VLBI mode: Instruments and Orbital Constraints

On behalf of Millimetron project team

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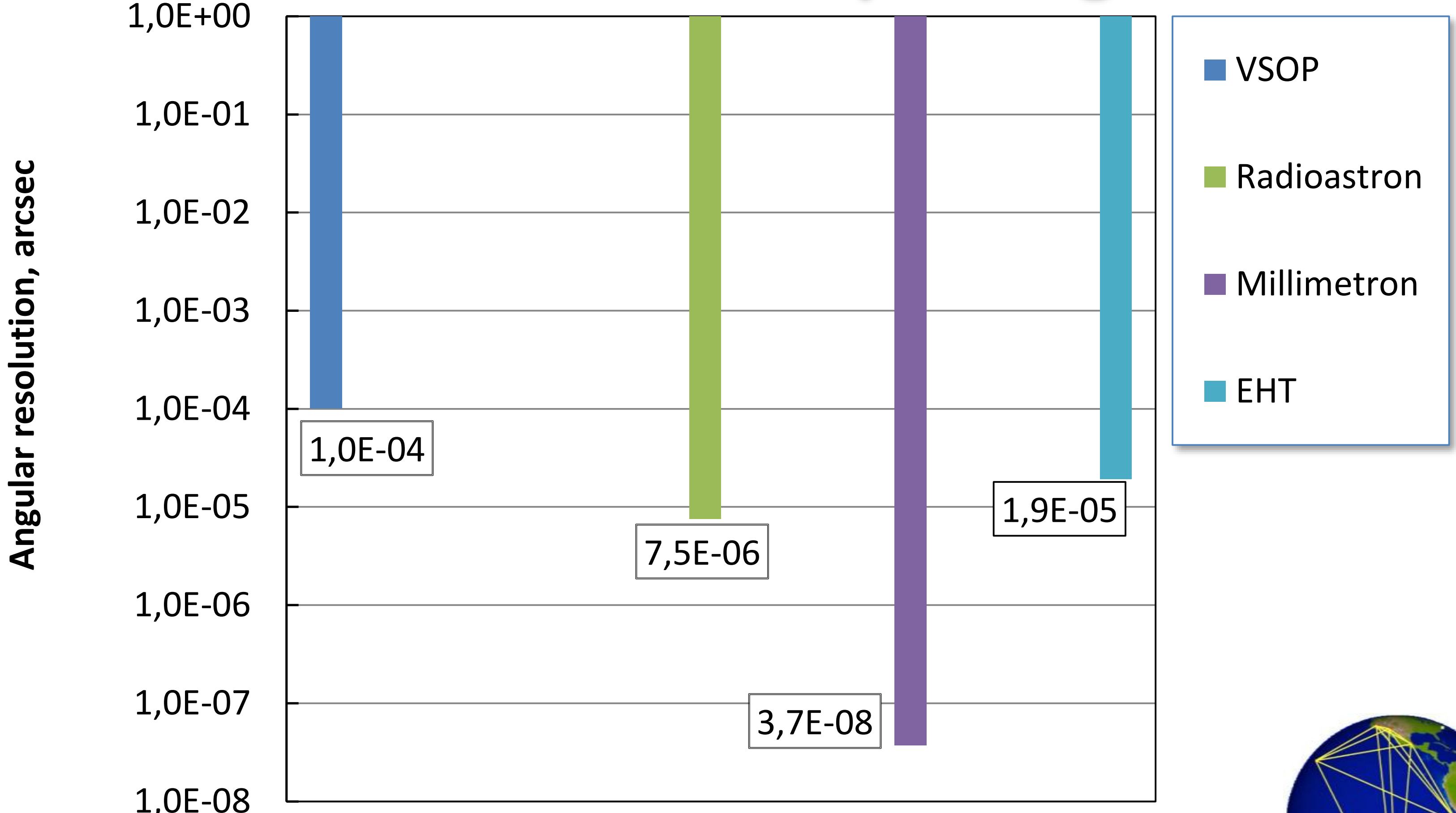
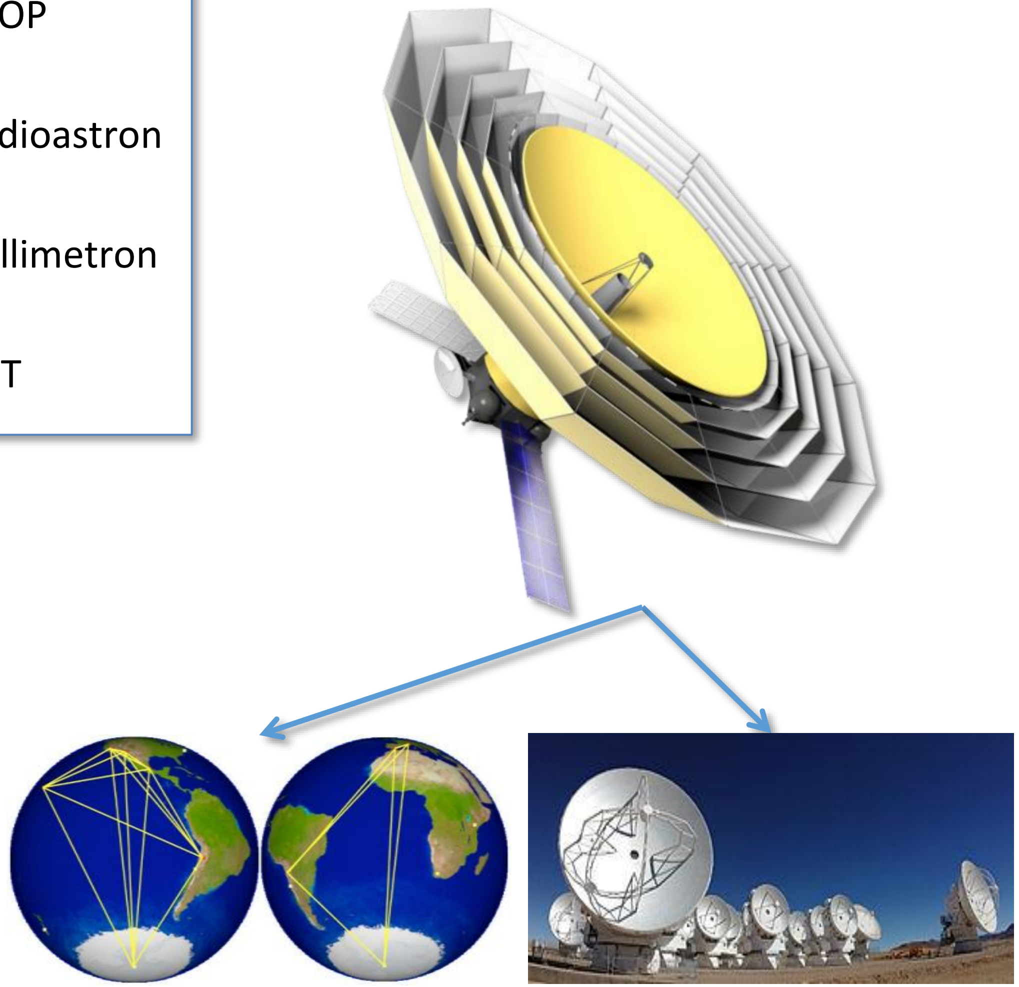
Millimetron

A New Step in Angular Resolution





Global mm-VLBI

ALMA

The 10-m telescope working in Space-VLBI mode can increase angular resolution ≈ 10-100 times (≈ 10^{-7}-10^{-8} arcsec).

Onboard VLBI Instruments

Freq. band, (GHz)	$T_{rx,}$ (K)	Polarization	№ of Channels*	Channel Bandwidth, (GHz)	Comment
31 - 45	< 17	RCP, LCP	2 RCP, 2 LCP	0.97 GHz	1.99 GHz, Option
84 – 136	< 37	RCP, LCP	2 RCP, 2 LCP	0.97 GHz	1.99 GHz, Option
211- 275	< 90	RCP, LCP	2 RCP, 2 LCP	0.97 GHz	1.99 GHz, Option
275-373	< 120	RCP, LCP	2 RCP, 2 LCP	0.97 GHz	1.99 GHz, Design
690	TBC	RCP, LCP	2 RCP, 2 LCP	0.97 GHz	TBC

Multi-frequency capabilities in talks of Taehyun Jung and Seog-Tae Han

(*) - 2 channels (USB, LSB) for each circular polarization correspond to the bandwidth of 1.99 GHz, 4 channels of 0.97 GHz for 2 polarization channels is 4 GHz in total

Millimetron Space-VLBI

Scientific Tasks & Constraints

<u>VLBI Scientific tasks:</u>

- High resolution 1D/**<u>2D imaging</u>** of black hole vicinity (M87 & Sgr A*)
- Search for wormholes
- High resolution AGN&QSO survey

Talks of Yuri Shchekinov and Dmitri Novikov

<u>Constraints:</u>

- Sensitivity of space telescope and space-ground baselines
- Onboard stable hydrogen clock
- Data downlink channel and onboard memory
- Tracking stations
- Space-ground VLBI geometry and space telescope orbit configuration
- Data processing and orbit accruacy
- Scheduling of observations (remarks)

Sensitivity

ALMA Band No.	Bandwidth (GHz)	Frequency* (GHz)	$SEFD_{MM}$ (Jy)	$SEFD_{ALMA}$** (Jy)	$SEFD_{MM\text{-}ALMA}$ (Jy)
1	31-45	40	1100	14	124
3	84-136	90	2760	42	340
6	211-275	240	5520	58	565
7	275-373	340	7180	70	710

RMS error of flux density measured at baseline between stations 1 and 2 can be estimated by known relation:

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

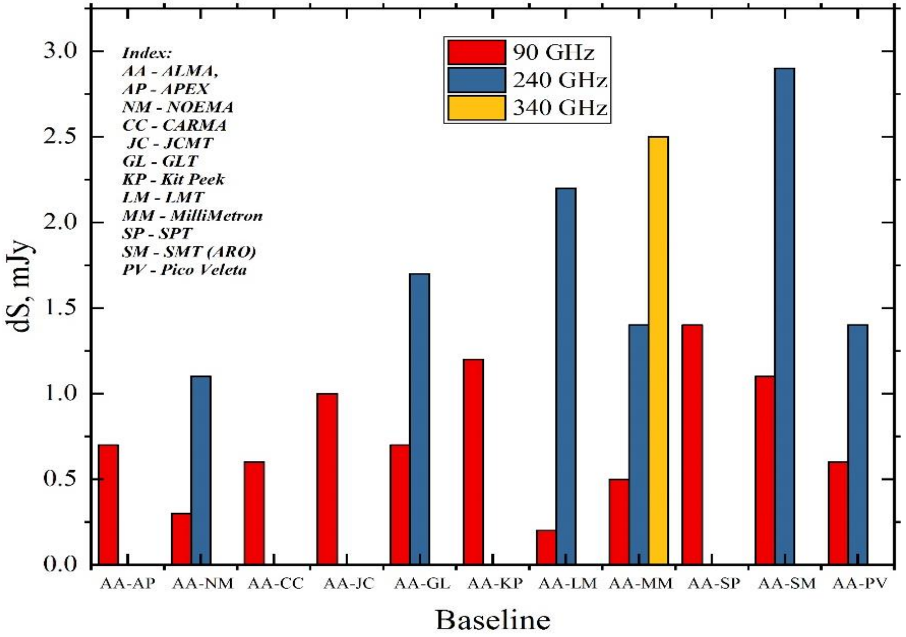
Where 1.14 coefficient is the correction coefficient due to a number of quantization bits per sample, ΔF - formatter input bandwidth (Hz) per specified frequency/ polarization channel and τ - integration time interval (sec).

(*) - Nominal observing frequency at MM bands; Note: assumption that Millimetron bandwidth is 4 GHz

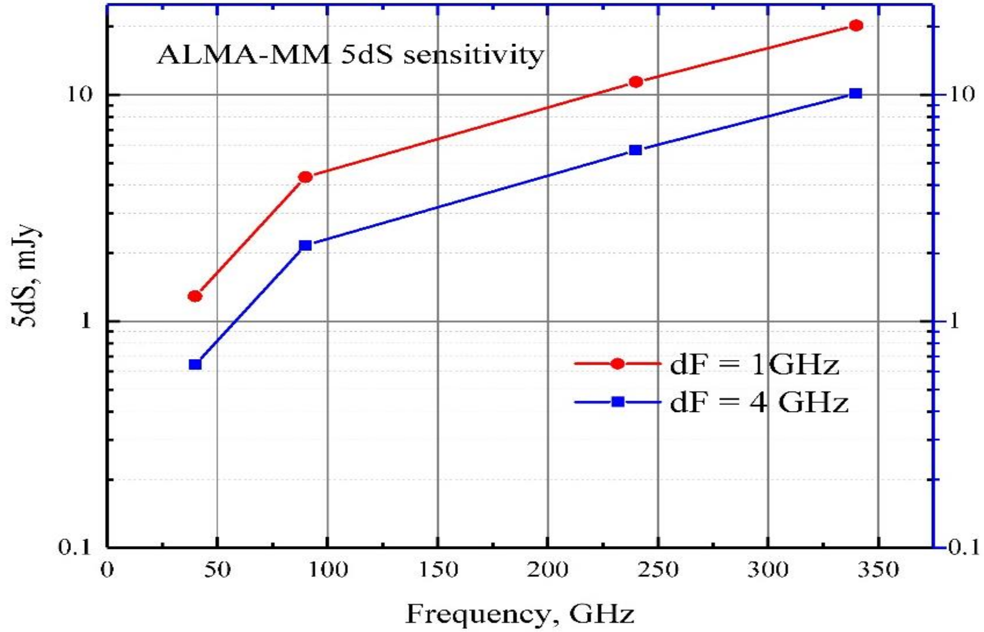
(**) - ALMA array: 50·12 m

Sensitivity

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



Sensitivity (1σ, dS mJy) at MM-ALMA-EHT baselines
Bandwidth is 4 GHz



ALMA-MM (5dS, mJy) sensitivity (table on top)
Bandwidth 1 & 4 GHz

(*) - Use atmosphere phase compensation at ALMA; Note: assumption, that data has 2 bits quantization

Onboard Hydrogen Clock

TRL 9

Frequency standard with high stability is very important for the space-ground VLB[...] [...] frequencies. “Vremya-Ch” is developing onboard hydrogen clock for “Millimetron”, the cu[...] [...]f development – technological models developed for tests.

Onboard hydrogen frequency standards

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	$7.10\cdot10^{-15}$	$4.86\cdot10^{-16}$	$\leq5\cdot10^{-16}$

(*) - adiabatic fast transition of atoms

Demidov et. al., Izmeritelnaya technika, 8, 2018

Downlink Channel and Onboard Memory

Current Parameters

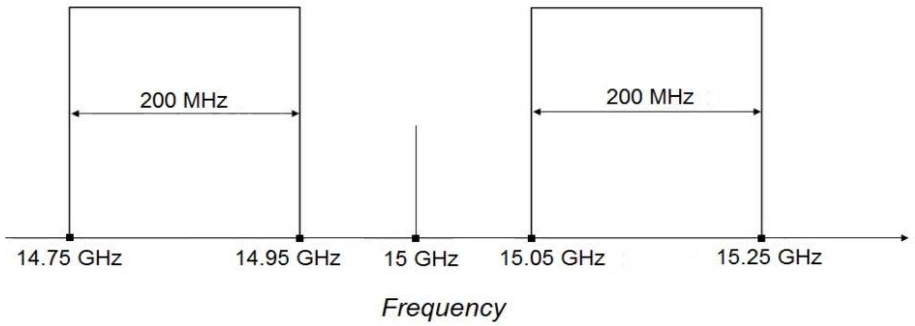
“Formator-P” is an onboard device for signal digitizing and onboard memory data storage.

Onboard memory – 10 Tb (~90 minutes of VLBI observations)

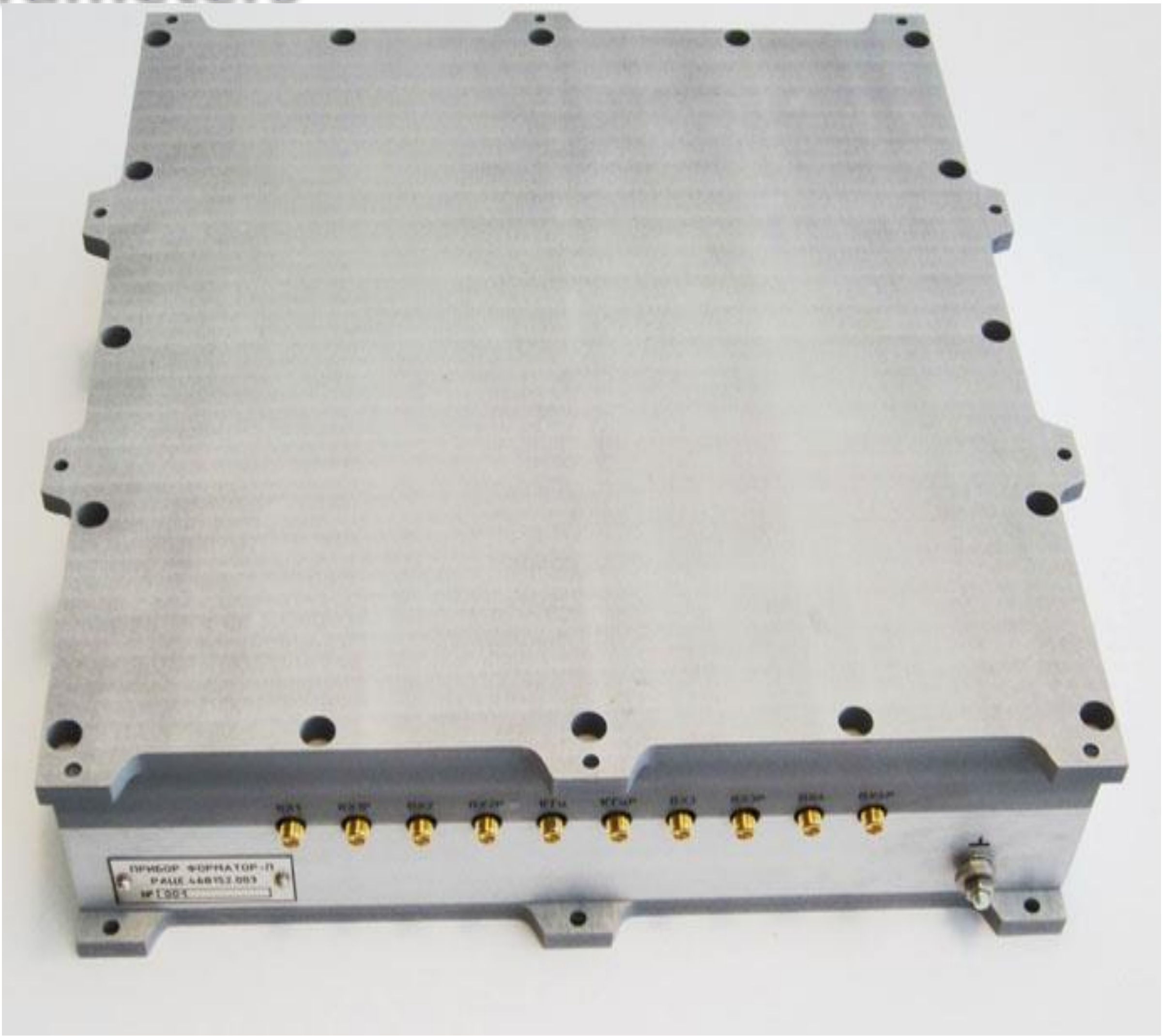
The recording rate at each of 4 channels is 2 Gbit/s. Accordingly, the total recording rate is 8 or 16 Gbit/s;

<u>Downlink channel with high gain antenna “VIRK-M”:</u>

Two instances of the PM-8 phase modulators allow data transmission at 1.2 Gbit/s.



Thus, the total recording time into memory **is ≈ 83.3 minutes**. The full memory read out time **can be ≈ 18.5 hours, i.e. more than 13 times** longer than the recording interval.



“Formator-P” technological model

More information: http://millimetron.ru/

Tracking Stations


Tracking and control station in Ussuriisk


Tracking and control station in Bear Lakes


Tracking station in Pushchino

Optimal coverage of tracking stations is required in order to provide:

- Continuous communication and monitoring of spacecraft
- Frequent measurements of “Millimetron” orbit
- Non-stop data receiving

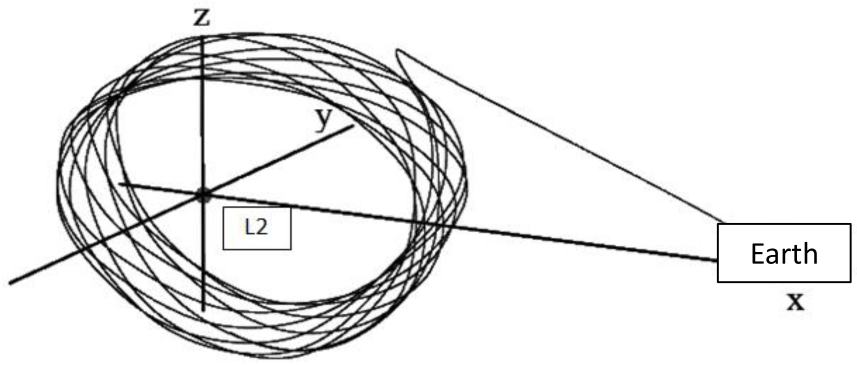
Millimetron Space-VLBI Geometry

L2 orbit

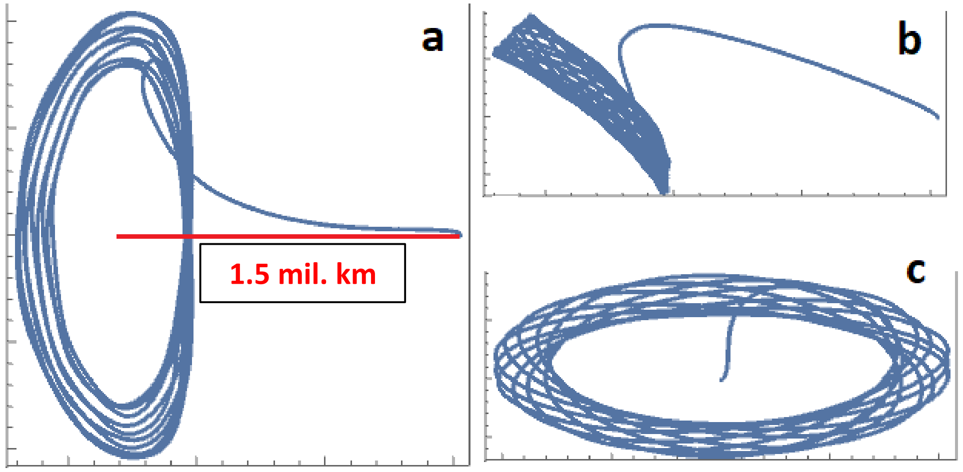
- Halo orbit around L2 point of
  Sun-Earth system, distance 1.5 million kilometers
- Orbit period – 178 days.
- Baseline – 1 500 000 km, max.
- Time of oscillation around L2 is about half of a year.
- Antenna view angle opening is ± 75° in ecliptic latitude and longitude.

Combined orbit (L2+near-Earth orbit)

- High elliptical near-Earth orbit (HEO)
- Orbit period – 10 days.
- Baseline – up to 350 000 km, max.
- Possible transition from/to L2 point of Sun-Earth system using the gravitational maneuver near the Moon



Halo orbit (coordinate system with respect to L2 point)

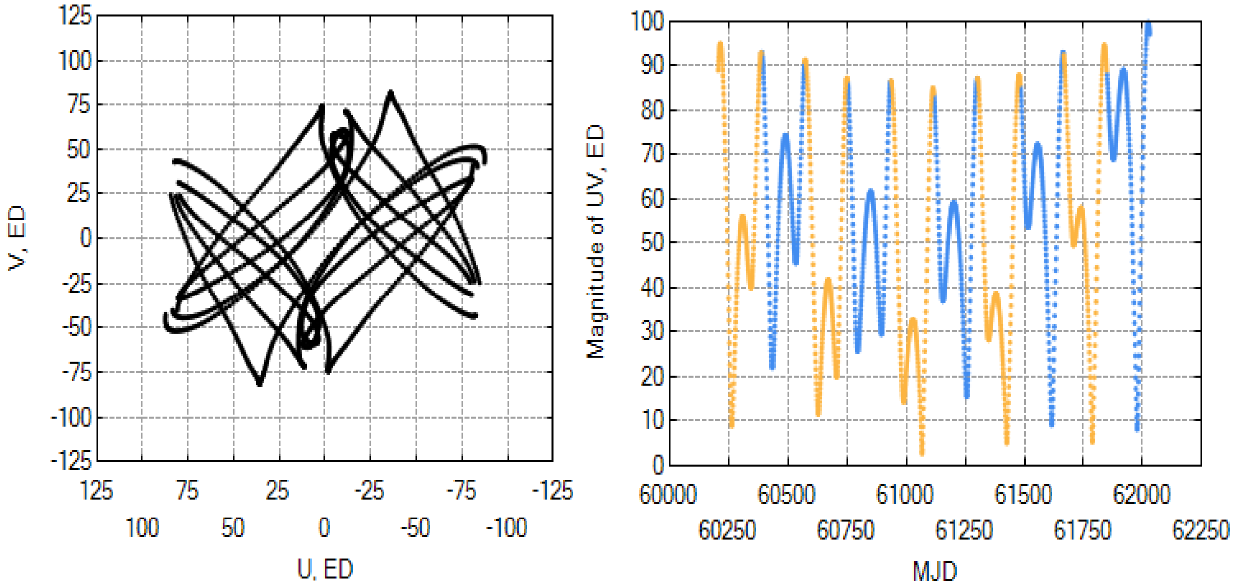


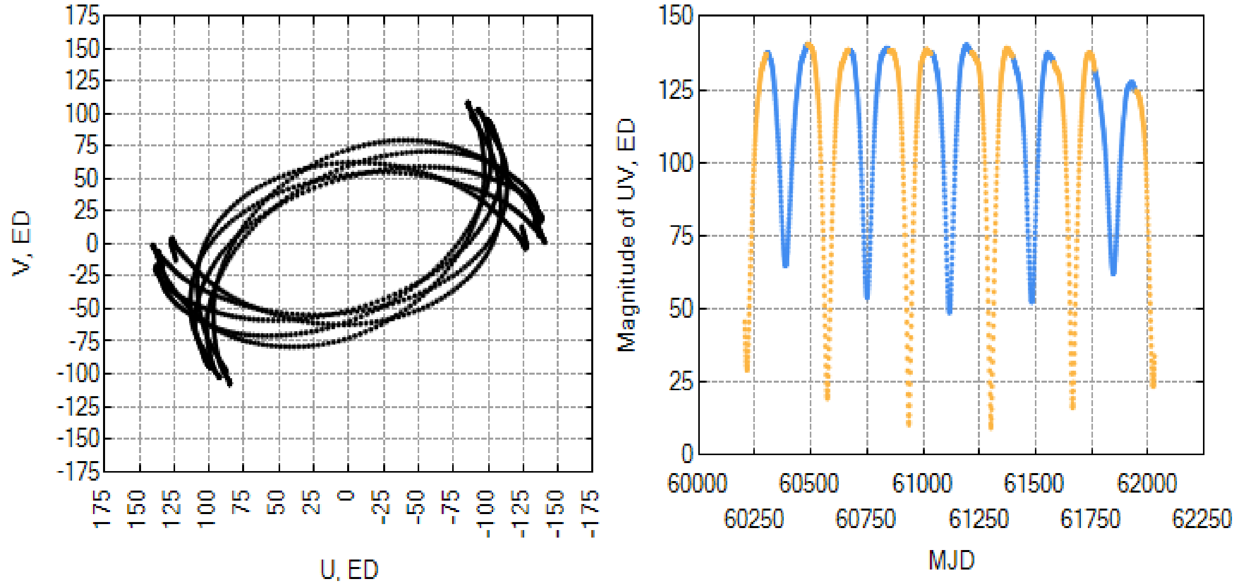
Halo orbit projections:
(a) – XY plane, (b) XZ plane, (c) – YZ plane

Overview of Millimetron Orbits

Halo Orbit

Sgr A* **5 years** **M87**

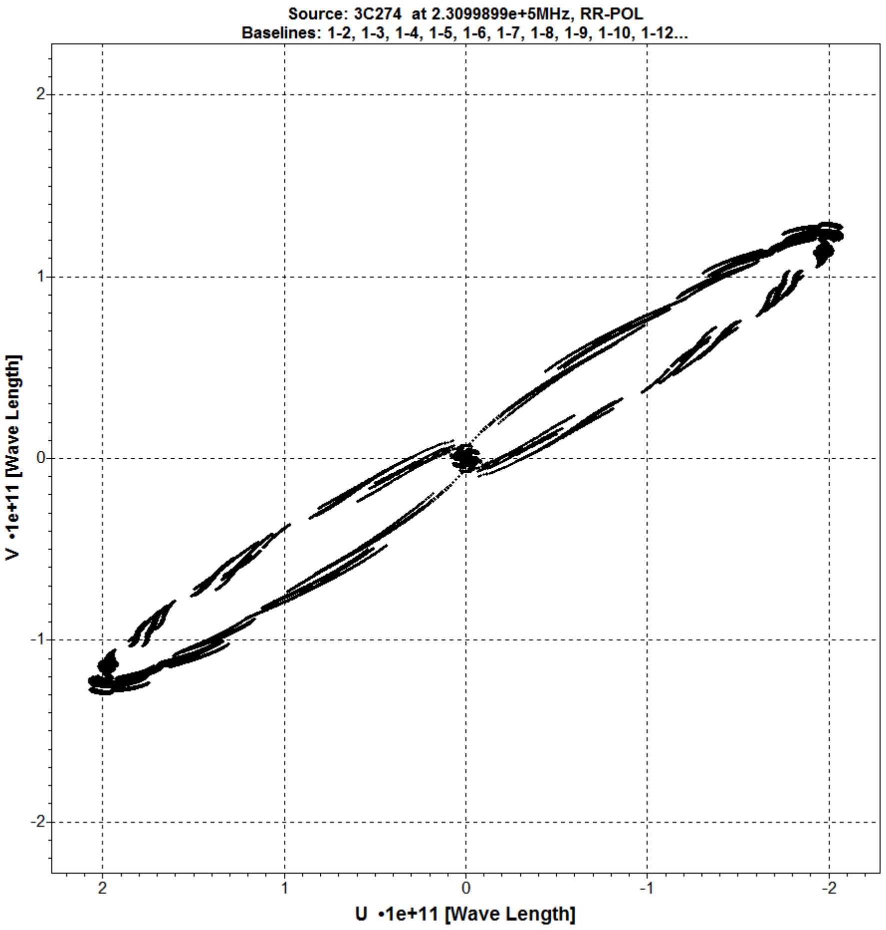




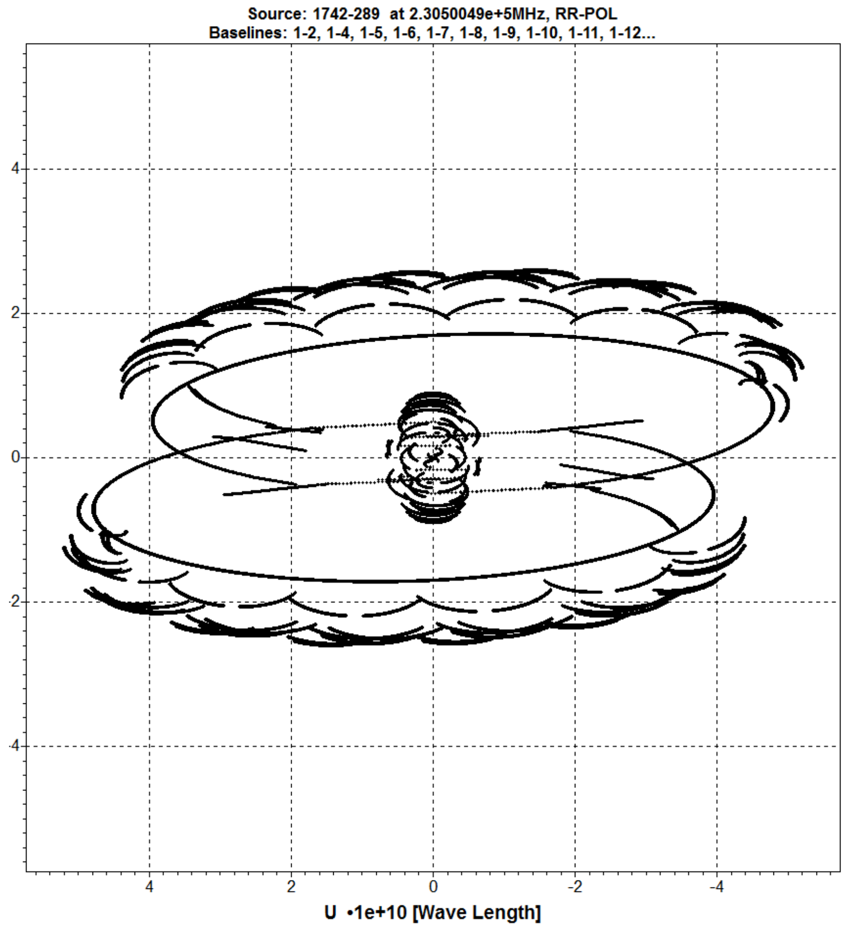
Observations at shorter baselines are available only once per year (blue points), considering the Sun constraints (yellow points). Duration is 5-7 days, which is comparable with EHT.

Overview of Millimetron Orbits

High Elliptical Orbit



UV-coverage for M87 (EHT+MM)



UV-coverage for Sgr A* (EHT+MM)

Orbit parameters:

a = 165 000 km
e = 0.939
i = 20.008 deg.
Ω = -3.583 deg.
ω = -92 deg.

Time interval:
one orbital period
(10 days)

Millimetron Space-VLBI Simulations

The following parameters were considered for the Sgr A* and M87 2D imaging simulation with “Millimetron”:

– Observing frequency: 230 GHz

– Bandwidth: 2 GHz

– Onboard memory 10 Tb (“Millimetron” total duration of observations – 90 minutes)

– Estimated sensitivity for “Millimetron” at 230 GHz was taken as 4000 Jy.

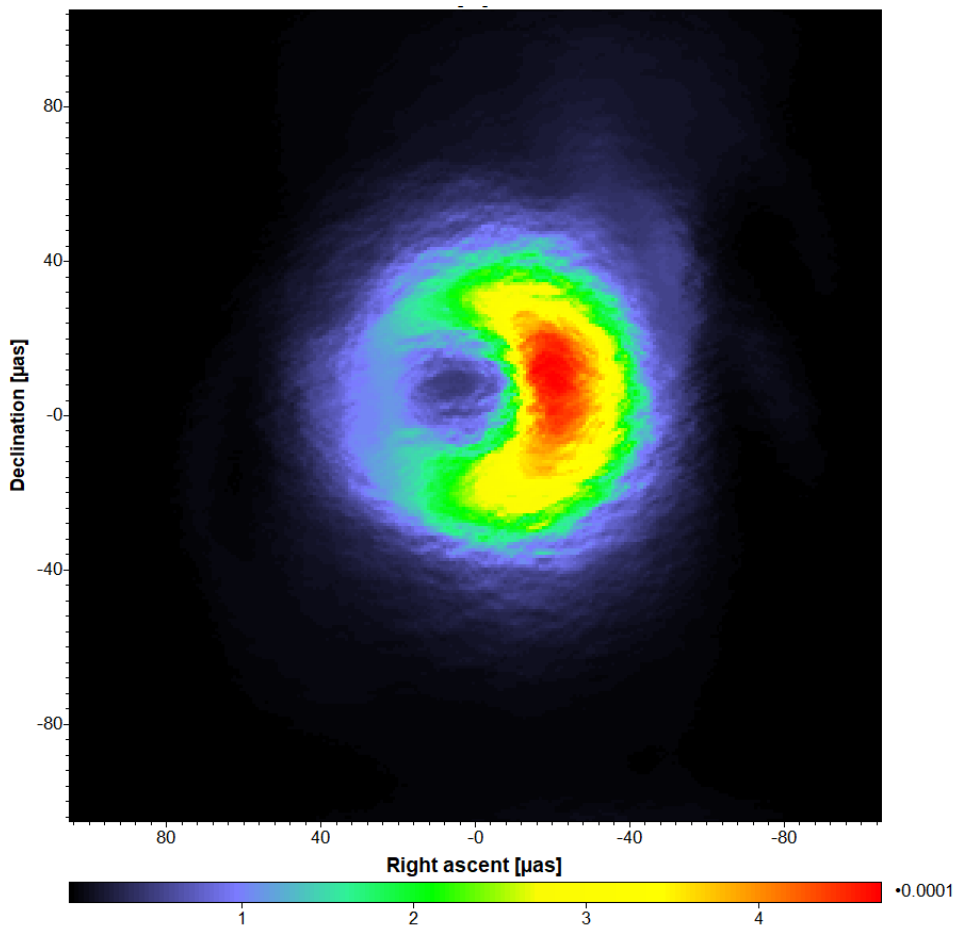
– EHT telescopes were selected as ground support

Telescope	X, (m)	Y, (m)	Z, (m)	SEFD, (Jy)	D, (m)
IRAM 30	5088967.900	-301681.6000	3825015.8000	3500	30
SMT	-1828796.200	-5054406.800	3427865.200	15000	10
SMA	-5464523.400	-2493147.080	2150611.750	5000	16
LMT	-768713.9637	-5988541.7982	2063275.9472	4000	50
ALMA	2225061.164	-5440057.37	-2481681.15	80	70
APEX	2225039.53	-5441197.63	-2479303.36	5000	12
JCMT	-5464584.68	-2493001.17	2150653.98	10000	15
GLT	1500692.00	-1191735.0	6066409.0	4000	12
NOEMA	4523998.40	468045.240	4460309.760	1000	47
KP	-1995678.840	-5037317.697	3357328.025	13000	12

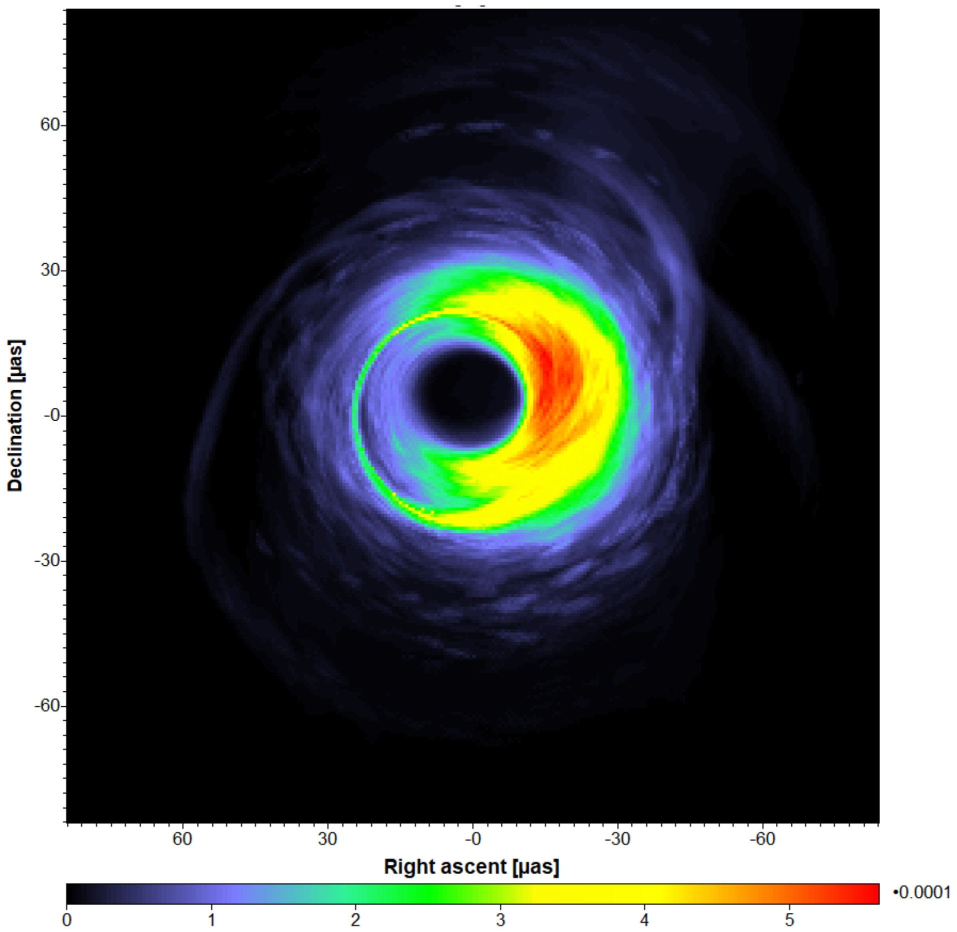
Andrianov et. al., in prep., 2019

Millimetron Space-VLBI Simulations

Models



Sgr A* Model

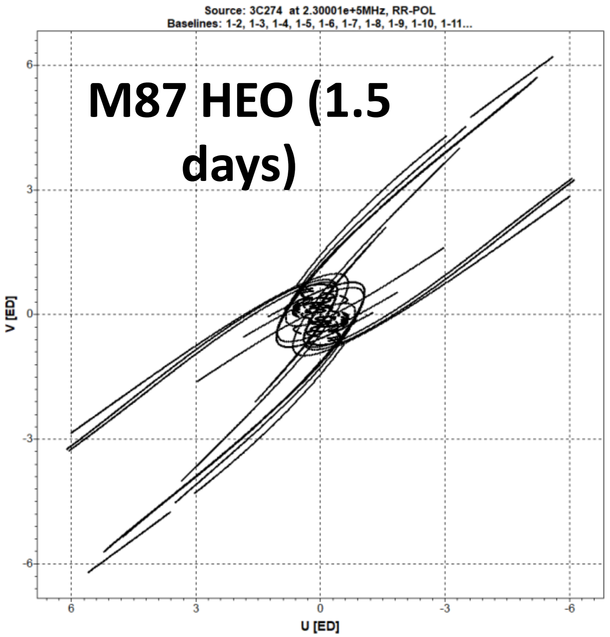


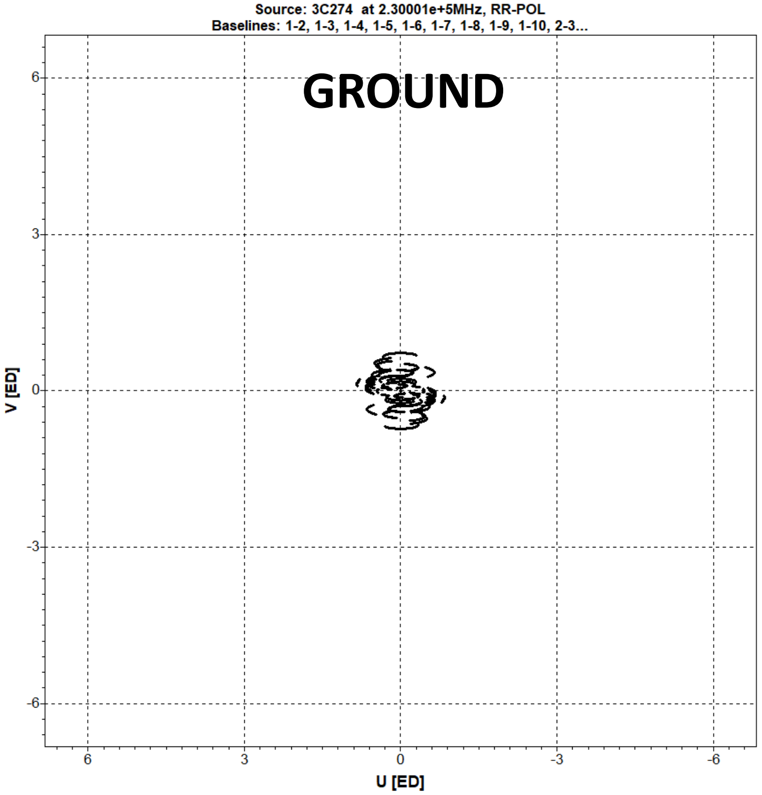
M87 Model

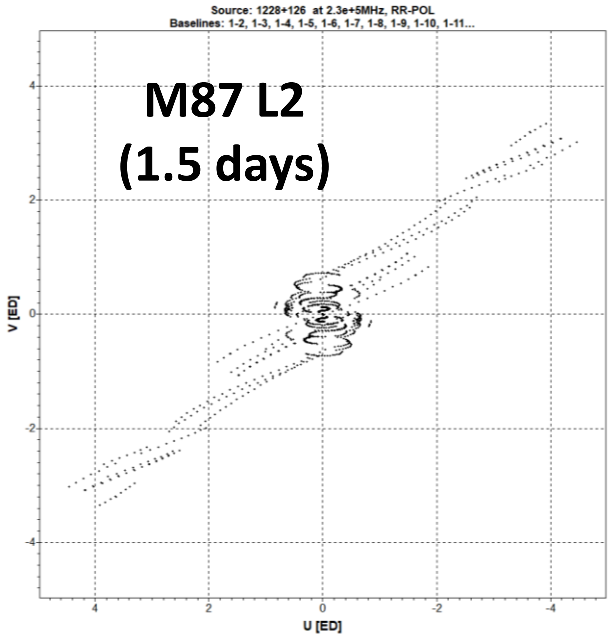
Moscibrodzka et al. (2014)

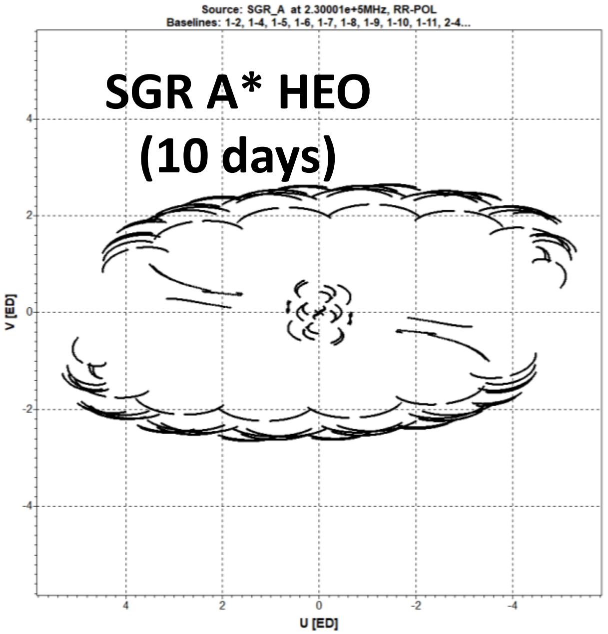
Andrianov et. al., in prep., 2019

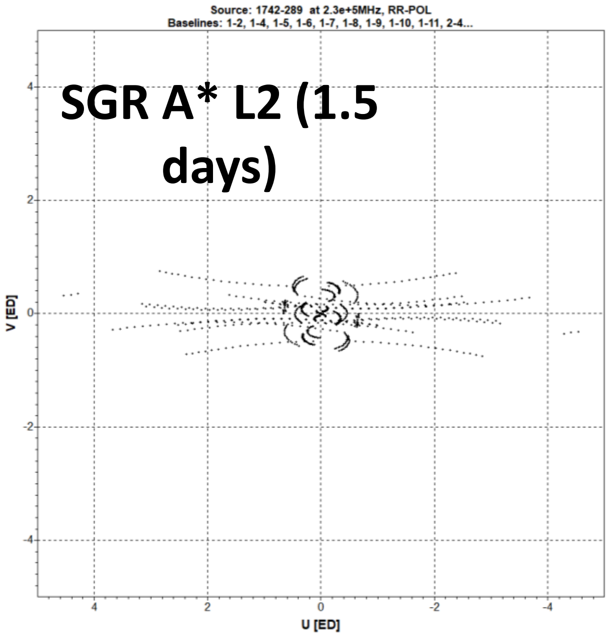
Millimetron Space-VLBI Simulations Coverage







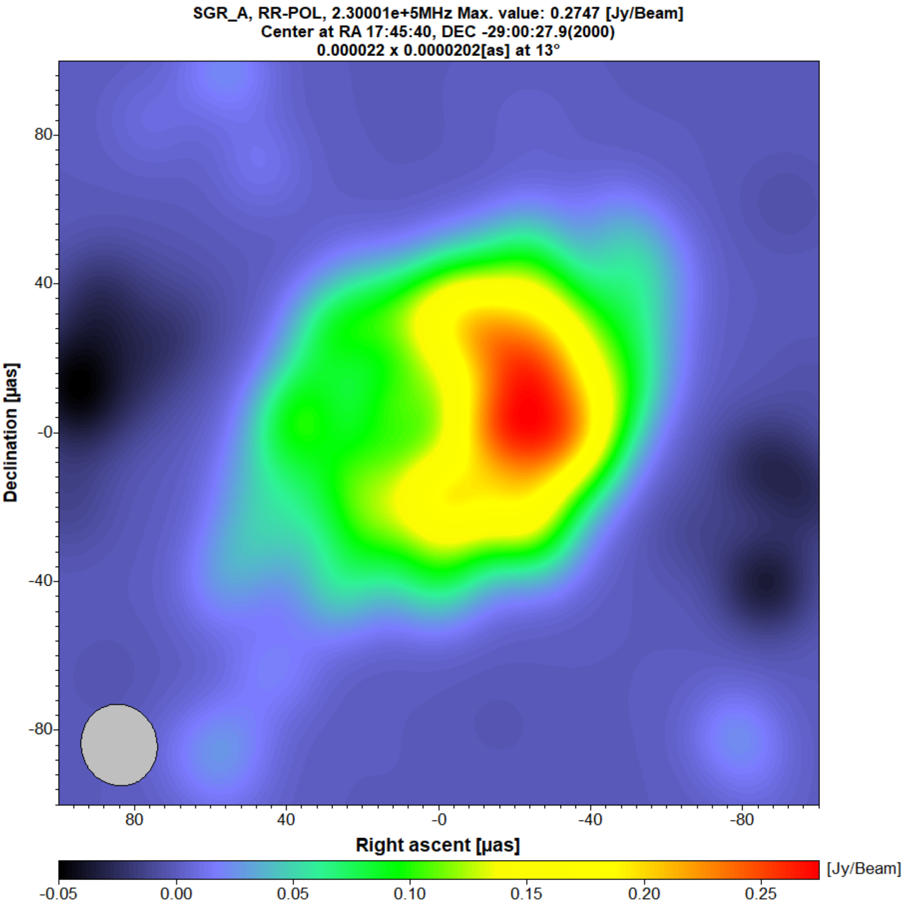




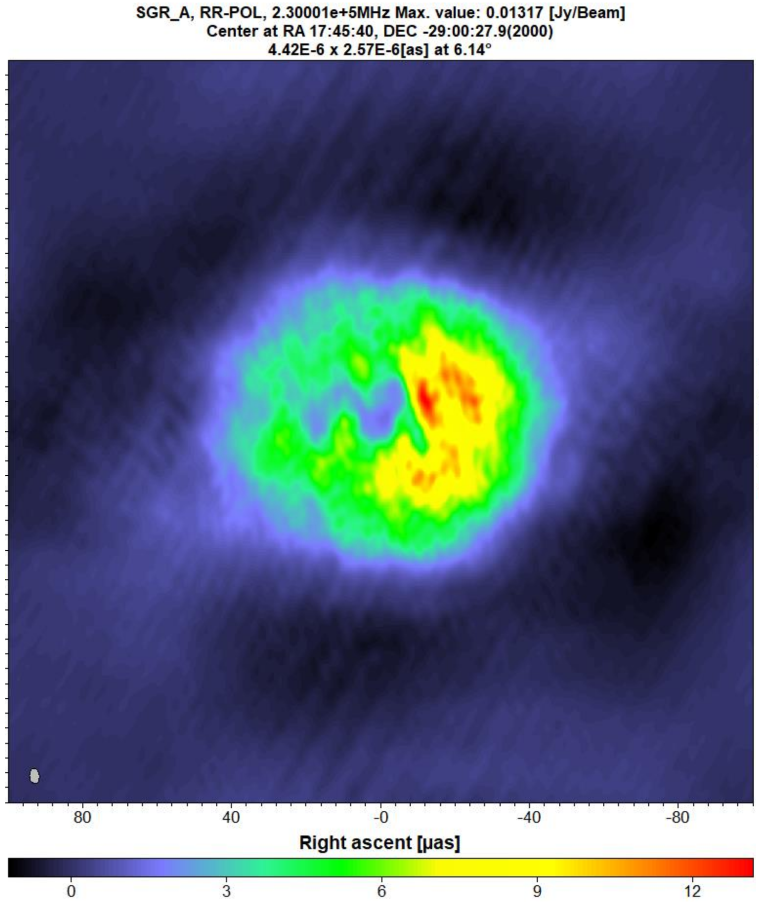
Andrianov et. al., in prep., 2019

Millimetron Space-VLBI Simulations

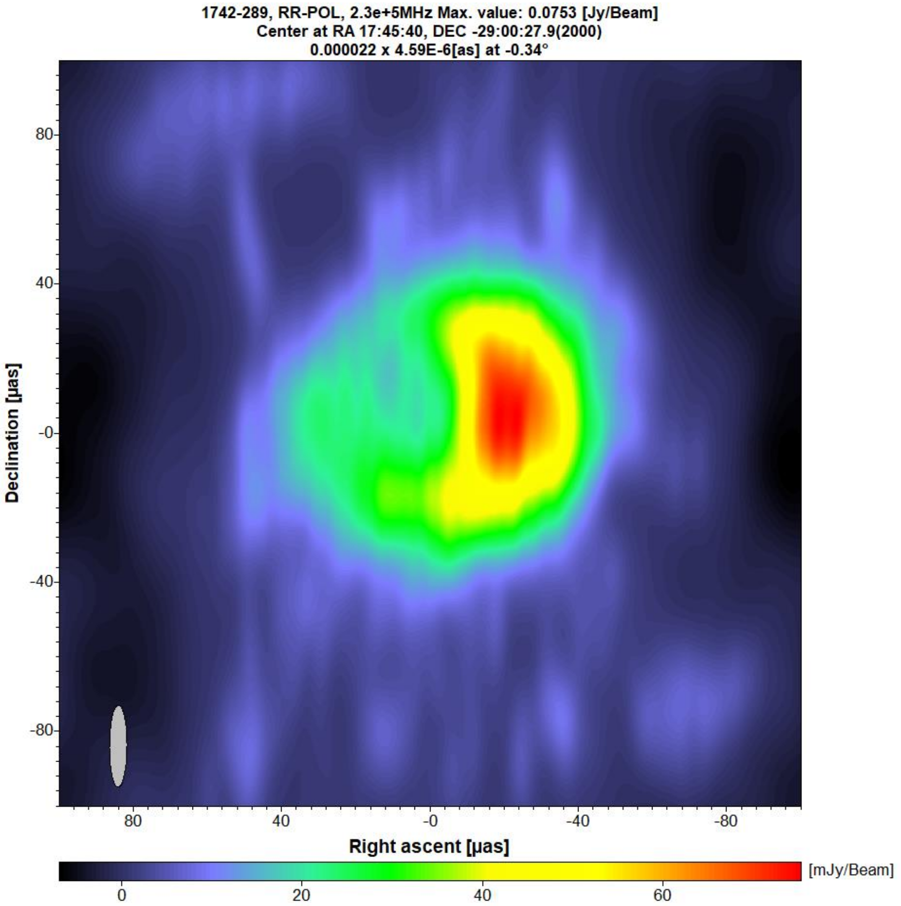
Results for Sgr A*



EHT Only



MM (HEO) + EHT

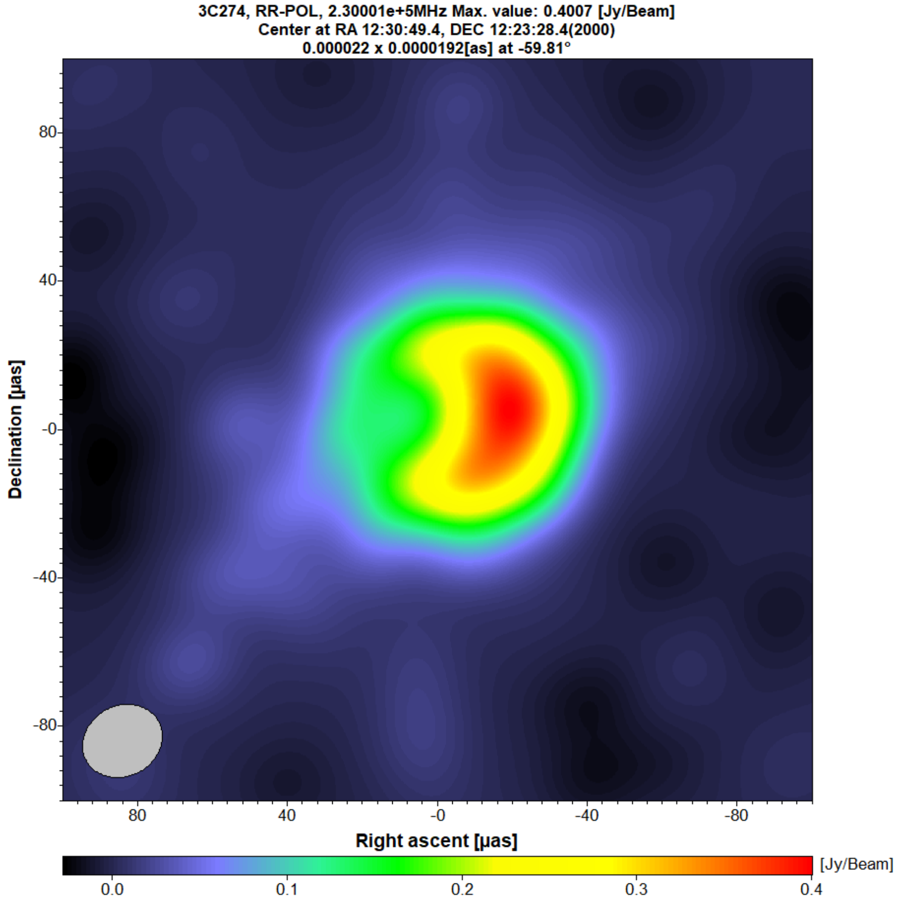


MM (L2) + EHT

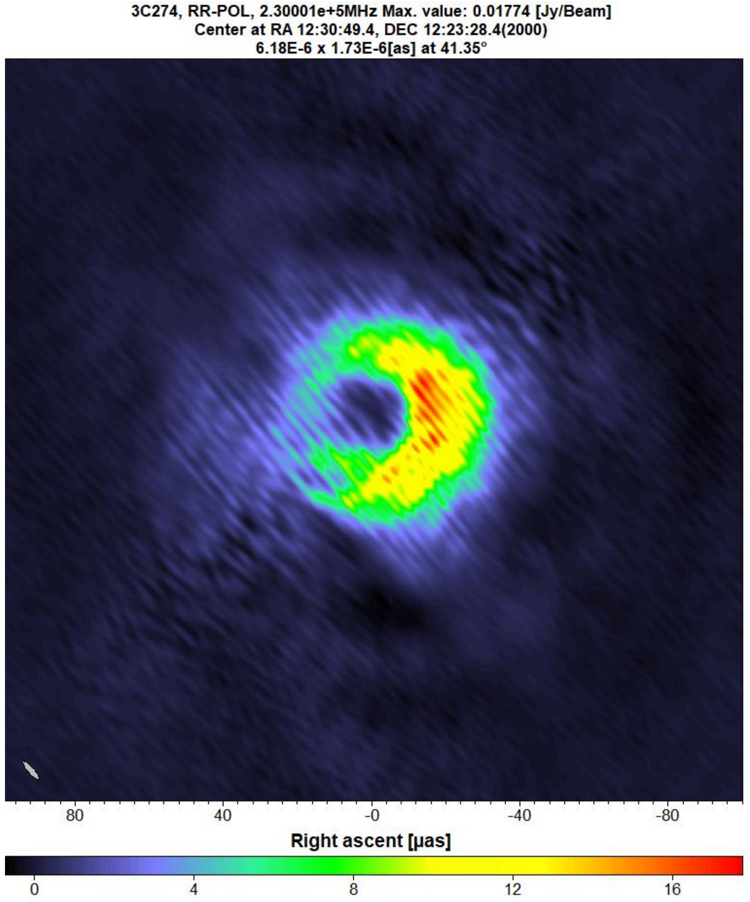
Andrianov et. al., in prep., 2019

Millimetron Space-VLBI Simulations

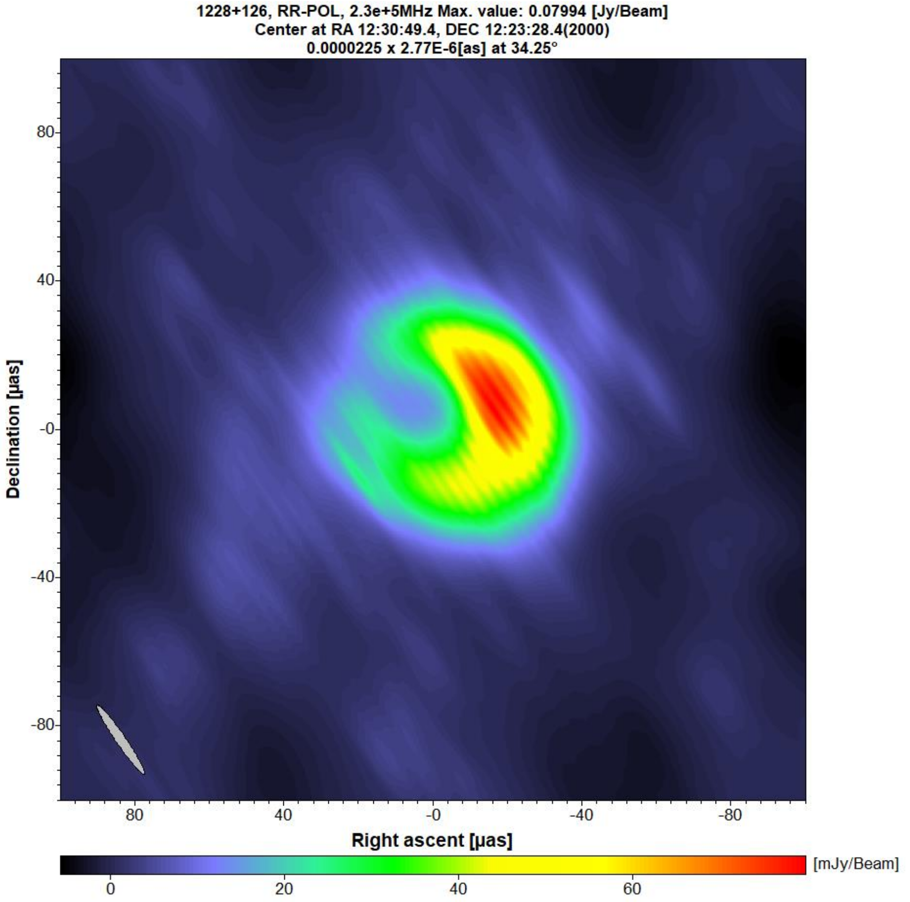
Results for M87



EHT Only



MM (HEO) + EHT

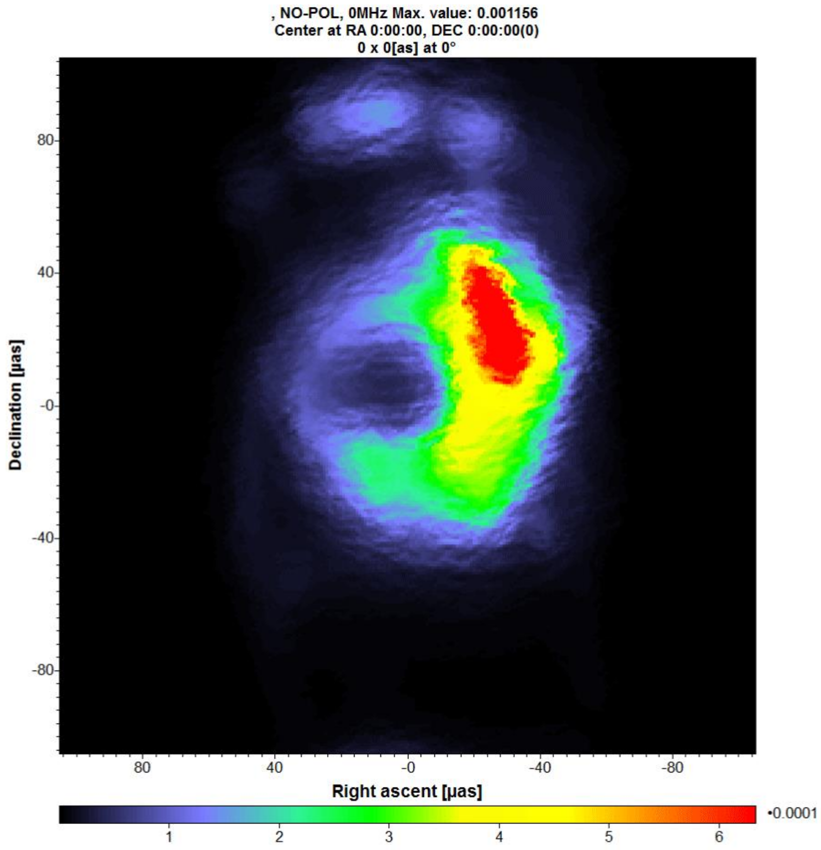


MM (L2) + EHT

Andrianov et. al., in prep., 2019

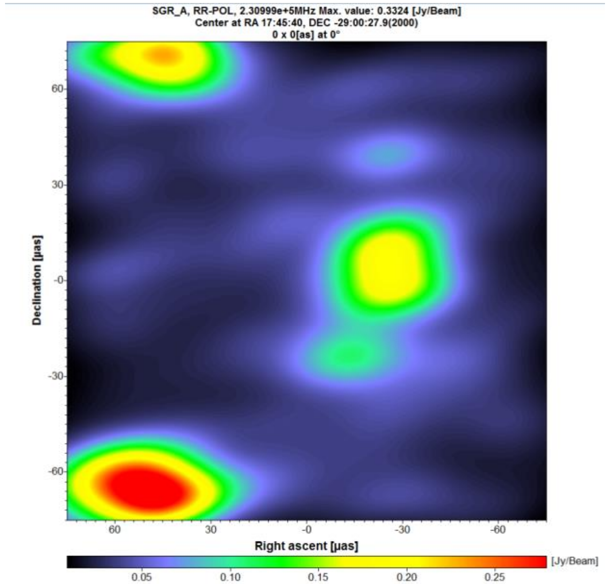
Millimetron Space-VLBI Simulations

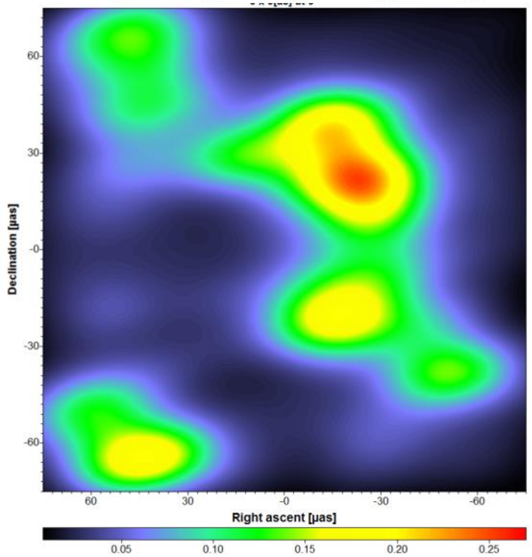
Dynamical Observations in HEO



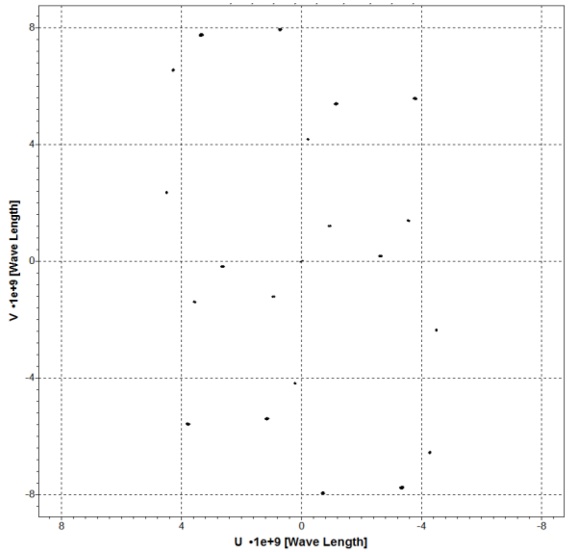
Sgr A* **Scattered** Dynamical Model
Moscibrodzka et al. (2014)

Clean map

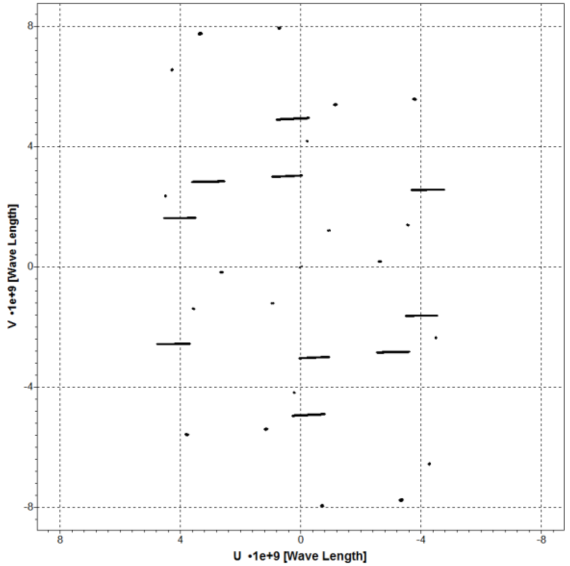




(u, v)-coverage



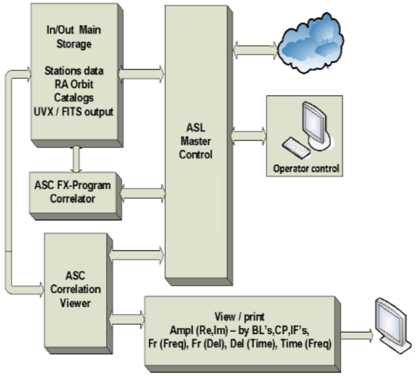
EHT



EHT + MM
30 minutes

Andrianov et. al., in prep., 2019

Development of Millimetron Data Center



- **Main objectives of DPC are: collecting, processing and archiving of all the observation data and organizing information exchange among mission's participants.**

- **Expected volume of data ~3300 PB/year or 33000 PB for 10 years of operation.**

- **It is necessary to connect the DPC with tracking stations and other ground telescopes with high speed channels.**

Radioastron mission experience will be used in creation of Millimetron Data Center.

In Millimetron:

- **Special atmosphere calibrations (wide bandwidth, multi-frequency observations, phase transferring, water radiometers)**
- **Delay model improvement**
- **Software package for single dish observations**

More information: http://millimetron.ru/

Data Processing

ASC Correlator

Main features:

– Correlated 95% of Radioastron mission data

– FX architecture

– MPI application

– Support all VLBI row data formats: RDF, Mark5A, Mark5B, VDIF, VLBA, K5.

– CPU+GPU computer cluster

– 250 Tb online storage for row data.

– 380 Tb online storage for correlated data.

– Raw data offline storage of 4500 Tb (HDD) and 4500 Tb (tapes).

– ASC Correlator can operate with more than 10 stations (45 baselines) in real time.

– Continuum, Maser Line and Pulsar data processing modes

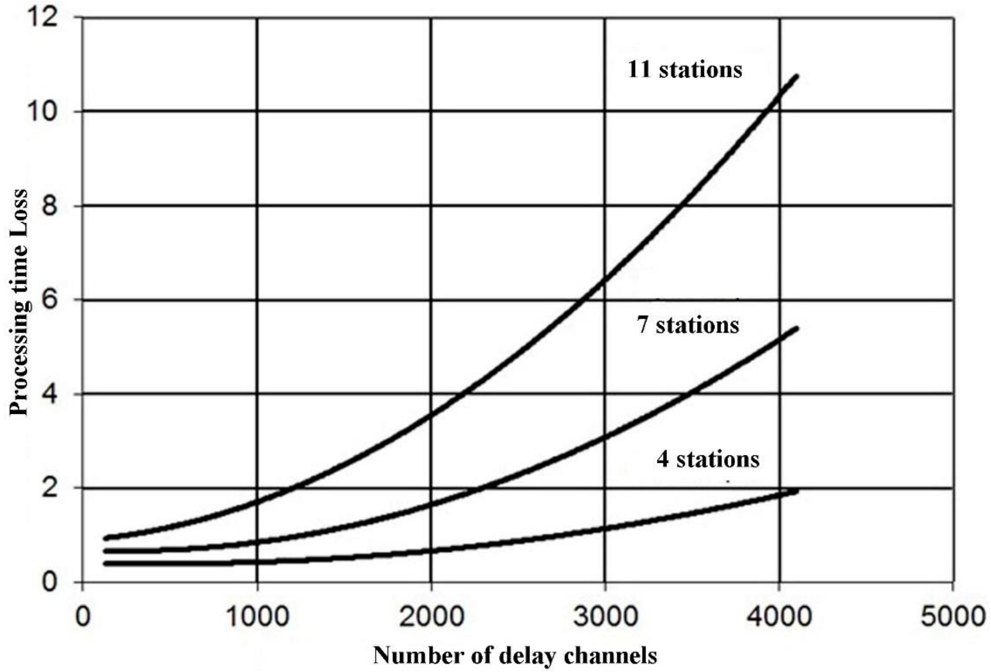
– ASC Correlator is the only correlator capable to process the data in “Coherent" mode (closed-loop) of delay restoration

More information: http://millimetron.ru/

Data Processing

Correlator Requirements

•BW:	4 MHz	f = 328 MHz	N_{ch} = 16,	T_{int} = 8 sec	< 0.1	Tflop/s
•BW:	32 MHz	f = 2700 MHz	N_{ch} = 128,	T_{int} = 1 sec	< 0.1	Tflop/s
•BW:	128 MHz	f = 15000 МГц	N_{ch} = 512,	T_{int} = 1/8 sec	0.5	Tflop/s
•BW:	1 GHz	f = 100 GHz	N_{ch} = 4096,	T_{int} = 1/64 sec	5	Tflop/s
•BW:	8 GHz	f = 240 GHz	N_{ch} = 32768,	T_{int} = 1/128 sec	20	Tflop/s



Correlator productivity plot depending from the number of delay channels in FFT of correlator for computer cluster with power of 1 Tflop/s ("Radioastron" project)

- The greatest complexity is delivery of data from tracking stations and storage of raw data, but also it can be solved at the relevant organization of necessary services!

Data Processing

Orbit Accuracy

Accuracy of predicted orbit for Millimetron: error of baseline length $\Delta_{bline} \approx$ 100-300 m, error of velocity $\Delta_{vel} \approx$ 2 mm/sec

For Radioastron case ($\Delta_{bline} \approx$ 200 m, $\Delta_{vel} \approx$ 2 cm/sec)
Correlator search parameters:

- f = 15 GHz Delay_error = 0.66 µs, Fr_rate_error = 3 Hz N_{ch} = 4096, T_{int} = 1/8 sec.
- f = 100 GHz Delay_error = 0.66 µs, Fr_rate_error = 20 Hz N_{ch} = 4096, T_{int} = 1/64 sec
- f = 240 GHz Delay_error = 0.66 µs, Fr_rate_error = 48 Hz N_{ch} = 4096, T_{int} = 1/128 sec.

Computational power of modern computers is sufficient for correlation data processing of Millimetron project.

Scheduling of Observations

Remarks

In general, scheduling of any such mission should be aimed at the maximum implementation of scientific tasks.

1) Clearly formulated scientific tasks. It forms the requirements both for the geometry of the interferometer and for planning. **It's pointless to just fill up the observational time with surveys like it was in Radioastron.** A clear understanding of the requirements for the geometry and sensitivity of the interferometer is needed and **what kind of scientific outcome is expected**. **Different configurations of orbit are possible.**
2) Preparation of an optimal observation program, taking into account the visibility of the observed sources by ground and space telescopes, taking into account the availability of the tracking stations to minimize the gaps between the downlink.
3) It is critically important to consider issues related not only to data transmission from the spacecraft, but also from ground telescopes (EHT experience has shown how difficult it could be to deliver the data from ground-based telescopes for subsequent processing). **In general logistics are crucial.**

Millimetron Orbit Configuration
Advantages and Challenges

Advantages of L2:

1) Best option for single dish observations
2) Longest baselines are available (up to 140 Earth diameters)
3) Observations with high angular resolution (1D, surveys)
4) Smaller are available (1-10 Earth diameters)
5) No complicated maneuvers

Challenges of L2:

1) Small baselines are available only for sources that have small ecliptic latitudes.
2) Slow evolution of orbit -> slow evolution of (u,v)
3) Smaller baselines for a given source are available once per year
4) Difficult to find optimal orbit configuration that provides acceptable (u,v)-coverage for more than one source

Millimetron Orbit Configuration
Advantages and Challenges

Advantages of HEO:

1) Possible to find good (u,v)-coverage for single source
2) Frequent VLBI imaging observations
3) More sources for observations
4) Faster (u,v) evolution
5) Observations in dynamics

Challenges of HEO:

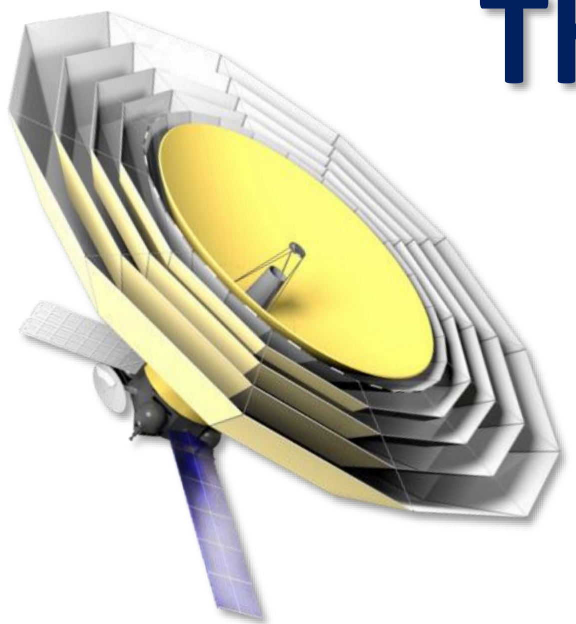
1) Complicated maneuvers related to the transition between L2 and HEO
2) Strict limitations on the spacecraft fuel related to the transition
3) Strict constrains of single dish mode observations in HEO
4) Difficult to find optimal orbit configuration that provides acceptable (u,v)-coverage for more than one source

CONSIDER THE COMBINED ORBIT – L2 POINT WITH TRANSFER TO HEO

Summary and Conclusions

Millimetron Space-VLBI Critical Points

- **Orbit configuration and accuracy of determination.** Millimetron will use combined orbit: L2 point with further transfer to HEO. **Important point: qualitatively developed scientific program!**
- **On-board maser stability for higher frequencies.** Onboard maser is currently under development.
- **Scheduling of observations**. Scheduling is a matter of balance between the spacecraft constraints and the scientific program. Requires accurate scheduling of the mission. It’s possible that successive scientific targets will be rare enough. **Important point: ground logistics are also crucial!**
- **Provide acceptable sensitivity.** Increase observing bandwidth, improve and reconsider noise temperature.
- **Data downlink channel supply and onboard memory.** Onboard memory expected to be increased at least 10 times, as well as the increasing the downlink bandwidth/frequency. It will provide an opportunity to increase the observing bandwidth and the total observing time of Millimetron, as well as the sensitivity.



Thank you for your attention!

Millimetron project web-page: http://millimetron.ru/

ROSCOSMOS ASC LPI