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

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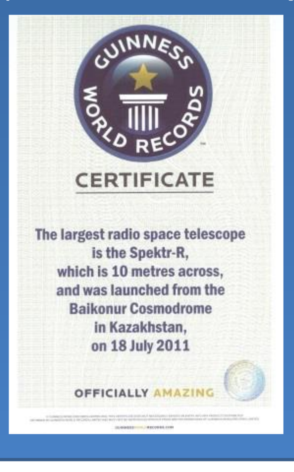
Any question? Ask me.

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 58 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, 4868 MHz, 22220 MHz
Capable of **multi-frequency** observations (18392 – 25112 MHz)



Studies on:
- 160 AGN+QSO (imaging, surveys)
- 12 galactic masers (imaging, surveys)
- 2 mega masers in NGC3079 and NGC4258
- 20 pulsars (ISM, scattering effects, etc.)

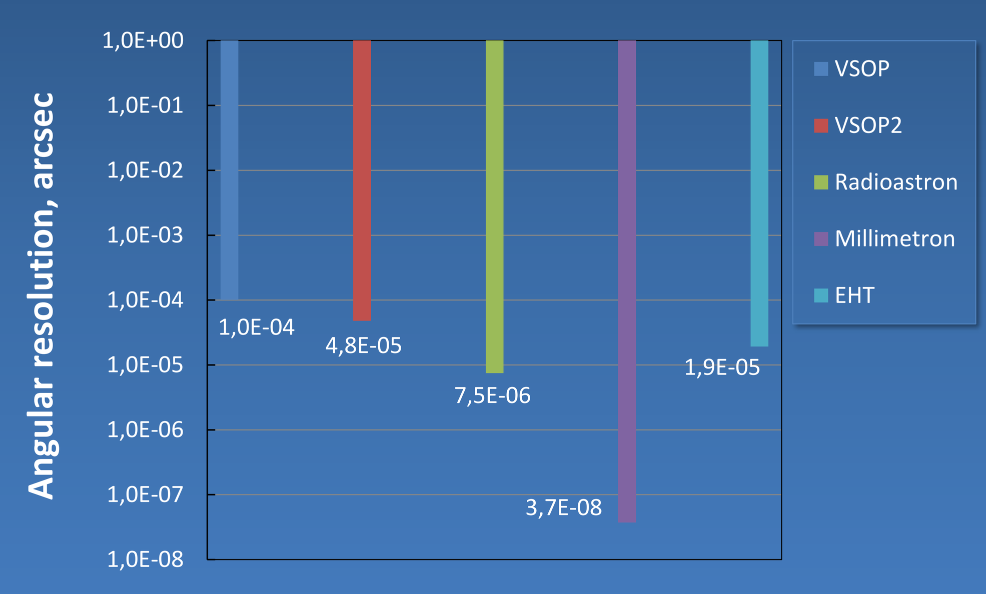
Over 100 publications so far:

http://www.asc.rssi.ru/radioastron/publications/publ.html

Millimetron mission

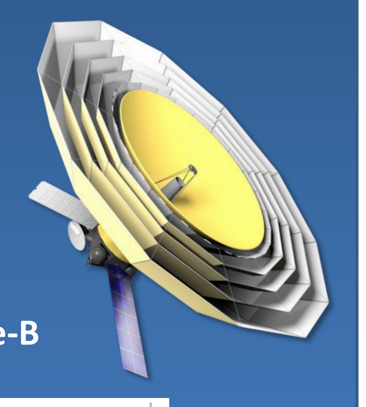
A New Step in Angular Resolution

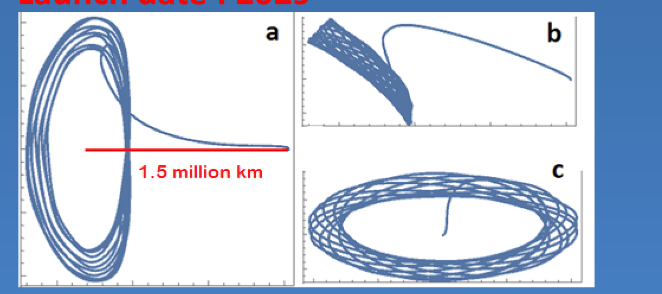
Mission has been approved and supported by Russian Space Agency



The 10-m telescope working in Space-VLBI mode can increase angular resolution ≈ 100 times (≈ 10^{-8} arcsec)

Two operation modes:
Space-VLBI at 1 – 7 mm
Single dish at 0.05 – 3 mm
Study of Early and Late Universe
L2 + HEO orbit
Spacecraft bus in Phase-A
Scientific payload in Phase-B
Launch date : 2029



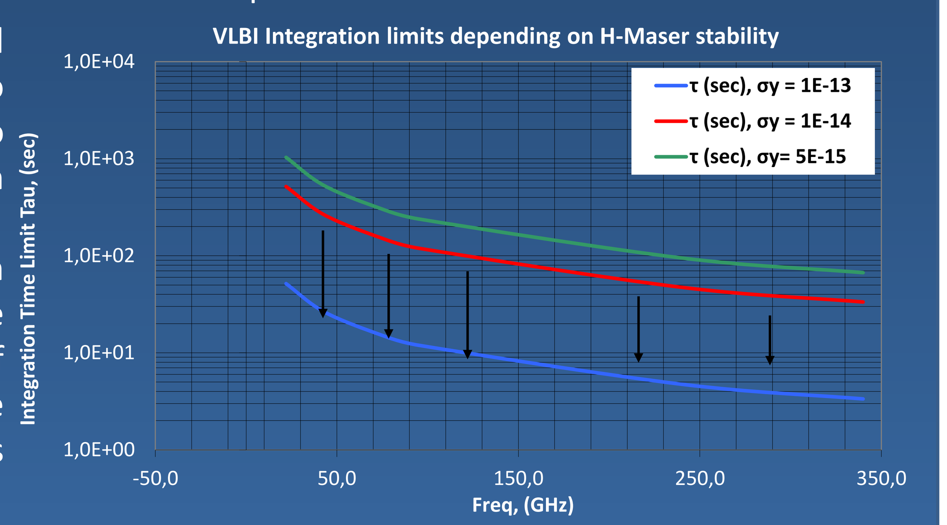


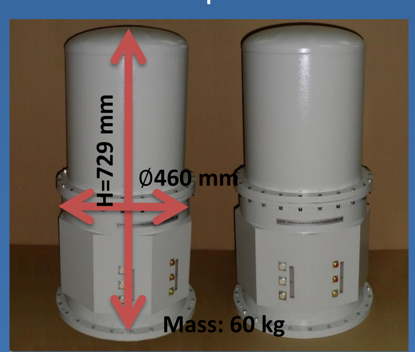
Millimetron orbit around L2 point

Time synchronization

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

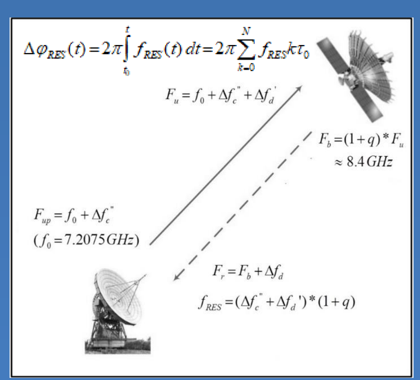
- Observed data received at space radio telescope and synchronized by onboard H-maser is transmitted to Earth and correlated with ground data taking into account compensation of geometric propagation delay.
- In "closed loop" mode the reference frequency from ground based H-maser transmitted to space telescope and then comes back to the Earth. Measurements of the residual Doppler frequency gives ways to restore 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.



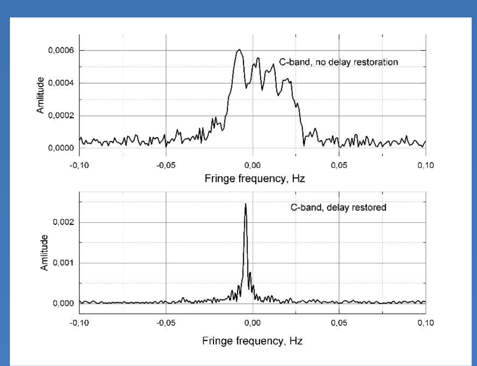


Time interval, (s)	Frequency Instability, σ		
	AFT* System		“Millimetron” requirements
	Disabled	Enabled	
1	$6.00\cdot10^{-14}$	$4.90\cdot10^{-14}$	$\leq7\cdot10^{-14}$
10	$1.05\cdot10^{-14}$	$8.30\cdot10^{-15}$	$\leq1\cdot10^{-14}$
100	$2.73\cdot10^{-15}$	$1.83\cdot10^{-15}$	$\leq2\cdot10^{-15}$
1000	$1.10\cdot10^{-15}$	$8.84\cdot10^{-16}$	$\leq5\cdot10^{-16}$
3600	$7.10\cdot10^{-15}$	$4.86\cdot10^{-16}$	$\leq5\cdot10^{-16}$

Onboard H-maser parameters for “Millimetron” mission



Principal scheme of closed loop mode implemented in “Radioastron” project



Example of correlator response for Radioastron closed loop mode. Top - no time correction applied. Bottom - time correction applied.

Onboard 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 can have 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)	τ* (sec)	$SEFD_{ALMA-MM}$ (Jy)	5dS, 1GHz (mJy)	5dS, 4GHz (mJy)
40	150	124	1.290	0.645
90	100	340	4.333	2.167
240	40	565	11.386	5.693
340	20	710	20.235	10.118

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

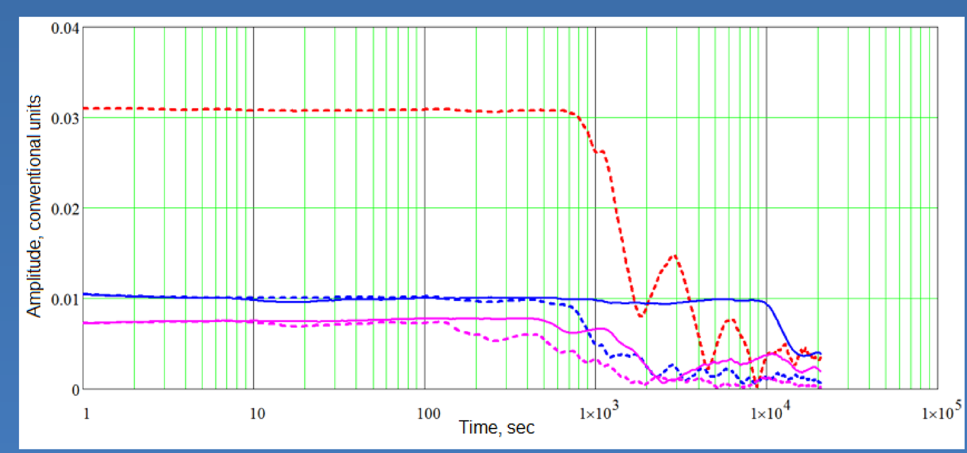
Sensitivity of interferometer:

$$\delta S = 1.14 \cdot \frac{SEFD_{12} \cdot 10^3}{\sqrt{2\Delta F \tau}},\ (\mathrm{mJy})$$

where 1.14 coefficient is the correction coefficient due to a number of quantization bits per sample, ΔF- formatter input bandwidth (Hz) per specified frequency/ polarization channel and τ - 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 that 340 GHz. For many places of EHT network coherence time don’t exceed 3 sec. Simultaneous multi-frequency observations with phase transferring calibration can improve coherence time 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 ASL software

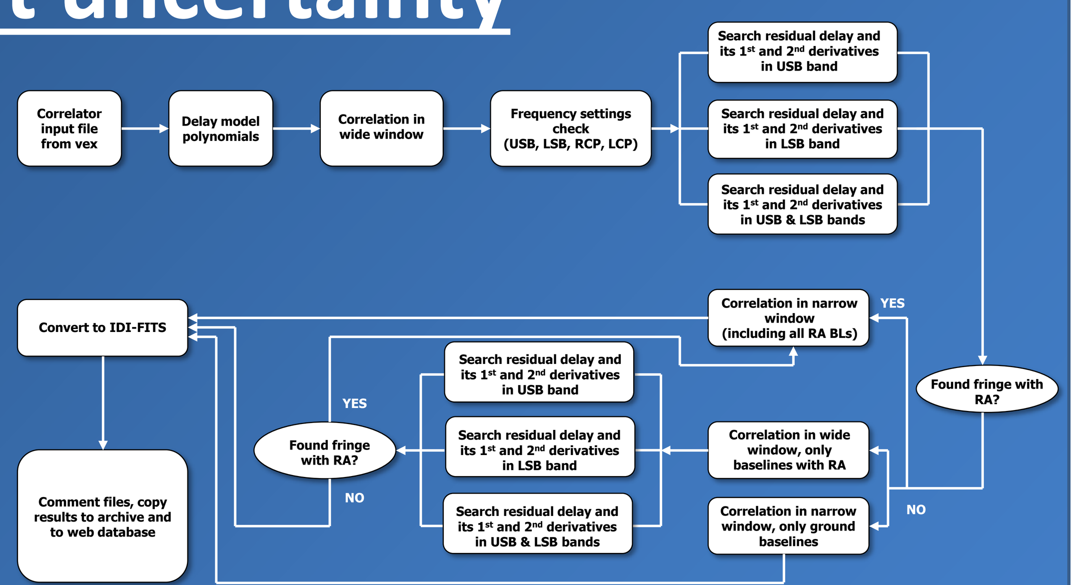


Example of phase transferring calibration in ASL software. Simultaneous observations of source 3C279 with frequencies 22 GHz, 43 GHz and 86 GHz on KVN network. Dashed lines corresponds to original coherence time, solid lines corresponds to coherence time after phase transfer calibration. Red lines 22 GHz, blue lines 43 GHz and purple lines 86 GHz.

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 «Wide correlator window». In case fringes were found for ground and space-ground baselines, the correlation will be repeated in «Narrow window» with corrected delay model
- Needed parameters of «correlator window» depends on orbit uncertainties. Observations at higher frequencies require wider «correlator window» for fringe detection.
- «Correlator window» 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 cm/sec. Millimetron orbit have position uncertainties 100-300 m and velocity uncertainties 2 mm/sec for orbit around L2 point. Corresponding parameters with «Wide correlator window» for Radioastron (top) and Millimetron (bottom) shown in tables



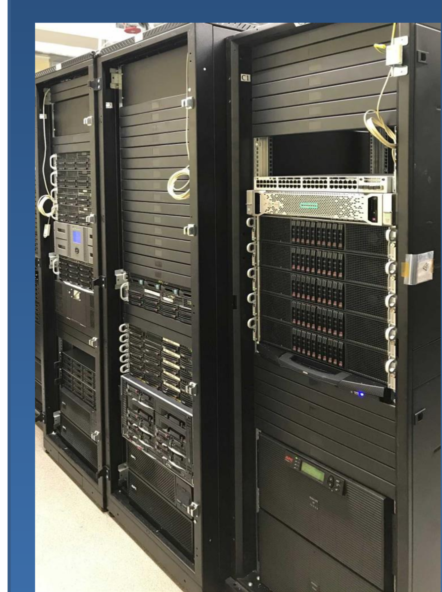
Band	FFT channels	Delay window (µs)	Integration time (sec)	Fr. Rate window (Hz)	Data volume (1 h observation), Gb
22 GH	2048	64	0.015	32	420
1.6 GH	2048	64	0.125	4	52
2 GH	2048	64	0.25	2	26
312 MHz	2048	64	1	0.5	6.6

Band	FFT channels	Delay window (µs)	Integration time (sec)	Fr. Rate window (Hz)	Data volume (1 h observation), Gb
340 GHz	131072	64	0.01	49	41 400
240 GHz	131072	64	0.015	35	29 500
90 GHz	131072	64	0.04	13	11 000
40 GHz	131072	64	0.085	5.8	4900

«Correlator window» parameters for Radioastron (top) and Millimetron (bottom). **Output data flow is large for first correlator run, so the correlator processing rate largely depends on the network bandwidth and data delivery than by FFT computation rate on computing nodes!**

Millimetron mission have two different orbit types. First L2 orbit: Halo orbit around L2 point of Sun-Earth system, distance 1.5 million kilometers, orbit period – 178 days, maximum baseline 1 500 000 km, oscillation period around L2 is about half of a year. Antenna view opening angle is ± 75° in ecliptic latitude and longitude. This orbit is the best choose for cryogenic 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 laser-ranging. 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 – 10 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 fast changing UV-coverage due to high velocity in perigee. 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



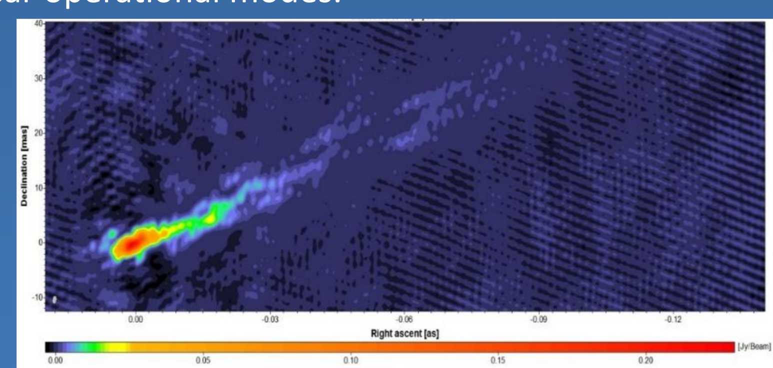
ASC Correlator

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
- CPU+GPU processing modes
- Support all VLBI row data formats: RDF, Mark5A, Mark5B, VDIF, VLBA, K5.
- Continuum, Maser Line and Pulsar operational modes.

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

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



Radioastron observations of M87 at 18 cm. Imaging in Astro Space Locator (ASL) software

Supported OS:
- Microsoft Windows (95/98/ME/2000/XP/Vista/7/8),
- 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 uncertainly, atmospheric phase variations, slow UV-coverage evolution and strong interstellar scattering in AGN vicinity. These problems can be solved with new generations of space qualified H-masers or with closed loop frequency transfer, two-steps correlation with improvement of delay model, multi-frequency observations and phase-transferring calibration and choosing fast 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