

P1-4

Computational aspects of Space-VLBI missions (“Radioastron” and “Millimetron”)

A.S. Andrianov, I.A. Guirin, A.O. Lyakhovets, V.I. Kostenko, A.G. Rudnitskiy, S.F. Likhachev, V.A. Ladygin and M.V. Shatskaya



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Radioastron mission

The largest in the world 10-m deployable space radio telescope. Launched on the 18th of July, 2011. Operation officially finished on the 4th of June, 2019.

- Daily Space-VLBI observations
- Support from more than 38 ground radio telescopes around the world
- Orbit around the Earth up to 350 000 km
- 7.5 years of successful operation (2.5 times longer, than guaranteed)
- Frequency bands: 316 MHz, 1668 MHz, 4865 MHz, 22220 MHz
- Capable of multi-frequency observations (16392 – 25112 MHz)

Studies on:

- ~100 AGN/CGO (imaging, surveys)
- ~12 galactic masses (imaging, surveys)
- ~2 mega masers in NGC3079 and NGC6258
- ~20 pulsars (DM, scattering effects, etc.)

Over 100 publications so far: <http://www.aic.rssi.ru/radioastron/publications/public.html>

Millimetron mission

A New Step in Angular Resolution

Resolution has been increased and supported by Russian radio astronomy

Two operation modes:

- Space-VLBI at 1 – 7 mm
- Single dish at Q103 – 1 mm

Study of Early and Late Universe

L2 + HEO orbit

Spacecraft has its Phase-A Scientific payload in Phase-B

Supports AGN, VLBI

The 10-m telescope working in Space-VLBI mode can increase angular resolution ~ 100 times (~ 10" arcsec)

Millimetron orbit around L2 point

Time synchronization

Time synchronization is very important for the space-ground VLBI observations especially at High frequencies. There are two main possibilities: on-board hydrogen maser and closed loop mode.

- Observed data received at space radio telescope and synchronized by onboard H-maser is transmitted to Earth and correlated with ground data taking into account compensation of geometric propagation delay.
- In “closed loop” mode the reference frequency from ground based H-maser transmitted to space telescope and then comes back to the Earth. Measurements of the residual Doppler frequency gives ways to realize on-board synchronization and time scale. Both modes has been successfully used in “Radioastron” mission.
- ASC Correlator can process data in H-maser and “closed loop” modes.

On-board H-maser features:

- Onboard H-maser don't require additional Doppler measurements and special processing during data correlation. This is more safe and stable mode.
- Space qualified H-maser has lower stability that ground-based one.
- On-board H-maser weight is about 60 kg and it is too much for small or weight-limited space missions.

Closed loop mode features:

- Closed loop mode require additional Doppler measurements and special delay model in correlator. This mode strongly depends from daily ground support.
- With closed loop mode can be used best quality ground-based H-maser.
- “Closed loop” mode don't require heavy and expensive space qualified H-maser

Atmosphere fluctuations

Frequency (GHz)	σ^2 (ns)	10% $\sigma_{\text{coherence}}$ (ns)	50% $\sigma_{\text{coherence}}$ (ns)	90% $\sigma_{\text{coherence}}$ (ns)
33	150	124	1,290	8,845
15	100	80	4,113	2,387
343	40	30	13,288	5,893
343	20	15	18,714	63,114

Coherence time and stability on baseline ALMA-Millimetron due to the atmosphere

Sensitivity of interferometer:

$$S = 1.34 \frac{\sigma_{\text{coherence}}}{\Delta t} \text{ (mJy)}$$

where 1.34 coefficient is the correction coefficient due to a number of quantization bits per sample, Δf – receiver input bandwidth (Hz) per specified frequency/polarization channel and Δt – coherence time interval (sec).

With frequency increasing the coherence time is dramatically falls due to atmosphere. So the most serious limitation for ground telescope or space-ground interferometer sensitivity on mm and sub-mm frequencies is phase fluctuations in atmosphere. The simplest method to increase sensitivity is choosing dry places for telescope geographical positioning or using water vapor radiometers. But even in this case the coherence time don't exceed 20 sec for ALMA at frequencies higher than 340 GHz. For many places of EHT network coherence time don't exceed 5 sec. Simultaneous multi-frequency observations with phase transferring calibration can improve coherence times and sensitivity.

- Simultaneous observations with 2 different frequencies allows to perform phase transfer from lower frequency to higher frequency and to compensate delay in troposphere.
- Simultaneous observations with 3 different frequencies allows to compensate delay in ionosphere.
- For next generation of sub-mm VLBI missions, including Millimetron mission it is important to use simultaneous observations on different frequencies and perform phase transferring calibration.
- Phase transferring is available in ASC software.

Phase transferring increases coherence time and sensitivity on high frequencies up to several times!

Orbit uncertainty

- Due to the orbit uncertainties a preliminary correlation for space-ground baselines is required while correlator windows, in case fringes were found for ground and space-ground baselines, the correlation will be repeated in “narrow” windows with corrected delay model.
- Needed parameters of correlator window depends on orbit uncertainties. Observations at higher frequencies require wider correlator windows for fringe detection.
- Correlator windows is determined by the number of frequency channels and selected solution interval. The maximum size of such correlation window is only limited by computational resources.
- Radioastron orbit have position uncertainties 200 m and velocity uncertainties 2 m/sec. Millimetron orbit have position uncertainties 100-300 m and velocity uncertainties 2 m/sec for orbit around L2 point. Corresponding parameters with wide correlator windows for Radioastron (top) and Millimetron (bottom) shown in tables.

Parameter	Radioastron	Millimetron
Position uncertainty (m)	200	100-300
Velocity uncertainty (m/sec)	2	2
Orbit period (days)	~12	~12
Baseline length (km)	~1500	~1500
Orbit inclination (deg)	~60	~60
Orbit eccentricity	~0.1	~0.1
Orbit semi-major axis (AU)	~1.5	~1.5
Orbit distance from Earth (km)	~350000	~350000
Orbit velocity (km/sec)	~10	~10
Orbit acceleration (km/sec^2)	~0.0001	~0.0001

Correlator windows parameters for Radioastron (top) and Millimetron (bottom). Output data files is kept for first correlator run, as the correlator processing rate largely depends on the network bandwidth and data delivery time by RF computation via an existing cables.

Millimetron mission have two different orbit types. First L2 orbit. Heli orbit around L2 point of Sun-Earth system, distance 1.5 million kilometers, orbit period – 378 days, maximum baseline 1 500 000 km, oscillation period around L2 is about half of a year. Antenna view opening angle is $\pm 25^\circ$ by ecliptic latitude and longitude. This orbit is the best choice for ongoing single-dish program. Also this orbit provide best angular resolution. Disadvantages of this orbit is slow UV-coverage evolution and relatively low accuracy due to difficulties with maneuvering. It is possible make a transition from L2 point of Sun-Earth system using the gravitational maneuver near the Moon to the Near-Earth orbit: high elliptical near-Earth orbit (HEO), orbit period – 30 days, maximum baseline up to 350 000 km. This orbit is best for imaging due to fast UV-coverage evolution and potentially high accuracy. One more attractive feature of HEO orbit is possibility of dynamic imaging. Black hole in SGR A* has short variability timescale due to smaller mass and strong interstellar scattering. It makes impossible to obtain instantaneous image of SGR A* with any ground VLBI network. Millimetron in HEO orbit has best changing UV-coverage due to high velocity in perihelion. Millimetron mission will give first possibility to make VLBI dynamic image (video) of SGR A*. Orbit accurate strongly connect to needed computer power for data correlation and for internal computing cluster network bandwidth.

Processing Software for “Radioastron” and “Millimetron” missions

ASC Correlator – FX software correlator

- Special delay model for space telescopes with H-maser and “closed loop” time synchronization.
- Only in ASC Correlator the “closed loop” mode of delay restoration have been implemented and successfully tested.
- Two step correlation and special utilities for fringe search and delay model correction.
- GPU/FPGA processing mode
- Support all VLBI raw data formats: RDP, Mark3A, Mark3B, VDR, VLSA, KS.
- Continuum, Maser Line and Pulsar operational modes.

ASC Correlator

Astro Space Lincator (ASL) – software package for post-correlation VLBI data processing and analysis with friendly graphical interface.

- Modeling of VLBI observations (including GPS and space based telescopes)
- Special atmosphere correction (wide bandwidth, multi-frequency observations, phase transferring)
- Viewer of correlated data
- Visual editor of correlated VLBI data
- Restoration of VLBI observations
- Maser data editing, calibration and analysis utilities
- MacOS

ASL Correlator

Radioastron observations of M87 at 18 cm. Imaging by Astro Space Lincator (ASL) software

Supported OS:

- Microsoft Windows (32/64-bit/2000/XP/Vista/7/10)
- Linux (now using in test mode portable WINE package, tested on Fedora 19/20, Ubuntu).
- MacOS

Summary

The main limitation in future space sub-mm VLBI is a clock-frequency stability, orbit uncertainty atmospheric phase variations, slow UV-coverage evolution and strong interstellar scattering in AGN vicinity. These problems can be solved of space qualified H-maser and with closed loop frequency transfer. Two-step correlation with improved delay model, multi-frequency observations and phase-transferring calibration and choosing best evolving orbits for dynamic imaging. All these features will be taken into account in the “Millimetron” project, the next generation of space VLBI missions.

For more details and information, please visit: <http://radioastron.ru> <http://millimetron.ru>

Radioastron mission 2011-2019

- The largest in the world 10-m deployable space radio telescope.
- Longest interferometer baselines in the world
- Broad frequency coverage of 0.3 – 22 GHz



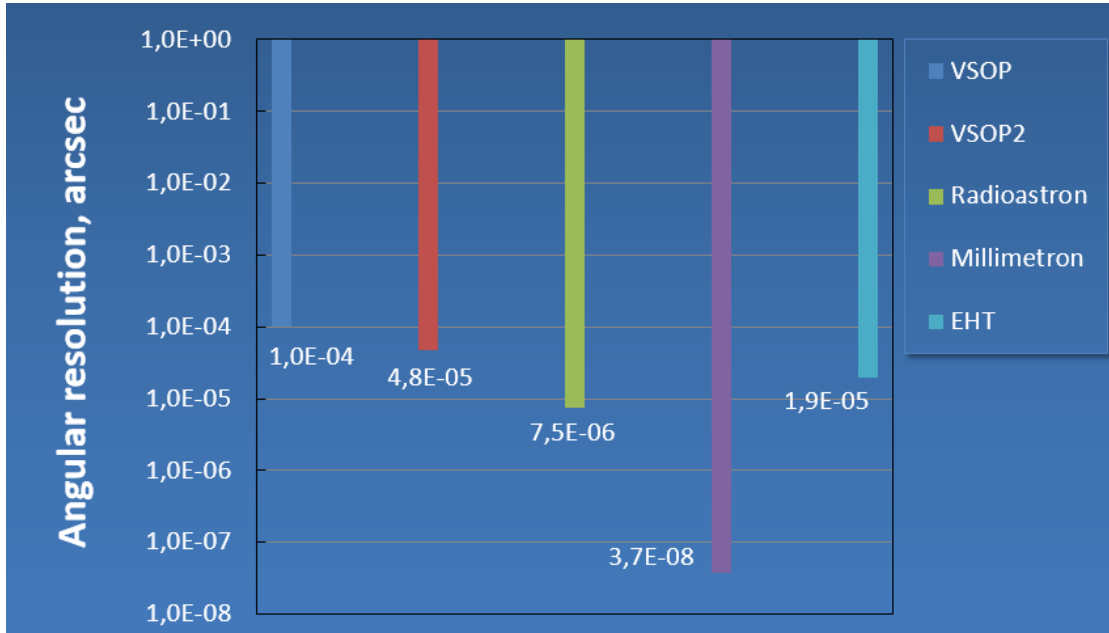
In poster P1-4 is discussing :

- Main challenges for Radioastron data processing strongly determined of computer power mainly by time synchronization and orbits uncertainty
- Processing software for Radioastron mission (all software free to download)



Millimetron mission (2029)

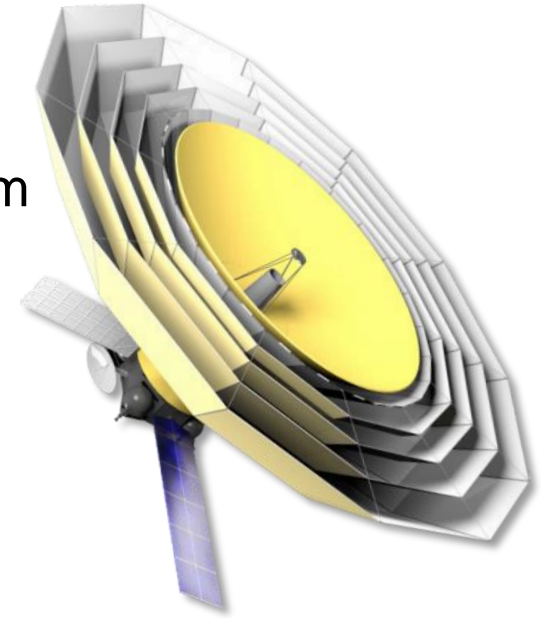
A New Step in Angular Resolution



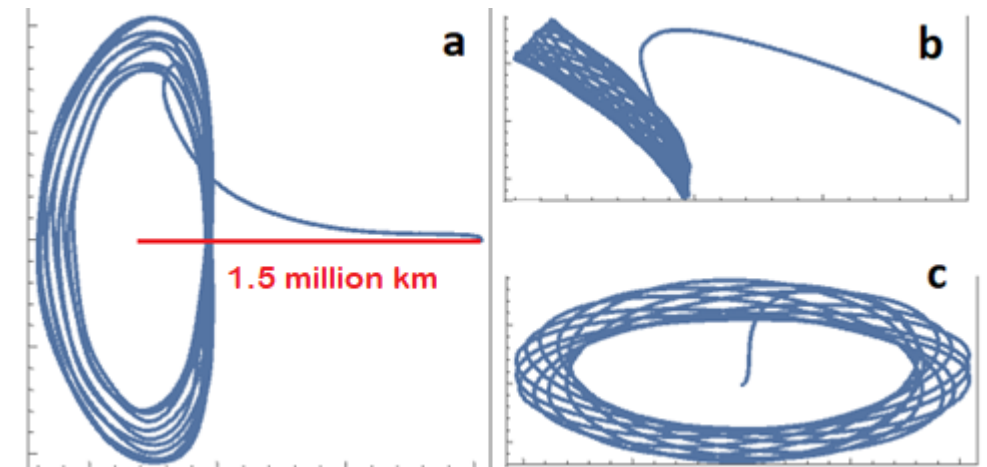
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- Space-VLBI at 1 – 7 mm
- Single dish at 0.05 – 3 mm

Study of Early and Late Universe
L2 + HEO orbit

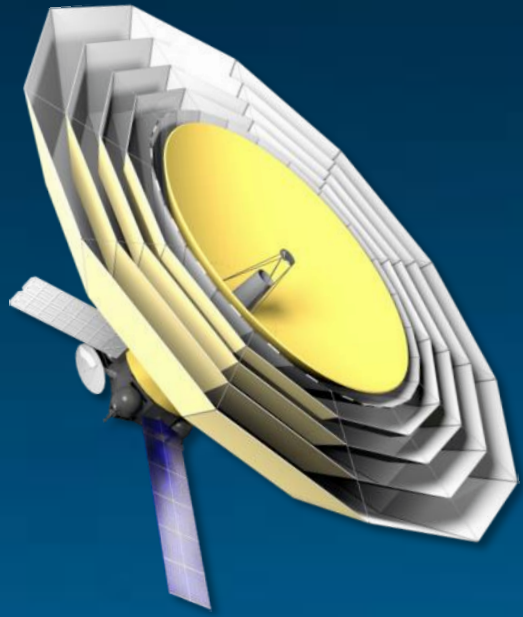


- The 10-m telescope working in Space-VLBI mode can increase angular resolution ≈ 100 times (up to $\approx 10^{-8}$ arcsec)
- Mission has been approved and supported by Russian Space Agency



The main limitation for future sub-mm VLBI (Millimetron, EHT, etc)

- Clock-frequency stability - solution is a space qualified H-masers or closed loop time synchronization
- Orbit uncertainty – solution is two-steps correlation with improvement of delay model. Orbit accuracy is strongly determine the rated computer power.
- Atmospheric phase variations – solution is simultaneous multi-frequency observation and phase transferring.
- Slow UV-coverage evolution and difficulties with dynamic imaging – solution is usage of the High Elliptical Earth Orbit of space telescope.



***Thank you for
your attention!***

More information are available in poster P1-4

