not exceed 10° . Solar panels can only rotate around the Y-axis.
3. **Star sensors:** Three star sensors have been mounted on a single plate fixed at the pitched truss carrying the SRT dish (see section 2.2.1). Only two star sensors need to be used to establish a three-axial SC orientation.

The optical axes of two star sensors (AX1 and AX2) are directed in the following manner: a) the axes AX1 and AX2 are placed in a semi-plane inclined by 15° to the semi-plane YOZ in the direction of the -X axis, b) the angle between the AX1 and the OY axes is 45° , and c) the same

angle of 45° exists between the AX2 and OY axes. In other words, the unit vectors parallel to the AX1 and AX2 directions have spherical coordinates of $\theta = 100.5^\circ$, $\phi = 134.0^\circ$, and $\theta = 100.5^\circ$, $\phi = 226.0^\circ$, correspondingly.

The AX0-axis of the third sensor is located in the XOZ-plane with an inclination from the -X-axis by 30° in the direction of the -Z-axis ($\theta = 150.0^\circ$, $\phi = 180.0^\circ$).

Constraints also apply for the positions of the Sun, the Moon, and the Earth relative to the optical axes of star sensor in use. The offset angles must be $> 40^\circ$ from the Sun center, $> 30^\circ$ from the Moon center, and $> 30^\circ$ from the Earth limb.

4. **High-gain communication antenna (HGCA):** The HGCA provides communication with the tracking station for data transfer and frequency synchronization. Science observations with the RadioAstron SRT are possible only when such communication is in operation. The HGCA is mounted at the bottom edge of the service bus NAVIGATOR (see Figure 1). The reference axis X_A lies in the XOZ plane with an angle of 30° from the -X-axis ($\theta = 150.0^\circ$, $\phi = 0.0^\circ$).

The HGCA has a bi-axial drive using the Y_A and Z_A rotation axes. The Y_A rotation axis is parallel to the main Y-axis, and the Z_A rotation axis forms a right-handed coordinate system. In this $X_A - Y_A - Z_A$ reference frame, the HGCA 1.5-m dish can be directed to any point of the hemisphere around the X_A -axis. To be complete, there are two small forbidden areas in this hemisphere, namely, the spherical segments near the Z-axis with cone angles of 12.5° and 4.5° for the +Z and -Z poles, respectively. These exclusion areas are connected with the constraints for the rotation of the antenna around the Y_A axis.

2.4.2 Constraints connected with the science payload

1. **The LNA and feeds passive cooling system:** The angle between the -Z-axis and the Sun must be strictly larger than 90° . Moreover, the Sun must not illuminate the surface of the cooling radiator, which represents a frustum of a cone with the X-axis as a main axis and an opening angle of 60° . The conical surface is outlined by the di-hedral angle of 60° ($\pm 30^\circ$) relative to the -Z-axis. The angle between the -Z-axis and the direction to the Earth center must be strictly larger than 30° for geo-centric distances of the SC less than 20,000 km.
2. **The thermal conditions for the SRT dish surface:** The surface of the SRT dish must not be exposed to the sunlight, i.e., the angle between the +X-axis and the Sun must be strictly larger than 90° . In fact, conditions 1 and 2 are less restrictive than condition 1 in Section 2.4.1.
3. **The radio astronomical receivers:** The angle between the +X-axis and the direction to the Moon center must be strictly larger than 5° . The angle between the +X-axis and the direction to the Earth's limb must be strictly larger than 5° .

2.5 Pointing offsets and gain measurements

The Spacecraft Attitude Control System provides two possibilities for pointing and gain measurements:

1. Drift rotations of the spacecraft with a constant angular velocity ($0.005^\circ/\text{s} = 18''/\text{s}$) in two perpendicular directions may be initiated in a such a manner that the trajectories of these two scans produce a rectangular net on the sky with the observed radio source in the center. The full span of each drift scan is 1, 4.5, 12, and 20° at 18-25, 4.85, 1.65 and 0.327 GHz, respectively.

2. Successive pointing of the antenna using a series of points close to the radio source at equidistant angles on a rectangular grid or the cross-like structure. The integration time for each point may be 1-10 minutes. This would be the equivalent of a five-point procedure.

Bore-sightings will be conducted during the In-Orbit Checkout (IOC) period to determine the SRT beam structure and the initial pointing offsets. For regular antenna gain calibrations with known pointing offsets, a procedure with successive pointings on the targets will be preferable because it is less time-consuming and makes it easier to obtain the required integration times.

For gain measurements (scanning or pointing), the power levels from a given receiver output (using the total bandwidth before the IF-system) is being recorded into the on-board telemetry memory, together with the required data from the Attitude Control System. This combined data can be transmitted directly to a ground telemetry stations during a control session or afterwards. Pointing offsets and gain corrections will be determined using off-line data processing.

2.6 Calibration

2.6.1 Noise calibration

Each frequency receiver has a noise calibration signal generator that injects a noise signal into the LNAs. There are two levels of Noise-Cal power: a high-level Noise-Cal that equals about half the system temperature T_{sys} , and a low-level Noise-Cal that constitutes a few percent of T_{sys} . The ON/OFF switch of the Noise-Cal generators may be operated by the commands: a sequence of calibration events may be stored in the spacecraft Time-Program System (TPS) for future execution. A continuously cycling ON/OFF mode can be used when the noise diode output is connected (or disconnected) to the noise injection system; the switching period equals double the length of the data frame in the on-board digital data stream Formatter. In this case, all even frames correspond to data records with the Noise-Cal signal ON, and all odd frames correspond to records with the Noise-Cal signal OFF.

The on-board Formatter synchronously detects a power level in the corresponding frequency band for each frame, and puts the data into frame headers. Science observations may continuously employ this mode using the low-level Noise-Cal generator.

2.6.2 Pulse calibration

A pulsed calibration signal can be injected into the LNAs at P-, L-, and C-bands; for the K-band it is injected at the IF frequency. The power level of the injected pulses is equivalent to 1-3% of the receiver noise. The pulse repetition period is $1\mu s$ and the spectrum of the signal with pulse injection will show narrow harmonics separated by 1 MHz. These calibration tones will be detected and analyzed during data correlation.

3 RadioAstron Ground Segment and Operations

The ground segment of RadioAstron consists of Control Stations (CS) for operating the satellite, Laser Ranging Stations for tracking the satellite position, Tracking Stations (TS) for receiving the satellite data, Ground Radio Telescopes (GRT) co-observing with RadioAstron, and Correlator Facilities (CF) for data processing.

3.1 Tracking stations

The primary TS for the RadioAstron Mission is based on the 22-m radio telescope of the Pushchino Radio Astronomical Observatory (PRAO). The hardware configuration of the TS and signal distribution and transformation are shown in the diagram presented at the RadioAstron web site¹.

The PRAO TS will carry out the following functions:

- Tracking the spacecraft in its motion along the sky during the communication session.
- Receiving binary stream science data at a 15 GHz central frequency with QPSK modulation at a maximum rate of 144 Mbps, decoding the data, and recording it with the RDR recording system.
- Selecting telemetry information (TM) from the frame-headers of the science data stream, recording the TM information, and distributing this TM-data among the customers in a near real-time fashion.
- Extracting the current 15 GHz carrier in the science data stream, and measuring the residual phase relative to the PRAO H-maser frequency standard.
- Transmitting to the SC of the reference tone signal synchronized in phase with the PRAO H-maser frequency standard at 7.2 GHz.
- Receiving the reference signal from the SC that is coherently transformed from 7.2 to 8.4 GHz.
- Measuring the full and residual phase, and recording the results.
- Measuring the time corrections between the on-board time scale and the local time for the correlator log-file.

3.2 Ground radio telescopes

The 10-m space radio telescope (SRT) has relatively small effective area. Consequently, the largest ground radio telescopes should be utilized in the RadioAstron mission to provide the highest possible sensitivity and guarantee efficient observations. A radio telescope with a diameter larger than 60-m in conjunction with the SRT will be at least equivalent to two 25-m dishes. A list of the most prospective radio telescopes to operate with RadioAstron is presented in Table 2. At present only VLA, GBT, Parkes, ATCA, and three DSN radio telescopes can operate in the MFS mode at 18-25 GHz.

Observing time at these observatories can be obtained on the basis of regular proposals to the selected observatories. More details on obtaining scientific access are given in Section 3.7 and the Announcements of Opportunity for the RA Mission.

3.3 Data recording

The RadioAstron Data Recorders (RDR) will be used at the TS in Pushchino and at all Russian radio telescopes. The RDR was developed and manufactured at the ASC. It utilizes a rack of four disks under the control of a PC. The main processor is a P4-3.06 GHz, the data input controller is a

¹<http://www.asc.rssi.ru/radioastron/documents/memo/2006/memo7/ts.htm>

Table 2: List of prospective radio telescopes

Telescope	Effective diameter (m)	RA-compatible frequency bands
Arecibo	300	P, L, C
GMRT	246	P
VLA	125	P, L, C, K
GBT	100	P, L, C, K
Effelsberg	100	L, C, K
WSRT	93	P, L, C
Jodrell Bank	76	P, L, C
DSN Goldstone	70	L, K
DSN Robledo	70	L, K
DSN Tidbilla	70	L, K
Ussuriisk	70	P, L, C, K
Eupatoria	70	P, L, C, K
Parkes	64	P, L, C, K
Kalyazin	64	L, C
Usuda	64	L, C, K
Sardinia	64	P, L, C, K

Notes: VLA: subject to the phased mode availability of the new WIDAR correlator; Sardinia: subject to its readiness for VLBI observations.

PCI-7300A, and the RAID-0 output controller is a Fast Track 100TX. The recording rate is 128 Mbps, the number of digital input channels is 8 or 16. The RDR operates under external synchronization using 1 Hz and 32 MHz. The RDR takes data from the Data Acquisition System (DAS) of the ground radio telescopes, and from the science data decoder at the TS.

Mk5 data recording at ground radio telescopes is possible. See next section for data correlation discussion.

3.4 Data correlation

The ASC software correlator (SWC) will be used for primary processing of the VLBI data using a 40-node cluster. Real-time data correlation can be conducted for a three baseline VLBI experiment with up to four frequency bands. The ASC correlator team will provide a preliminary quality testing after correlation. There is no principal restriction on the number of channels (delays) to be processed. The input data can be formatted in the RDR, SDF and TCI protocols, but principally any standard digital data format can be accepted, especially Mk5A and Mk5B formats.

3.5 Satellite operations and experiment scheduling

The Mission Operations Plan calls for a long-term 4-months (16 orbits) schedule (LTS) for a given trimester and short-term schedules (STS) for the current 5 weeks. The STS will be updated every week. Both LTS and STS schedules are presented as Space Radio Telescope Schedule files (SRS) in a format similar to those of the VSOP mission. The observing schedules for observations within the LTS and STS will be created with the SCHED software by the RadioAstron Mission Scheduling Team (RMST) for all participating ground radio telescopes.

To obtain observing time for Key Science or PI-driver projects, scientists will need to submit proposals to Program Committees of Radioastron and participating ground-based observatories or networks. It is also possible to secure access to ground radio telescopes on the basis of special agreements. In particular, radio telescopes in Russia will be used on the basis of separate agreements.

Mission operations will be carried out by the ASC RMST, in close interaction with the General Operative Control Group (GOCG) of Lavochkin Associates. The RMST will create the Long-Term Schedules in the standard SRS for every trimester. The GOCG at LA will convert these SRS commands into the spacecraft operation commands. Mission operations are described in the RadioAstron Mission Operation Handbook (RMOH). It may be found on the ASC web site at

<http://www.asc.rssi.ru/RadioAstron/documents/rmoh/eng/contents.htm>

3.6 Observational modes and procedures

Let us distinguish continuum ($B = 2 \times 16$ MHz) and spectral ($B = 2 \times 4$ MHz) modes of observations in the correspondence with the frequency setup given in paragraph 4.1. In the spectral mode both USB and LSB are being recorded, and one of the sub-bands may be useless. ASC software correlator can provide required spectral resolution through the zoom technique. In standard configurations both RCP and LCP polarization channels are being recorded. Due to concentric feed construction two-frequency observations in any frequency combinations are also possible. Note, that in two-frequency mode channels with opposite sense of polarization will be used. Because of low speed of SRT at the apogee portion of the orbit, it may be useful to observe the source sequentially at different frequencies. Switching time between frequency channels is negligible. But one shall understand that all used receivers must be with power ON (including thermostats), thus increasing power consumption.

Spacecraft control will be conducted on a daily basis. Control session will take from 2 to 4 hours depending on the volume of transmitted commands. Additional session of orbit measurements by radio and by laser will take about 15 minutes each. All these events will be scheduled by the LA group well in advance. As for a torque wheel spin-down procedures they will be added on a later stage of scheduling, when the main science program will be composed. Therefore there might be several iterations of scheduling between the ASC and the LA. We expect that every day about 20 hours will be left for science observations. The continuous observing time for a single target can be in the range from 1 to 20 hr. Up to 15 re-pointings are allowed between the control sessions. The setting time after each re-pointing is about 5 minutes. The slew rate is 0.1 deg/s. The observing procedure (using of fringe finders, switching noise and pulse calibrations etc.) must be defined by the PI or responsible science team. There is a special observing procedure performing cycling in pointing between the source under investigation and one or two reference sources located on the sky in the range of few degrees. The slew rate in this procedure is 0.005°/s, and the setting time is about a minute. Observing time (on-source) can be specified as a parameter, but it must be equal for every sources (main and reference) in a given cycling. Number of cycles is also a parameter. These cycling do not count against number of re-pointings. The procedure may be used for astrometry or fringe calibrators.

3.7 Science access

The RadioAstron mission will begin with a *commissioning phase*, or In-Orbit-Checkout (IOC) period. The first part of the IOC includes an *engineering commissioning* with a spacecraft bus checkout, the unfolding of the SRT, receiver checks and tests of the radio astronomy antenna in single-dish mode (bore-sighting), and communication tests with the tracking stations (using the HDRC system). It is expected that this engineering commissioning period will occupy about five orbits (45 days). The

Table 3: The frequency set for the RadioAstron SRT

LO2-frequency (MHz)	Designation	P-band	L-band	C-band	K-band
500	S1		1652	4820	22220
508	C2		1660	4828	22228
516	C3		1668	4836	22236
524	S4	324	1676	4844	22244

second part of the IOC is a *scientific commissioning phase* that consists of tests of the SRT science payload in VLBI mode using large ground radio telescopes. For this process the largest ground-based radio telescopes are required, including those located in Russia.

The second phase of the IOC, although designed for engineering checkouts, will give the first scientific results of the mission. This IOC phase will be smoothly transitioned into a *scientific verification phase* — an Early Science Program (ESP) with a duration of about 10-20 orbits (3-6 months) to be executed by international Early Science Program Teams (ESPT). There will be no AO for the ESP period but the ESPT will need to secure access to ground radio telescopes on the basis of proposals or special agreements. The international ESPT is being organized by the mission from individuals and institutions that have contributed to the Radioastron project development.

After the ESP period, there will be observations for the Key Science Programs (KSPs) with each KSP representing different important areas of the scientific research program for the mission. Scientists may participate in the KSPs by responding to an open announcement of opportunity (AO) issued before the launch date. KSPs may continue during the whole mission as appropriate. After the commissioning phase, yearly series of open AO's for individual investigators will be issued by the Mission for the observing period starting after the ESP phase.

4 Observations with RadioAstron

4.1 The Frequency setup

Four frequency ranges are available for astronomical observations: 92-cm (P-band), 18-cm (L-band), 6.2-cm (C-band), and 1.19-163 cm (K-band). In each band two output channels that produce circular polarization (LCP and RCP) signals, which may be used simultaneously. Alternatively two different frequency bands may be used instead of two polarizations. In principle, any frequency combination is possible, except that the two frequency channels will have an opposite polarization.

The RadioAstron IF-to-VIDEO converter (the Formatter) can operate at two sampling rates of 16 and 64 MHz. Low-rate sampling provides simultaneous sideband recording (LSB+USB) with a 4 MHz width in both polarization (or in two frequency ranges) with one-bit sampling. This sampling mode will be used for observations of spectral lines and always in the 92-cm range, which is restricted in bandwidth by interference. In narrow-band (4 MHz) mode the Formatter will generate a binary data stream of 36 Mbps. High-rate sampling is used for continuum observations and provides recording in two polarizations (RCP+LCP) or in two frequency ranges with two 16-MHz bands (LSB+USB). The resulting data stream has a rate of 144 Mbps with a parity control bit for every byte. Note, that the LSB spectra will always be inverted.

The High-Frequency Synthesizer (HFS) provides fixed LO-1 frequencies at 200, 1152, and 4320 MHz for the P-, L- and C-bands respectively. The K-band has a different setting and is treated separately.

The first LO moves the selected frequency range to an IF of about 490-540 MHz, and supplies the input signal for the Formatter. The Formatter uses four LO-2 frequencies of 500, 508, 516, and 524 MHz in order to permit some tuning of the desired sky frequency. Table 3 gives the correspondence between the LO-2 and sky frequency values, that separate lower and upper sub-bands (LSB/USB). For the K-band only main sky frequencies are indicated, and details are given in the subsection 4.1.1.

Many combinations of frequency range and polarization are possible for observations with the RadioAstron SRT. In order to simplify proposal composition and subsequent scheduling, we present in Table 4 the most probable observing configurations with their corresponding conventional acronyms. The table shows the frequency configurations for every mode. Channels 1 and 2 corresponds to the two input channels of the Formatter. For the every channel LSB and USB frequency range are presented in the table. Remember, that the LSB spectra are inverted. The last column indicates the total recorded band.

The spectral line observing modes in the table are characterized by their 4 MHz observing bandwidth, while the continuum modes have a 16 MHz bandwidth.

Observations in the L-band facilitate limited capability of observing OH Megamaser activity. The LO-2 settings in Table 4 suggest a maximum redshift for extragalactic OH emission of $z = 0.0104$ (3123 km/s); only four OH MM have been found in this redshift range.

4.1.1 K-band observing and MFS

The last two observing modes (m135RLSYNC2, m135LRSYNC2) describe the procedure for multi-frequency synthesis (MFS) in the 18 to 25 GHz frequency range. In these modes one polarization channel (RCP or LCP) operates at a fixed frequency, while the second polarization channel switches frequency in steps of 960 MHz starting at the lowest value of 18392 MHz, which corresponds to the 512 MHz IF input of the Formatter. The highest frequency is 25112 MHz. The observing interval is 300 seconds for each of the eight frequencies and the whole cycle takes 40 minutes. The next cycle starts again at the lowest frequency.

Besides these automatic MFS modes, one may select a particular frequency switching or a static configuration by issuing a specific sequence of commands. Below is a simple expression to calculate the possible sky frequency values correspondingly to the center point of USB/LSB band:

$$F_{j,k} = 22232 + 960j + 32k + (512 - F_f),$$

where $j = -4, -3, -2, -1, 0, 1, 2, 3$, $k = 0, -1, -2, -3$, and the F_f are the LO-2 values used in the Formatter (Table 3). The j values select the MFS frequencies, and k provides additional frequency tuning to allow for observations of the extragalactic H_2O Megamaser emission. Thus, the coarse (j) and the fine (k) tuning provide narrow redshift windows of $z = 0.0000 - 0.0053$, $0.0424 - 0.0485$, $0.0855 - 0.0917$, $0.1287 - 0.1348$, and $0.1719 - 0.1780$. Note, that seventeen H_2O MM have been detected in the first redshift window and only two in the second window, and none (yet) in the higher windows.

4.2 Observing strategy and imaging

4.2.1 All-sky UV-plots

The functional constraints described in section 2.4 restrict available areas on the sky. These areas are presented in Figures 9, 10 as all-sky uv-plots, calculated by FakeSat software for the orbit starting on June 21, 2009. The UV-plots are calculated for the K-band for 200 hours (full orbit) time interval

Table 4: The observing modes for the RadioAstron SRT

N	Observing mode	Channel 1		Channel 2		BW (MHz)
1	m92LRS4	P-band, LCP		P-band, RCP		2*(4+4)
		320-324	324-328	320-324	324-328	
2	m92L18RS4	P-band, LCP		L-band, RCP		2*(4+4)
		320-324	324-328	1672-1676	1676-1680	
3	m92R18LS4	P-band, RCP		L-band, LCP		2*(4+4)
		320-324	324-328	1672-1676	1676-1680	
4	m6LRC2	C-band, LCP		C-band, RCP		2*(16+16)
		4812-4828	4828-4844	4812-4828	4828-4844	
5	m6LRC3	C-band, LCP		C-band, RCP		2*(16+16)
		4820-4836	4836-4852	4820-4836	4836-4852	
6	m6R135LC2	C-band, RCP		K-band, LCP		2*(16+16)
		4812-4828	4828-4844	22212-22228	22228-22244	
7	m6R135LC3	C-band, RCP		K-band, LCP		2*(16+16)
		4820-4836	4836-4852	22220-22236	22236-22252	
8	m6L135RC2	C-band, LCP		K-band, RCP		2*(16+16)
		4812-4828	4828-4844	22212-22228	22228-22244	
9	m6L135RC3	C-band, LCP		K-band, RCP		2*(16+16)
		4820-4836	4836-4852	22220-22236	22236-22252	
10	m18LRC2	L-band, LCP		L-band, RCP		2*(16+16)
		1644-1660	1660-1676	1644-1660	1660-1676	
11	m18LRC3	L-band, LCP		L-band, RCP		2*(16+16)
		1652-1668	1668-1684	1652-1668	1668-1684	
12	m18LRS3	L-band, LCP		L-band, RCP		2*(4+4)
		1664-1668	1668-1672	1664-1668	1668-1672	
13	m18L6RC2	L-band, LCP		C-band, RCP		2*(16+16)
		1644-1660	1660-1676	4812-4828	4828-4844	
14	m18L6RC3	L-band, LCP		C-band, RCP		2*(16+16)
		1652-1668	1668-1684	4820-4836	4836-4852	
15	m18R135LC2	L-band, RCP		K-band, LCP		2*(16+16)
		1644-1660	1660-1676	22212-22228	22228-22244	
16	m18R135LC3	L-band, RCP		K-band, LCP		2*(16+16)
		1652-1668	1668-1684	22220-22236	22236-22252	
17	m18L135RC2	L-band, LCP		K-band, RCP		2*(16+16)
		1644-1660	1660-1676	22212-22228	22228-22244	
18	m18L135RC3	L-band, LCP		K-band, RCP		2*(16+16)
		1652-1668	1668-1684	22220-22236	22236-22252	
19	m135LRC2	K-band, LCP		K-band, RCP		2*(16+16)
		22212-22228	22228-22244	22212-22228	22228-22244	
20	m135LRC3	K-band, LCP		K-band, RCP		2*(16+16)
		22220-22236	22236-22252	22220-22236	22236-22252	
21	m135LRS2	K-band, LCP		K-band, RCP		2*(4+4)
		22224-22228	22228-22232	22224-22228	22228-22232	
22	m135LRS3	K-band, LCP		K-band, RCP		2*(4+4)
		22232-22236	22236-22240	22232-22236	22236-22240	
23	m135LRS4	K-band, LCP		K-band, RCP		2*(4+4)
		22240-22244	22244-22248	22240-22244	22244-22248	
24	m135LRSYNC2	K-band, LCP		K-band, RCP		2*(16+16)
		22212-22228	22228-22244	Switching frequency		
24	m135RLSYNC2	K-band, LCP		K-band, RCP		2*(16+16)
		Switching frequency		22212-22228	22228-22244	

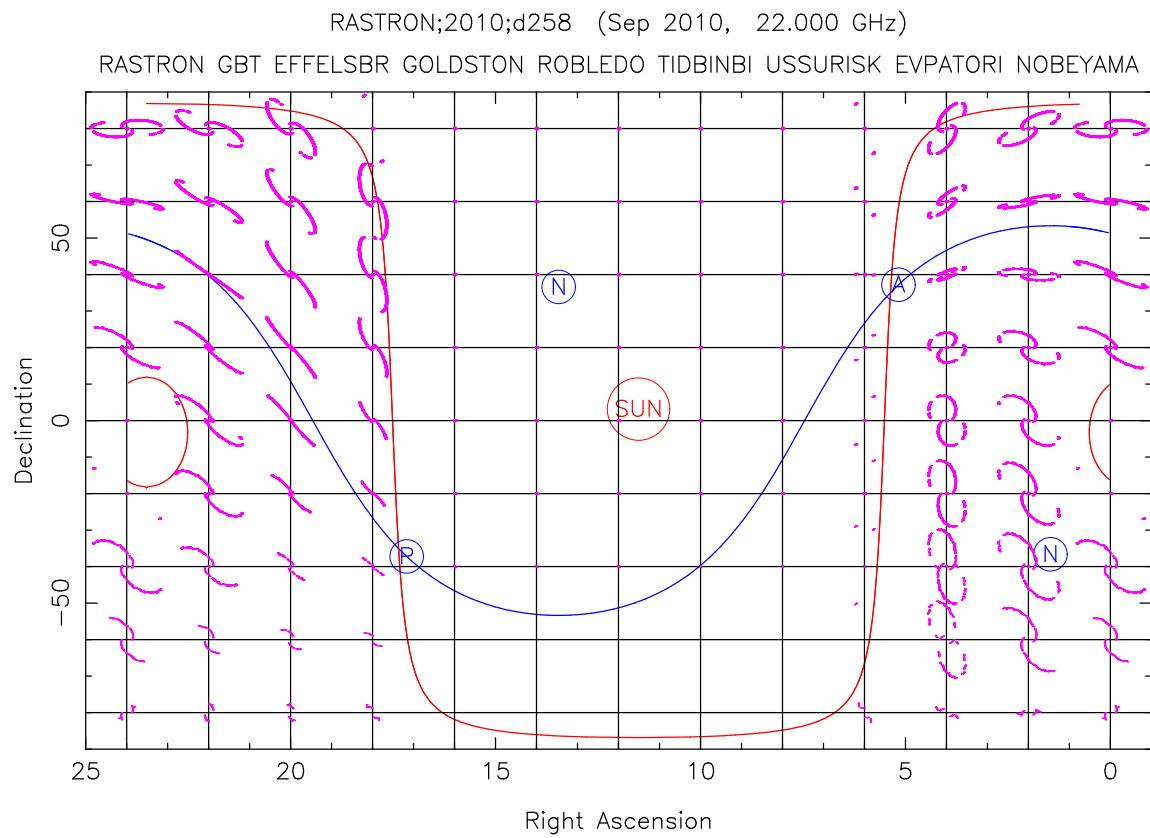


Figure 9: All-sky UV-plots for September 15, 2010. Only one tracking station (Puschino) is used in the calculation.

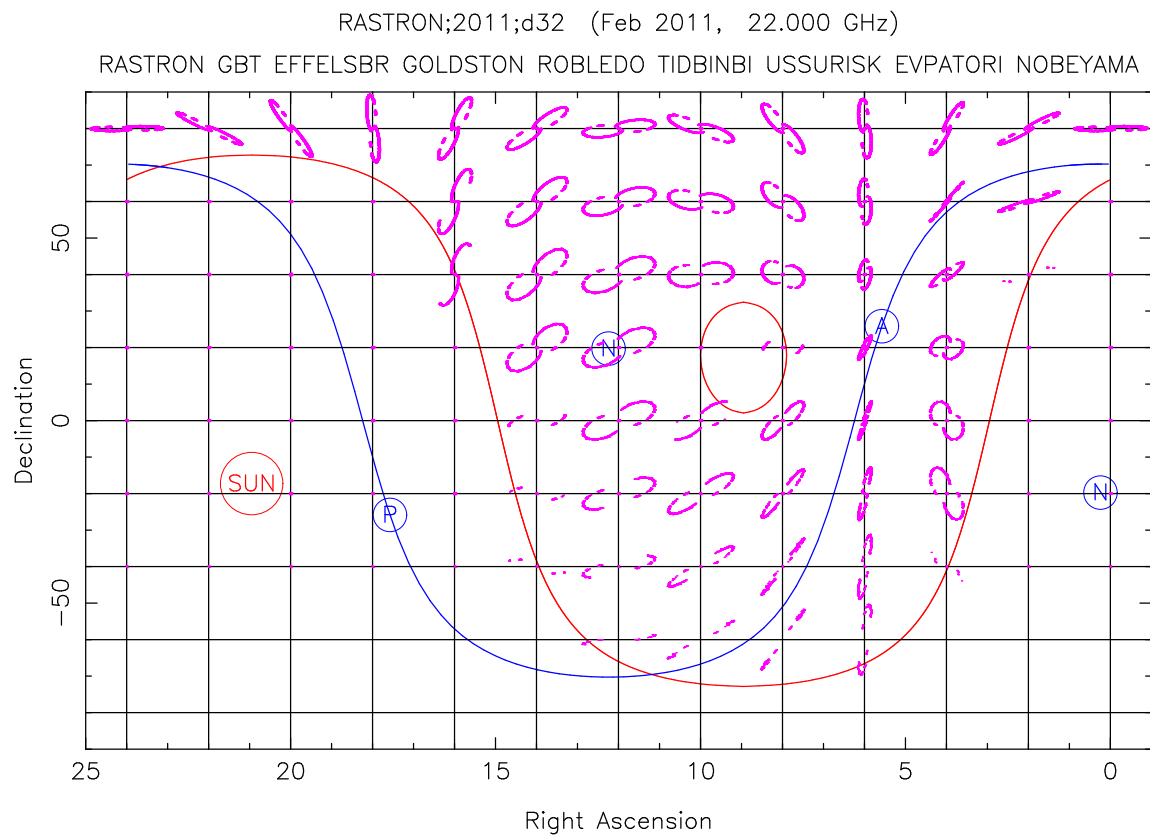


Figure 10: All-sky UV-plots for February 1, 2011. Only one tracking station (Puschino) is used in the calculation.

at the every crossing of the coordinate draw (net) with a step of 20° in declination and two hours in right ascension. In these figures line drawn through “P” (perigee) and “A” (apogee) presents orbit projection on the sky, and another solid line designates a border separating regions available and forbidden for observations because of constraints related with the Sun position. As was explained in section 2.4 the hemisphere with the Sun at the pole is unavailable for observations; there is also a “blind spot” in the anti-Sun point. The most favorable conditions for observations are during the periods when the Sun is close to the perigee (November-February). Unfavorable circumstances occur when the Sun is close to the apogee (May-July). This is because of constraints connected with the communication antenna, which must be pointed to the tracking station (TS); communication with the TS is impossible when the spacecraft is between the Earth and the Sun in the apogee portion of the orbit. Figure 9 shows UV-coverage for September 2010, when the first fringe search is expected, and figure 10 presents UV-coverage for February 1, 2010, when ESP will be carried out.

4.2.2 Examples of observing strategies

In order to implement peculiarities of high-apogee moon-perturbed RadioAstron orbit the mission envisages some typical strategies of the observations: survey of brightness temperatures, perigee imaging, near-orbit-plane imaging, apogee imaging, all-orbit synthesis, astrometric measurements. Survey of brightness temperatures will be conducted by observing large sample of radio sources at progressively increasing baselines. Transfer to longer baselines will be made on the basis of visibilities obtained at shorter baselines. The Near-perigee imaging is continuum observations of single radio source during 4-12 hours with the SC passing perigee portion of the orbit. Duration of an observing set will be restricted by the functional constraints. Space-ground baseline projections will be in the range of 30000 km, thus providing reasonably good UV-coverage. The examples of such UV-coverage are presented in Fig. 11. The Near-orbit-plane imaging will be conducted recurrently for several radio sources located close to the orbit plane during SC passing this direction providing relatively short baselines. The observing session will take from 12 to 24 hours because of low speed of the SC. Therefore, during this period several sources may be observed alternatively. The near-apogee imaging would take even longer time of every source (24-48 hours). Such observations may be combined with other measurements, such as survey of brightness temperatures. All-orbit synthesis will be used for prospective bright sources by observing a source during a whole orbit or even during several orbits. Such observations will be combined with other types of measurements. This strategy is especially useful in MFS frequency mode which reduces the gaps in UV-coverage.

4.2.3 Imaging capabilities

As discussed above, there are three basic modes envisaged for imaging experiments: perigee imaging, apogee imaging and orbital plane imaging. Several typical imaging experiments with RadioAstron are described in Table 5 and Figs. 11–13. In all these experiments, RadioAstron tracking is assumed to be done with a single tracking station in Puschino. The experiment 1(P) is a perigee imaging observation, the experiments 2–4(A) are examples of apogee imaging observations and the observation 5(O) is an observation of an object near the orbital plane of RadioAstron. The latter mode allows sampling small spatial frequencies also on baselines to RadioAstron, which will be beneficial for improving the uv -coverage and calibrating space baseline data. Respective uv -coverage and histograms of visibility distributions are shown in Figs. 11 and 13.

The effect of the individual uv -coverage on imaging is estimated by the uv -gap parameter, $\Delta u/u$, calculated as a normalized difference $(u_2 - u_1)/u_2$ for any two visibility points within a sufficiently small angular sector (the sector size can be set by the scan length of an observation, with the latter assumed to be 5 minutes, in the examples discussed here). Azimuthal averages of $\Delta u/u$ are shown

Table 5: Image parameters of selected RadioAstron experiments

Exp.	t_{obs} (hrs)	δ ($^{\circ}$)	Ground Telescopes	Beam ($\mu\text{as} \times \mu\text{as}, ^{\circ}$)	$\langle \Delta u/u \rangle$	$\langle \sigma_{\text{uv}} \rangle$ (σ_{rms})	SDR_{uv} (SDR_{FOV})
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1 (P)	5	+30 $^{\circ}$	EbGbJbNbRoUsEv	184 \times 92,+37 $^{\circ}$	0.25	19.5	0.58
2 (A)	28	+40 $^{\circ}$	EbGbJbNbY1RoUsEvGoTb	94 \times 24,+152 $^{\circ}$	0.09	9.0	0.83
3 (A)	28	+80 $^{\circ}$	EbGbJbNbY1RoUsEvGo	80 \times 25,+156 $^{\circ}$	0.05	5.3	0.90
4 (A)	24	+20 $^{\circ}$	EbGbJbNbY1RoUsEvGoTb	156 \times 22,+101 $^{\circ}$	0.11	6.0	0.82
(O)	48	+45 $^{\circ}$	EbGbJbNbY1RoUsEvGo	290 \times 89,+54 $^{\circ}$	0.04	3.2	0.91

Notes: (1) – Experiment code: numbers refer to plot panels in Figs. 4.1–4.3; letters denote observations near the perigee (P), the apogee (A), and the orbital plane (O); (2) – observation duration (hrs); (3) – declination of the target source; (4) – participating ground telescopes; (5) – estimated beam for uniformly weighted data; (6) – average uv -gap parameter; (7) – noise contribution from incomplete uv -coverage, normalized to the r.m.s. noise; (8) – structural dynamic range (range of structural scales that can be imaged), normalized to the full SDR_{FOV} given the ratio of primary beam of the largest radio telescope participating in an observation to restoring beam of the interferometry data.

in Fig 12 for a range of uv -radii. Overall averages of the uv -gap parameter are given in Table 5 and used for deriving the effect of RadioAstron uv -coverage on the image noise and spatial dynamic range (defined as a ratio of largest and smallest structures that can be imaged).

The examples described above indicate that the best imaging performance will be achieved with long observations that sample a larger range of spatial frequencies and provide a better chance for inter-calibrating ground and space baselines.

4.3 Resolution

The smallest fringe spacing of 7 μas is achieved with the largest ground-space baseline at K-band, see Table 1 for details. Effective resolution of reconstructed space-VLBI images for different types of uv -coverage can be found in Table 5.

4.4 System sensitivity

The parameters of the RadioAstron on-board receiver system have been measured in the laboratory at a physical temperature equivalent to the one expected during space operation, where passive cooling will give a physical temperature of $t_{\text{LNA}} = 130\text{K}$. The losses in the cable connections to the feeds were measured separately, as well as losses in the feeds themselves. The T_{sys} values may then be calculated using the following expression:

$$T_{\text{sys}} = T_{\text{sky}} + t_{\text{dish}}(L_{\text{dish}} - 1) + t_{\text{feed}}L_{\text{dish}}(L_{\text{feed}} - 1) + t_{\text{cbl}}L_{\text{dish}}L_{\text{feed}}(L_{\text{cbl}} - 1) + L_{\text{dish}}L_{\text{feed}}L_{\text{cbl}}T_{\text{LNA}},$$

where L_{feed} , L_{cbl} , and L_{dish} are losses in the feed, cable and SRT surface, respectively. The t_{feed} , t_{cbl} , and t_{dish} values are the respective expected physical temperatures in K. Table 6 presents an L values and the expected physical temperatures (t) (in K) for each frequency, where L has been defined as $L = 1/k$ with k being the partial power loss in the corresponding device; for example, for $k = 0.98$, $L = 1.020$.

Table 7 presents the measured T_{LNA} and calculated T_{sys} values for the RadioAstron receiver system. Table 8 shows estimates of the expected sensitivity of space-ground interferometry with SRT and using

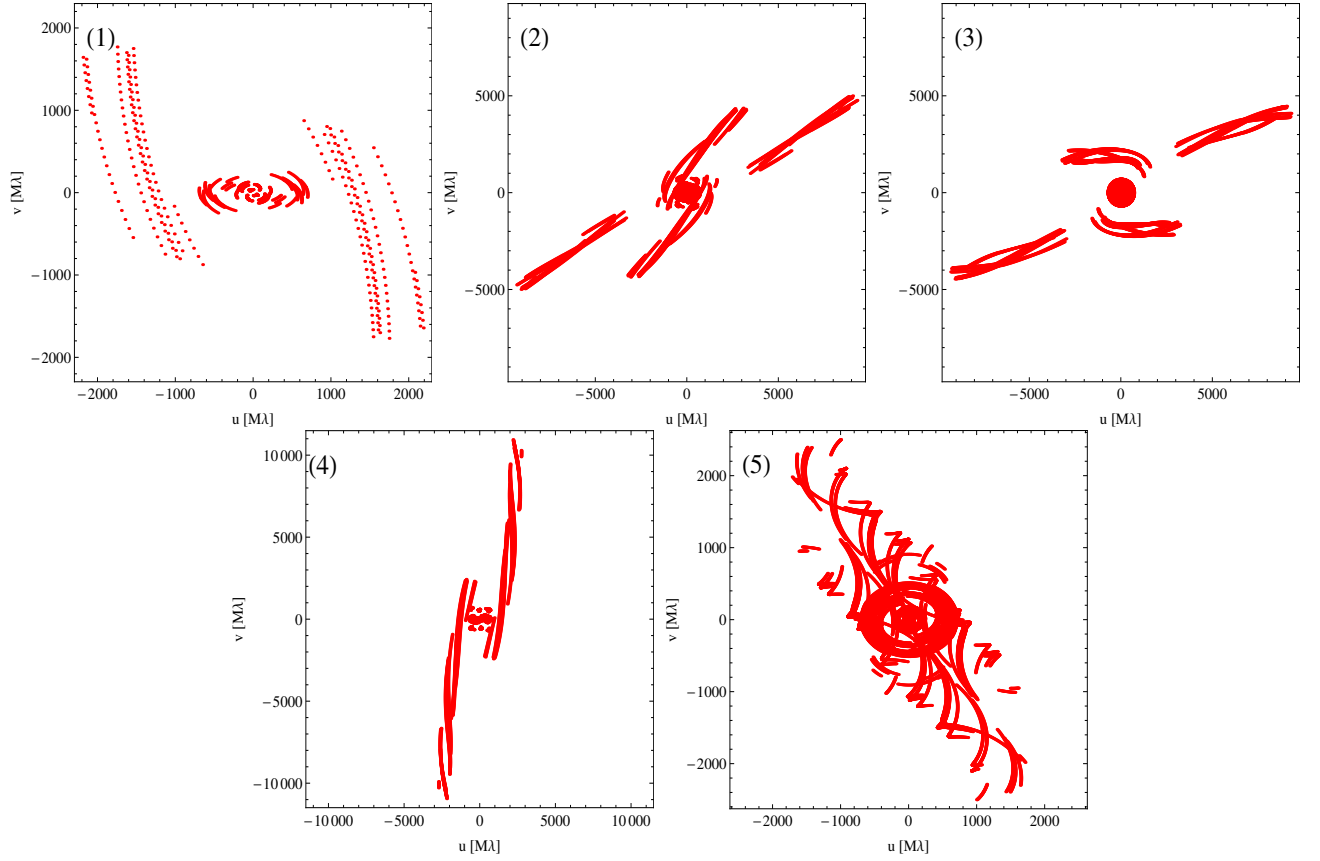
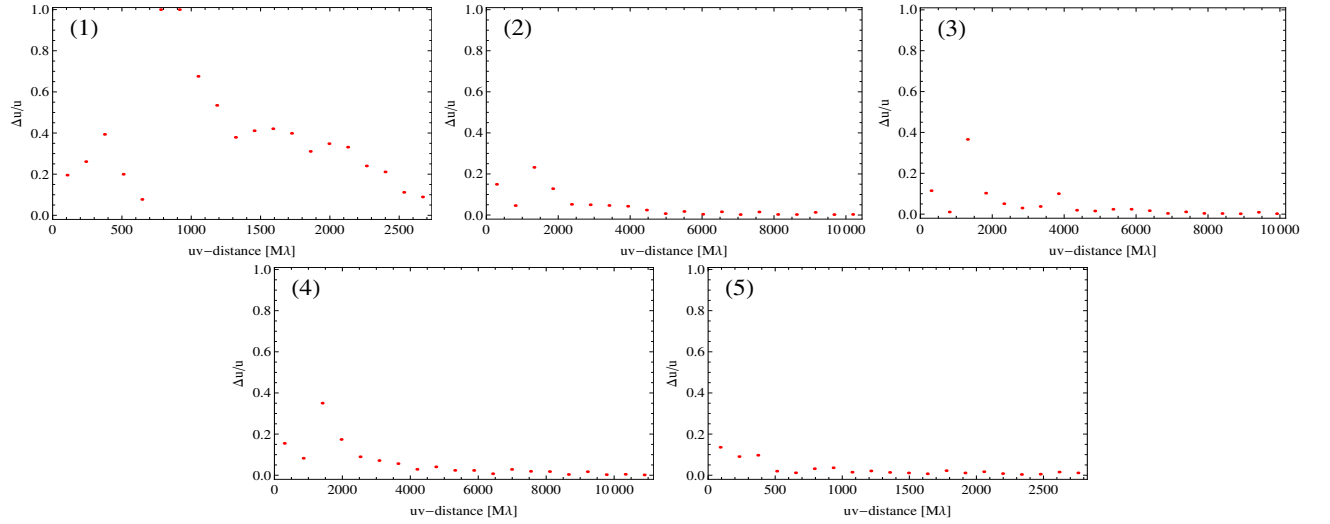
Figure 11: Coverages of the uv -plane for the five experiments listed in Table 5.Figure 12: Radial averages of the uv -gap parameter, $\Delta u/u$, for the five experiments listed in Table 5.

Table 6: The losses L and physical temperatures t of the RadioAstron receiver system

	P-band		L-band		C-band		K-band	
	L	t (K)	L	t (K)	L	t (K)	L	t (K)
Cable	1.040	230	1.036	150	1.058	150	1.000	150
Feed	1.250	170	1.020	170	1.106	170	1.076	170
Dish surface	1.020	200	1.020	200	1.020	200	1.020	200

Table 7: The budget of system temperature

	P-band	L-band	C-band	K-band
T_{LNA}	35	15	25	40
ΔT_{cbl}	9	6	11	0
ΔT_{feed}	54	5	22	20
ΔT_{dish}	6	4	5	7
T_{sky}	60	3	3	3
T_{sys}	164	33	66	70

Table 8: The sensitivity of the RadioAstron mission

	RadioAstron			
	P-band	L-band	C-band	K-band
Band width per polarization (MHz)	4	2×16	2×16	2×16
T_{sys} (K)	164	33	66	70
$A_e(m^2)$	30	40	40	30
SEFD (Jy)	15400	2300	4400	6500
	GBT			
T_{sys} (K)	105	20	18	35
$A_e(m^2)$	5500	5500	5500	4800
SEFD (Jy)	55	10	8	23
	RadioAstron+GBT			
S_{min} (mJy) ($\sigma, \tau = 1$ s)	720	55	85	210
S_{min} (mJy) ($\sigma, \tau = 300$ s)	42	4	4	10

Notes: The 1σ baseline sensitivity is shown for the 16 MHz (4 MHz for the P-band) bandwidth of a single polarization single frequency channel (IF) to be used for detection cutoff estimates.

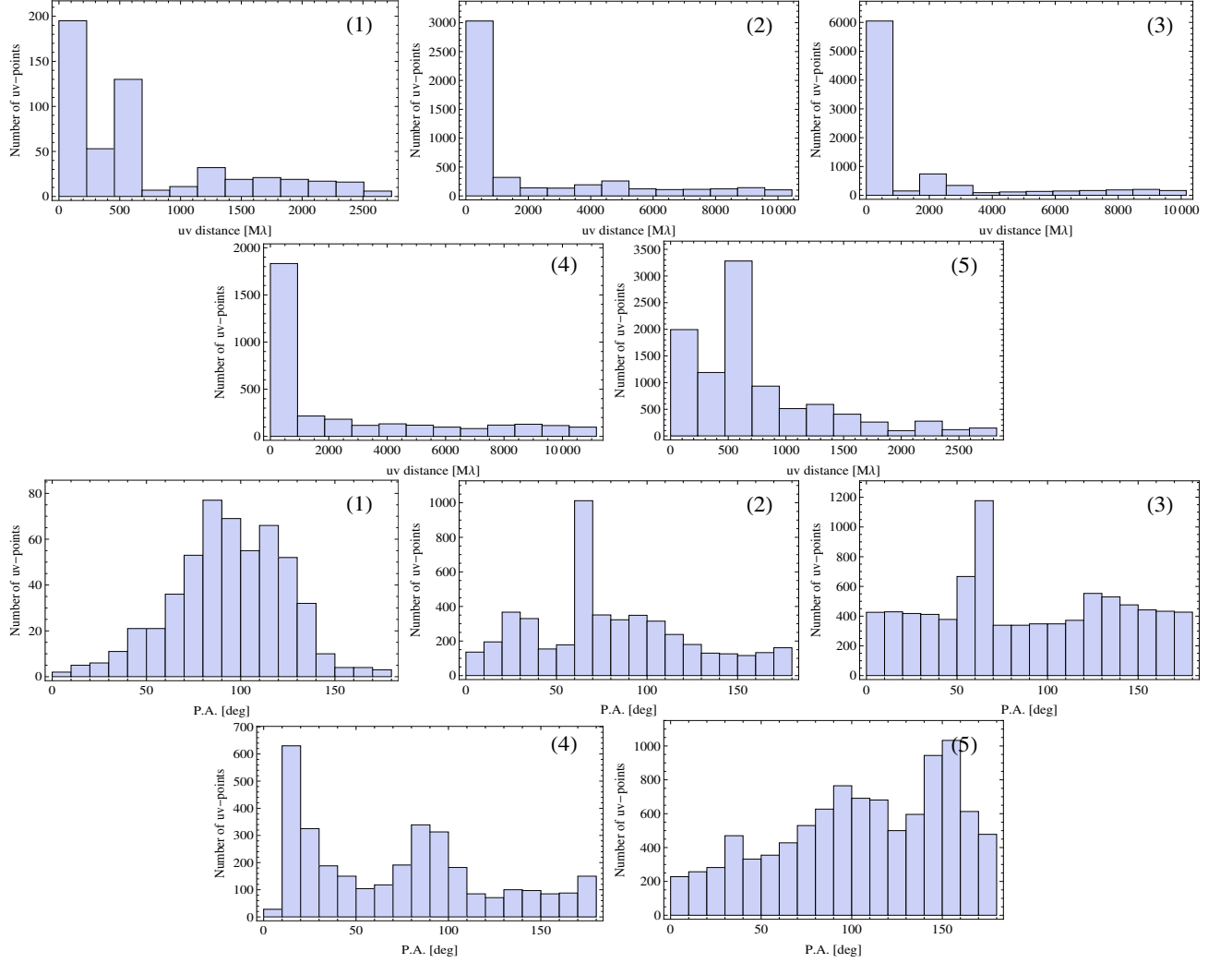


Figure 13: Radial (top two rows) and angular (bottom two rows) distributions of the visibility measurements for the five experiments listed in Table 5.

the NRAO GBT telescope as a example ground station. The system equivalent flux density (SEFD) has been calculated as $SEFD = 2kT_{sys}/A_e$. Estimates of the minimum detectable correlated flux density ($\sigma = \frac{1}{\eta_Q} \sqrt{\frac{SEFD_1 SEFD_2}{\Delta\nu\tau}}$) are made for single polarization frequency channel (IF) with 4 or 16 MHz width for P-band and for the L-, C-, and K-bands, respectively, and with $\eta_Q = 0.637$ for one bit sampling. The sensitivity for L, C, and K-bands channels is two times better when LSB/USB and LCP/RCP channels are combined.

4.5 Experiment preparation

The modified software package FAKESAT, originally developed by Dave Murphy, can be used as planning software for potential observer. FAKESAT works under the LINUX operation system. Required modifications to the package include a presentation of the RA orbit as a table of the state vectors provided by the ballistic center (BC), since a Keplerian orbit treatment does not apply for the Moon-perturbed orbit of RadioAstron. Other modifications concern any operational constraints intrinsic

to the RadioAstron spacecraft. The FAKESAT package can be obtained at the RadioAstron server together with a *FAKESAT User's Guide*. The FAKESAT provides all-sky UV-coverage for a given date and a session duration; UV-coverage for a selected source, source visibility from ground radio telescopes, and conditions for communication with the tracking stations.

4.6 Data reduction

Astro Space Center has developed a software package ASC Locator which will be used for Radioastron data calibration.

It is also possible to utilize AIPS with its space-VLBI extension for the purpose of Radioastron data processing. The ASC software correlator provides results in the FITS format which is readable by AIPS. However, no specific tests with AIPS are done so far. This is expected to be a responsibility of the Early Science Program working group and Key Science Program teams with a limited support provided by the mission.

DETAILS TO BE PROVIDED LATER.

A Document abbreviations

ACS	Attitude Control System
ADC	Analog-to-Digital Convertor
AE	Autonomous Electronics
AO	Announcement of Opportunity
ASC	Astro Space Center
ATCA	Australia Telescope Compact Array
CCW	Control Code Words
CS	Control System
CUFC	Control Unit of the Focal Container
CUIM	Control Unit of the Instrumentation Module
DAS	Data Acquisition System
ESA	European Space Agency
ESP	Early Science Program
ESPT	Early Science Program Team
GOCG	General Operation Control Group
HDRC	High Data Rate Communication radio link (or VIRK)
HEMT	High Electron Mobility Transistor
HFS	High-Frequency Synthesizer
HGCA	High-Gain Communication Antenna
IOC	In-Orbit Checkout
KSP	Key Science Program
LCP	Left-hand Circular Polarization
LFS	Low-Frequency Synthesizer
LNA	Low-Noise Amplifier
LO	Local Oscillator
LSB	Lower Side Band
LTS	Long Term Schedule
MFS	Multi-Frequency Synthesis
MRC	Main Radio Complex
NRAO	National Radio Astronomical Observatory
OCE	Orbit Correction Engines
OM	Orbit Measurements
PRAO	Pushchino Radio Astronomical Observatory
PSS	Power Supply System
QPSK	Quadrature Phase Shift Keying
RAM	Random Access Memory device
ROM	Read-Only Memory
RCP	Right-hand Circular Polarization
RDR	RadioAstron Data Recorder
SC	Spacecraft
SEFD	System Equivalent Flux Density
SFS	System of Frequency Synthesis
SPAS	Solar Panel Attitude control System
SRS	File format of LTS and STS
SRT	Space Radio Telescope
STS	Short Term Schedule
SWC	Software correlator
TCS	Thermal Control System

TM	Telemetry activity
TMAFS	TM-Antennas and Feeds System
TMS	Telemetry System
TPS	Time-Program System
TS	Tracking Station
UDPTR	Up-Down Phase Transfer Radio link
USB	Upper Side Band

B Abbreviations used in the Diagrams

BRC	Backbone Radio Complex
CU DP	Control Unit of the Device Package
CU FP	Control Unit of the Focal Package
DC-DC HF C conv.	Power Supply of the C-band Receiver and Low-Noise Amplifier [C]
DC-DC HF L conv.	Power Supply of the L-band Receiver and Low-Noise Amplifier [L]
DC-DC HF/M conv.	Power Supply of the K-band Receiver and Low-Noise Amplifier
DP	Device Package (The Instrumental Module)
FA	Feeding Antenna
FP	Focal Package (The Focal Container)
FU	Focal Unit (The Feed Module)
HCFS	Heterodyne and Clock Frequency Synthesizer
HRIRC	High Rate Information Radio Complex
IF Selector	Intermediate Frequency Selector
IF	Intermediate Frequency
LNA-1.35 cm	K-band Low Noise Amplifier
LNA-18 cm	L-band Low-Noise Amplifier
LNA-6 cm	C-band Low-Noise Amplifier
OFFS-SRT	Space Radio Telescope On-board Frequency Forming System
OHCFs	On-board Heterodyne and Clock Frequency Synthesizer
OHCFs-SRT	Space Radio Telescope On-board Heterodyne and Clock Frequency Synthesizer set
OHFS-SRT	Space Radio Telescope On-board Hydrogen Frequency Standard
ORFS-SRT	Space Radio Telescope On-board Rubidium Frequency
OUHFS	On-board Ultra high Heterodyne Frequency Synthesizer Standard
PCS	Pulse Calibration System
PS HCFS	Power Supply of the Heterodyne and Clock Frequency Synthesizer
RF	Reference Frequency
RFS	Space Radio Telescope On-board Rubidium Frequency Standard
R-SRT-1.35 cm	K-band receiver
R-SRT-92 cm	P-band Receiver
SRT-18 cm	L-band Low-Noise Amplifier
SRT-6 cm	C-band Receiver
TRM	TRansMitter of the High Rate Information Radio Complex
TRP	TRansPonder of the High Rate Information Radio Complex
UHFS	Ultra high Heterodyne Frequency Synthesizer
VDC-SRT	Control Video Digital Converter (Formatter)