RadioAstron Mission Heritage

On behalf of Radioastron project team
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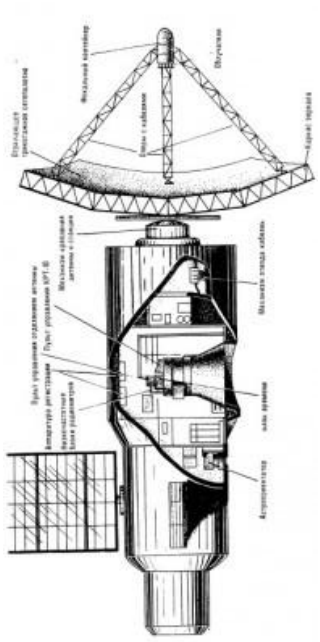
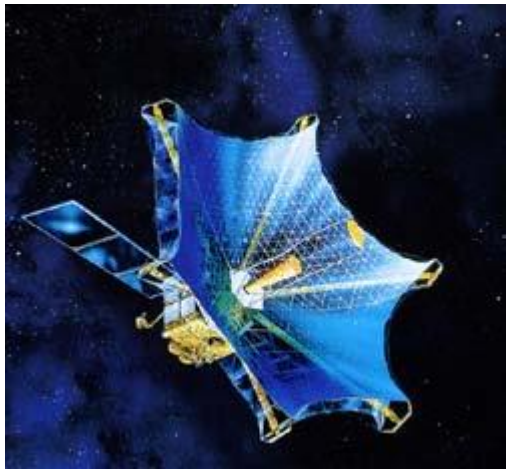
Introduction



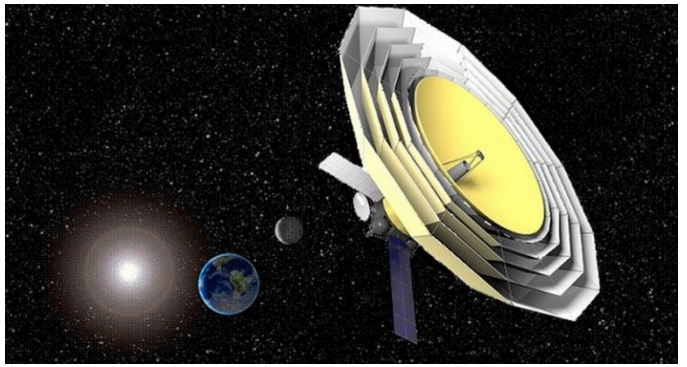
SRT-10
(Salyut-6 Orbital Station)
July, 1979 – August, 1979

HALCA (VSOP)
February, 1997 –
November, 2005



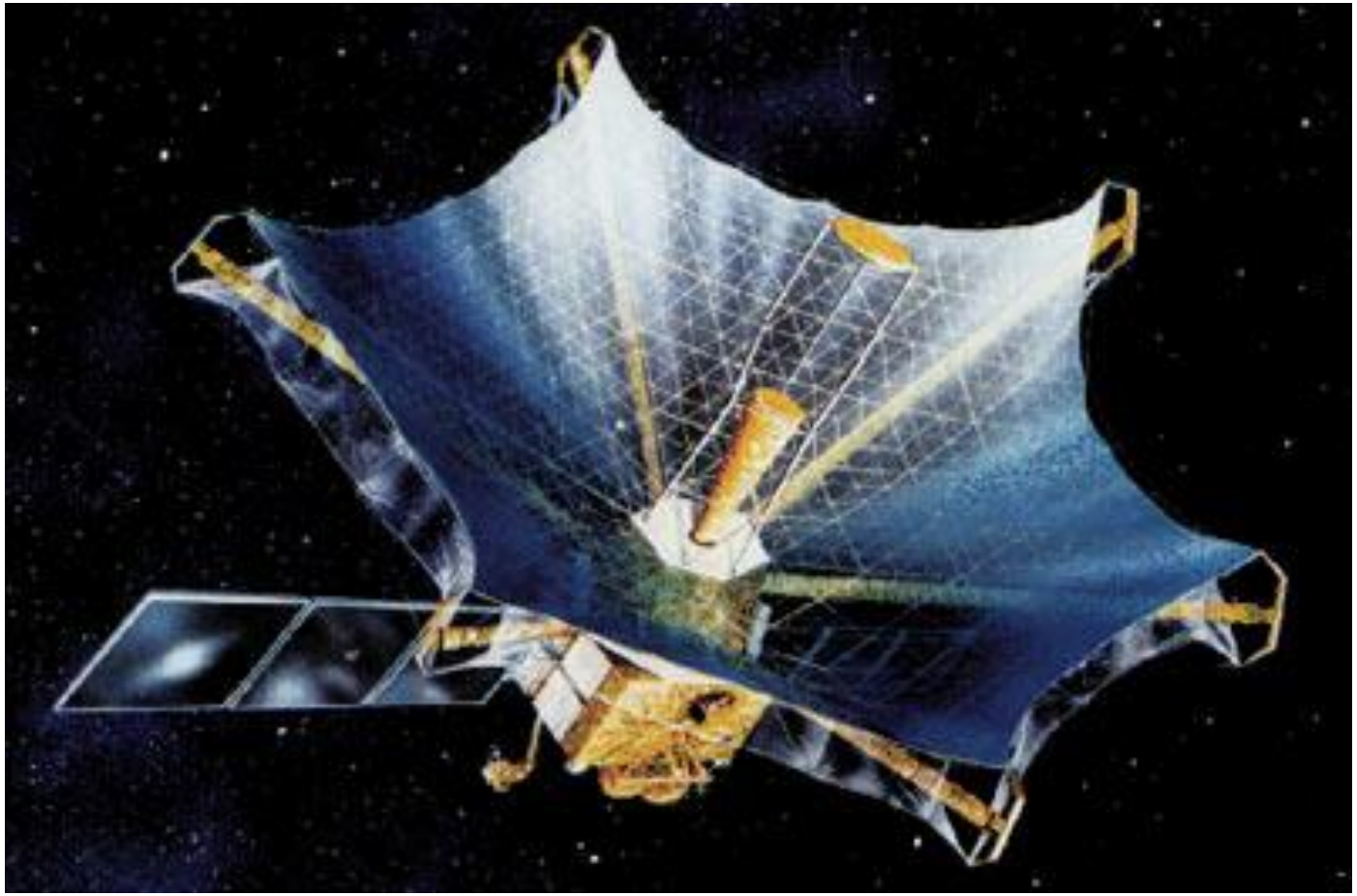
ASTRO-G (VSOP-2)
Cancelled

Radioastron (Spektr-R)
July, 2011 – June, 2019



Millimetron (2029)

HALCA Space Telescope (VSOP Project)



HALCA (**Highly Advanced Laboratory for Communications and Astronomy**), also known for its project name **VSOP** (**VLBI Space Observatory Program**) - a Japanese 8 meter diameter radio telescope satellite which was used for VLBI. The space-borne telescope dedicated to VLBI.

Launched in February 1997, made its final VSOP observations in October 2003, far exceeding its 3-year predicted lifespan.

Designed to observe in three frequency bands: 1.6 GHz, 5.0 GHz, and 22 GHz. Later it was found that the sensitivity of the 22 GHz band had severely degraded after orbital deployment, thus limiting observations to the 1.6 GHz and 5.0 GHz bands.

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)
- Capable of **multi-frequency** observations (18392 – 25112 MHz)

Studies on:

- AGN+QSO (imaging, surveys)
- Masers (imaging, surveys)
- Pulsars (ISM, scattering effects, etc.)

Frequency bands:

316 MHz, 1660 MHz, 4868 MHz, 22220 MHz

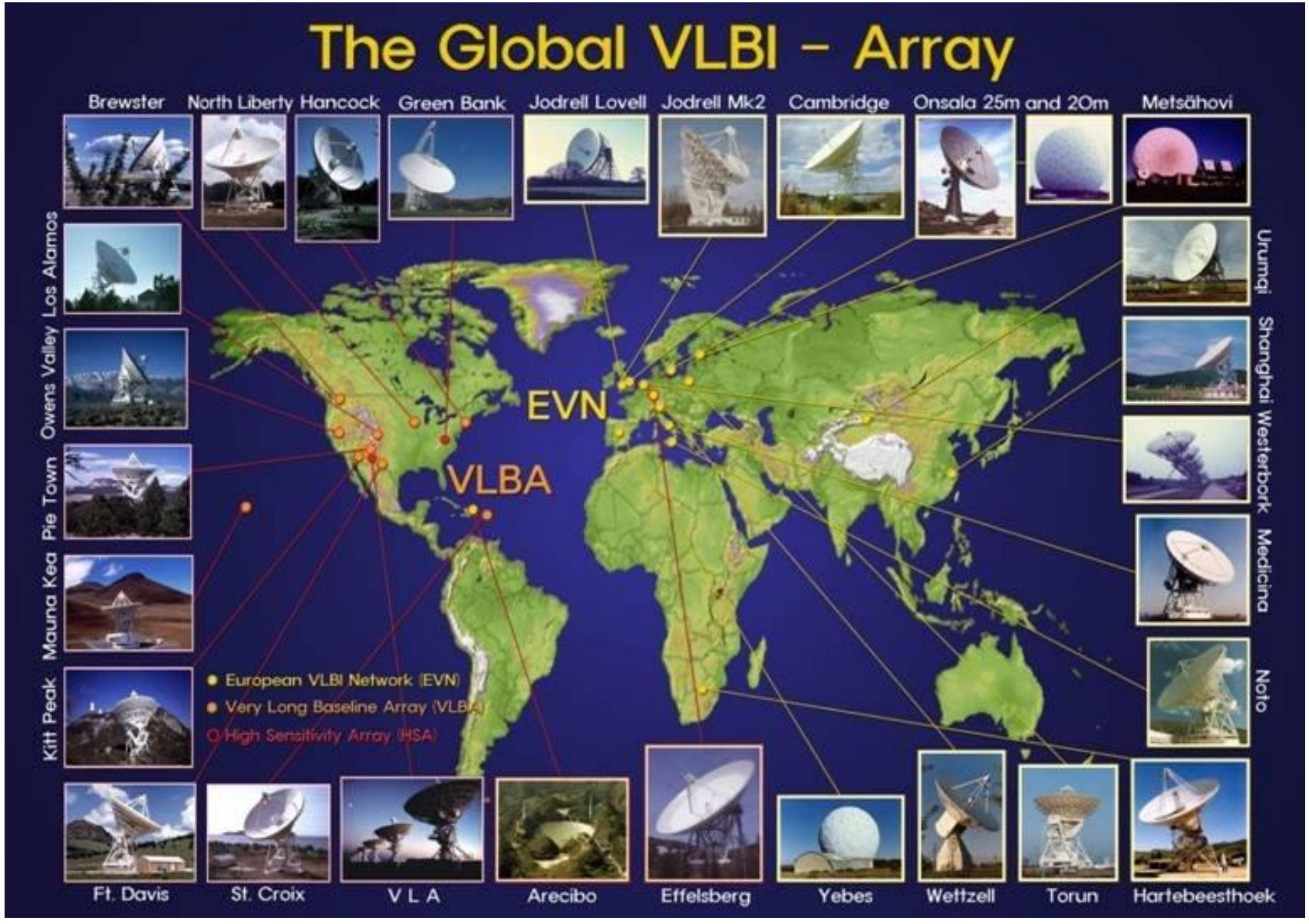
More information: http://radioastron.ru/

Parameters of VLBI Missions

	VSOP	Radioastron	Millimetron
Antenna diameter [m]	8	10	10 (cooled)
Apogee height [km]	21 244	350 000	1 500 000
Orbital period	6.3 hrs	9.5 days	178 days
Polarization	LCP	LCP/RCP	LCP/RCP
Data downlink	128 Mbit/s	128 Mbit/s	1.2 Gbit/s
Observing frequencies [Ghz]	1.6 – 22	0.2 – 22	30 – 370
Highest resolution [μas]	360	8	0.03
Launched	1997	2011	2029

Ground VLBI Support

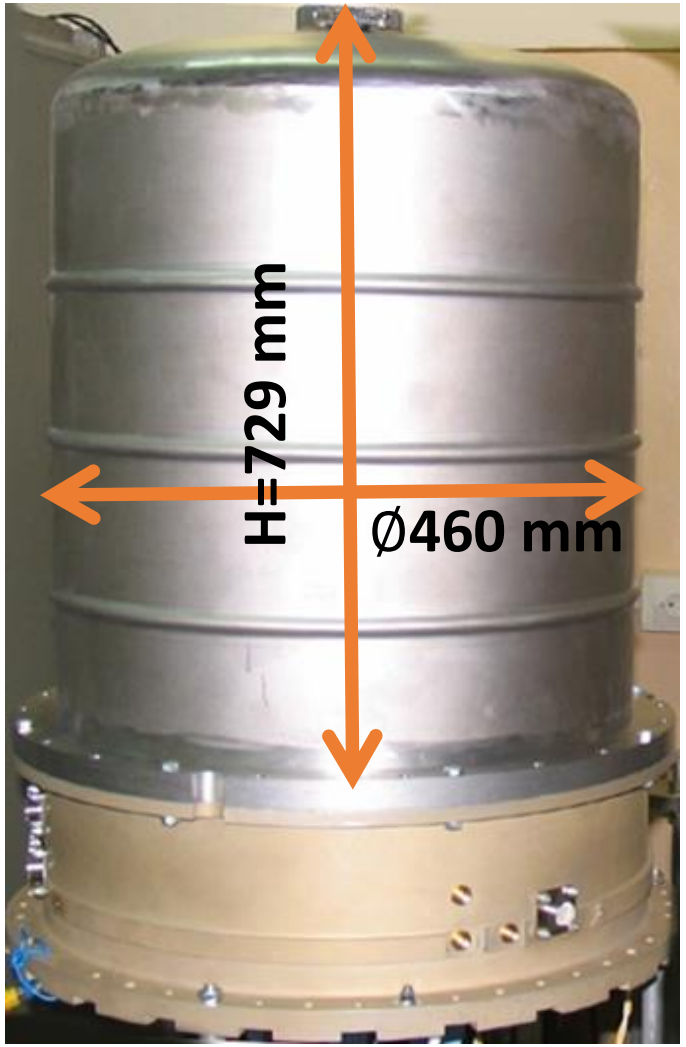
Up to 58 Ground Telescopes



Onboard Active Hydrogen Maser

The only onboard frequency and time standard in the world operating in orbit.

Product of "Vremya-CH“ (Russian enterprise).

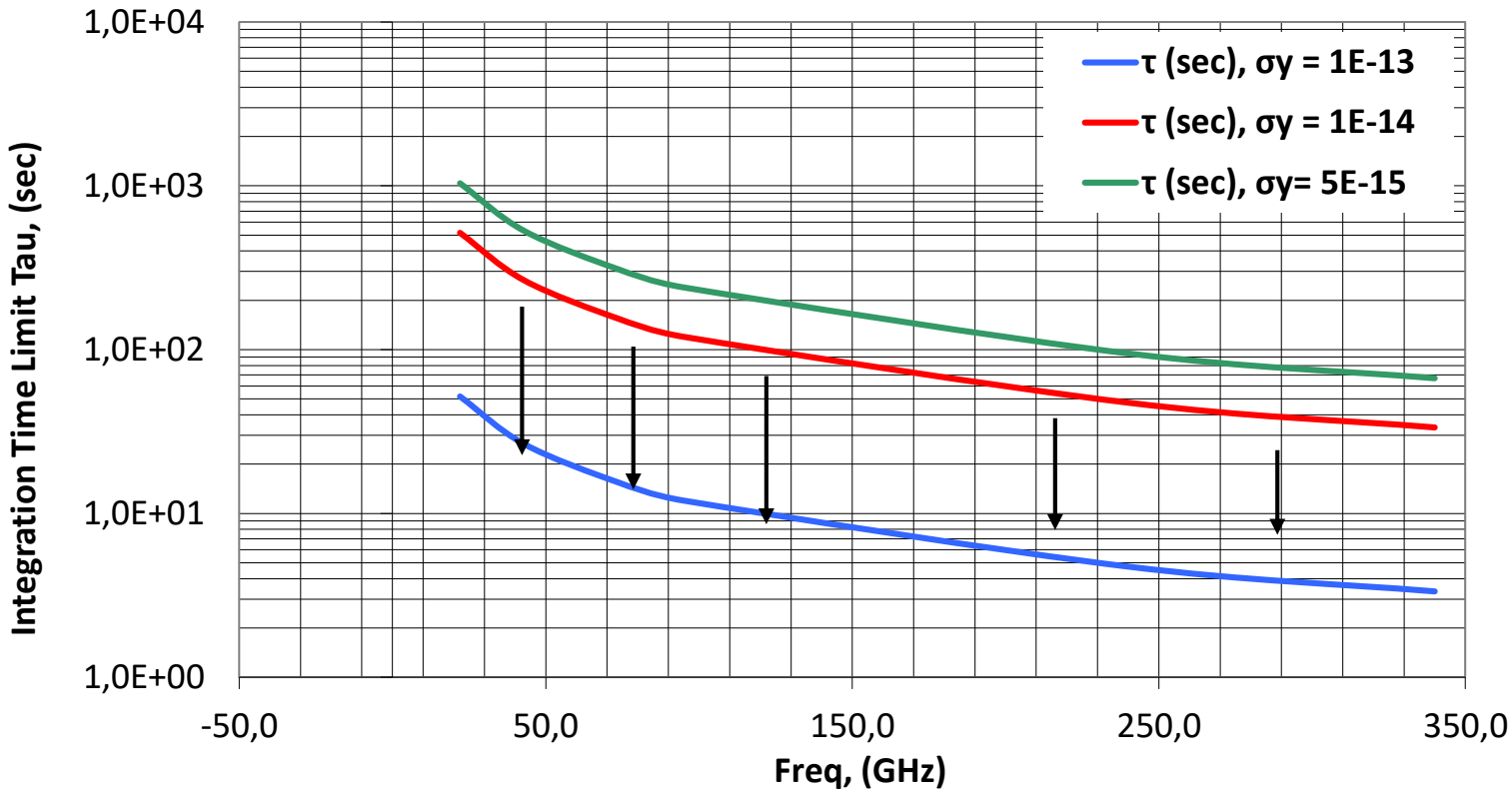


Mass: 60 kg

Relative frequency uncertainty is:

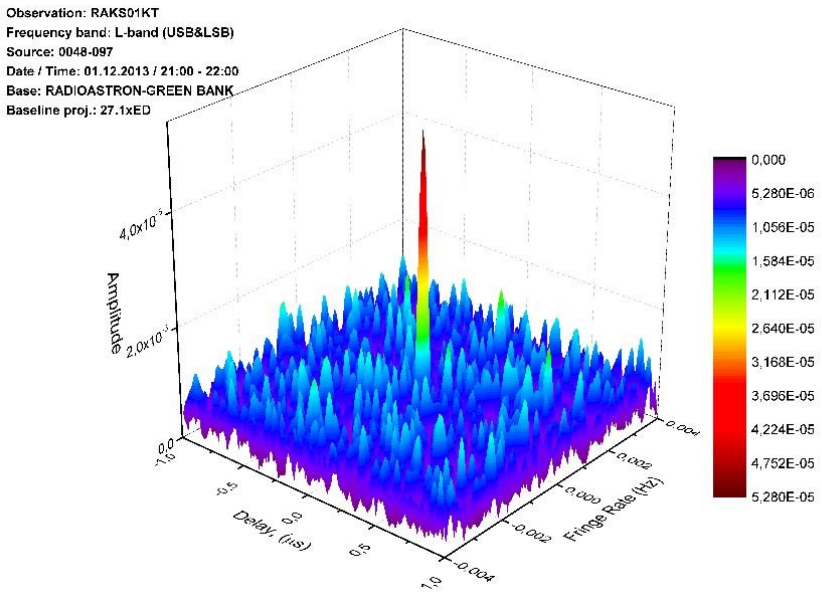
- 3×10^{-13} for T_{int} = 1 s
- 3×10^{-14} for T_{int} = 10 s
- 7×10^{-15} for T_{int} = 100 s
- 3×10^{-15} for T_{int} = 1000 s

VLBI Integration limits depending on H-Maser stability

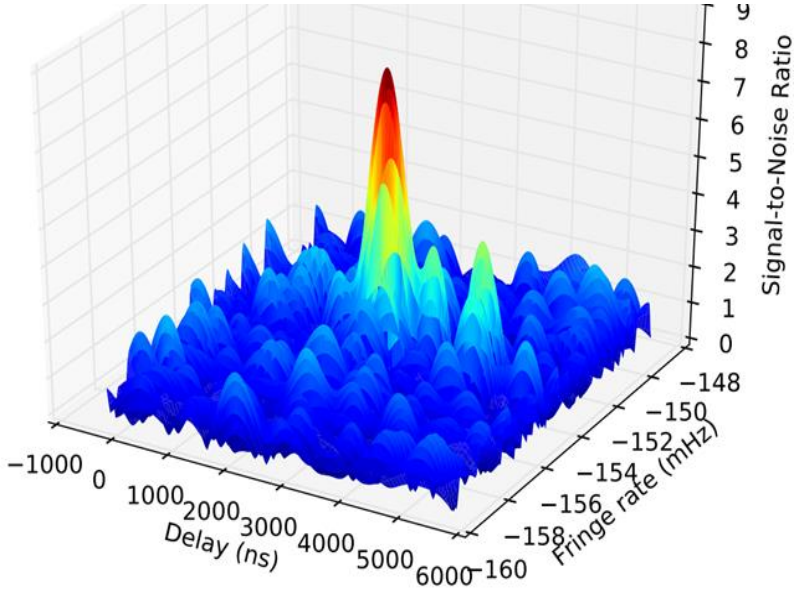


Main Results of Radioastron

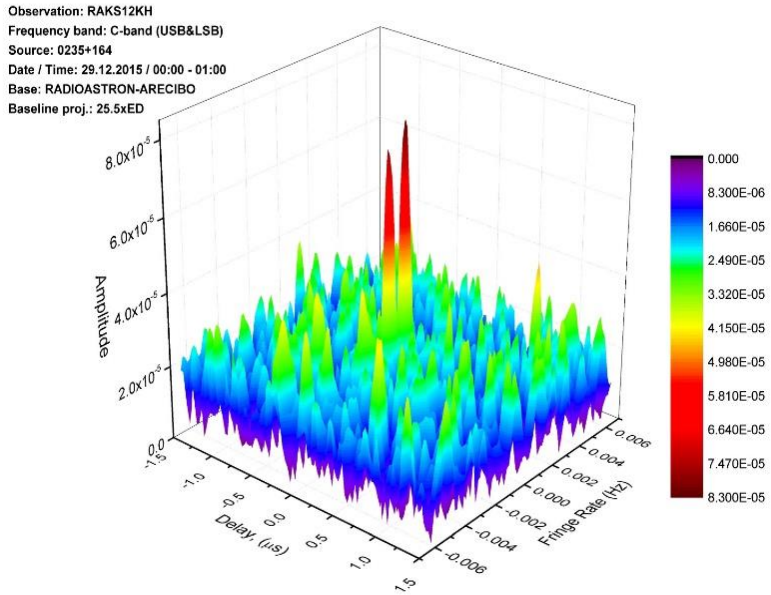
Extremely High Resolution with Space-VLBI



0048-097
L-band
27.1 ED
ϕ = 104 μas



NGC 4258
K-band
26.9 ED
ϕ = 8 μas



0235+164, RA-AR,
BL ≈ 25.2 ED,
ϕ = 37 μas

Main Results of Radioastron

- **More than 4000** observations done during **7.5** years of operation
- Observations with high angular resolution (achieved **8 μas at 1.3 cm**, baseline projection: ~**26 Earth diameters**) for:
- **160 AGN&QSO**,
  - **20 pulsars**,
  - **12 galactic masers** (18 cm and 1.35 cm),
  - **2 mega masers** in NGC3079 and NGC4258.
- **Over 100 publications so far:** http://www.asc.rssi.ru/radioastron/publications/publ.html

Main Results of Radioastron

- Substructure in the scattering disk was revealed
- The effect of brightening of relativistic jets on the edge was discovered
- Plasma instabilities in quasar jets are discovered
- Radioastron discovered that jets in some active galaxies start wide.
- That is, participation in this process of accretion disk is proved
- Sub-relativistic envelope around jets has been discovered, previously predicted indirectly from the Faraday rotation
- It has been discovered that the disk of the extragalactic maser of water vapor (NGC4258), turned out to be extremely thin – (8 μas)
- Experiment to verify the general theory of relativity by measuring the deceleration of time on board of Radioastron SRT due to gravitational redshift in the Earth's field, statistics were accumulated and processed to measure the value of gravitational time dilation at the accuracy level of the best experiments performed so far

Radioastron Data Processing Center

- On-line storage system for collecting information – **600** TB
- On-line storage system for data processing – **80** TB
- On-line storage system for processing results – **120** TB
- Offline HDD data archive – **2000** TB
- Offline archive tapes – **2000** TB
- Backup storage **20** TB in Pushchino
- The total storage capacity is about **5** PB!
- 10 Gbit/s network infrastructure and 600 Mbit/s Internet channel.

Radioastron Data Opened!

The correlated data of Radioastron observations conducted from 2011 to June 2015 is available:

http://opendata.radioastron.ru/

AGN & quasar survey and imaging, pulsar, maser data.

Millimetron Mission

Space-VLBI to be continued…

Mission has been approved and supported by Russian Space Agency

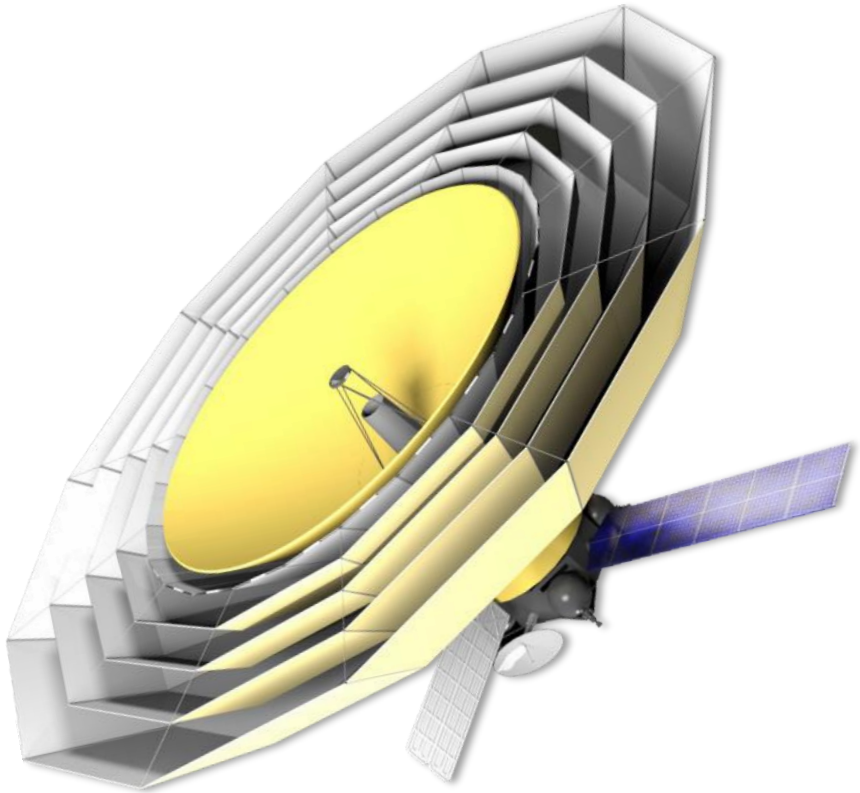
- FIR, sub-mm and mm range
- In orbit deployable and adjustable antenna
- Cosmology and astrophysics studies
- Mechanically cooled (<10K) with post-cryo life
- Orbit around L2 Lagrange point
- Lifetime: 10 years; at cryo >3 years

Two operation modes:

Space-VLBI at 1 – 7 mm

Single dish at 0.05 – 3 mm

Study of Early and Late Universe



- **Spacecraft bus in Phase-A**
- **Scientific payload in Phase-B**
- **Launch date : 2029**

Web-page: http://millimetron.ru/

Radioastron Experience

- **Antenna.** The world's first 10 meter deployable antenna with solid surface.
- **International Cooperation.** Extensive interaction with global ground VLBI. Established coordination.
- **Onboard hydrogen frequency standard.** The first onboard hydrogen frequency standard that was launched proved its operation and parameters.
- **Data center.** The data center, that has been created store not only all processed data, but also the raw data.
- **Software.** Software package for data processing (correlation) and analysis was developed (ASC Correlator, ASL Software). 95% of Radioastron data was correlated by ASC Correlator.
- **Resolution.** Achieved the highest angular resolution (8 μas).

Radioastron Experience

- **Coordination of ground telescopes.** No detailed information on the telescopes configurations during the observations (frequency setup failures, mismatch of the channel configurations, low quality and incorrect data for calibrations). Low usability of provided log-files.
- **Data acquisition logistics.** Transferring of the data was performed mostly via Internet, thus the delivery speed of the data was limited by the bandwidth. In some cases the better approach is to transport disks with the data directly.
- **Scientific management in the project.** Approach in scientific management will be reviewed and improved comparing to Radioastron International Scientific Council (RISC).
- **Scientific program.** No strong scientific cases were addressed to the project. This resulted to the relatively low significance of the scientific output. Most of the scientific program could be addressed as the continuation of VSOP program.

Conclusions

Radioastron mission brought the VLBI observations to a new level providing the new technologies, software instruments, the data center and the highest angular resolution.

Millimetron will be a new generation observatory that will provide the world scientific community with new opportunities for observations.

Definitely, the experience of Radioastron will be taken into account the most critical points of Radioastron mission:

Scientific management of the project. Approach in scientific management will be reviewed and improved comparing to Radioastron International Scientific Council (RISC).

Scientific program. The goal is to have an optimized and adequate scientific program with strong scientific cases a significant expected scientific outcome.

Scheduling. Scheduling must be done to meet the scientific goals, taking into account the constraints.

Extensive international cooperation. Joint coordination of ground telescopes participating in the observations, including data transferring, calibration.

Thank you for your attention!

Radioastron project web-page: http://radioastron.ru/

RESHETNEV COMPANY ROSCOSMOS ASC LPI