Simulations of M87 and Sgr A$*$ imaging with the Millimetron Space Observatory on near-Earth orbits

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Millimetron Space Observatory

The first 10-m deployable and cooled
space sub-mm and FIR telescope

<u>The mission is approved and supported by Russian Space Agency</u>

- FIR, sub-mm and mm range
- In orbit deployable and adjustable antenna
- Mechanically cooled (<10K) with post-cryo life
- Orbit around L2 Lagrange point; launch with new launcher Angara-5M
- Lifetime: 10 years; at cryo >3 years

<u>Two operation modes:</u>

Space-VLBI at 0.3 – 7 mm

Single dish at 0.08 – 3 mm

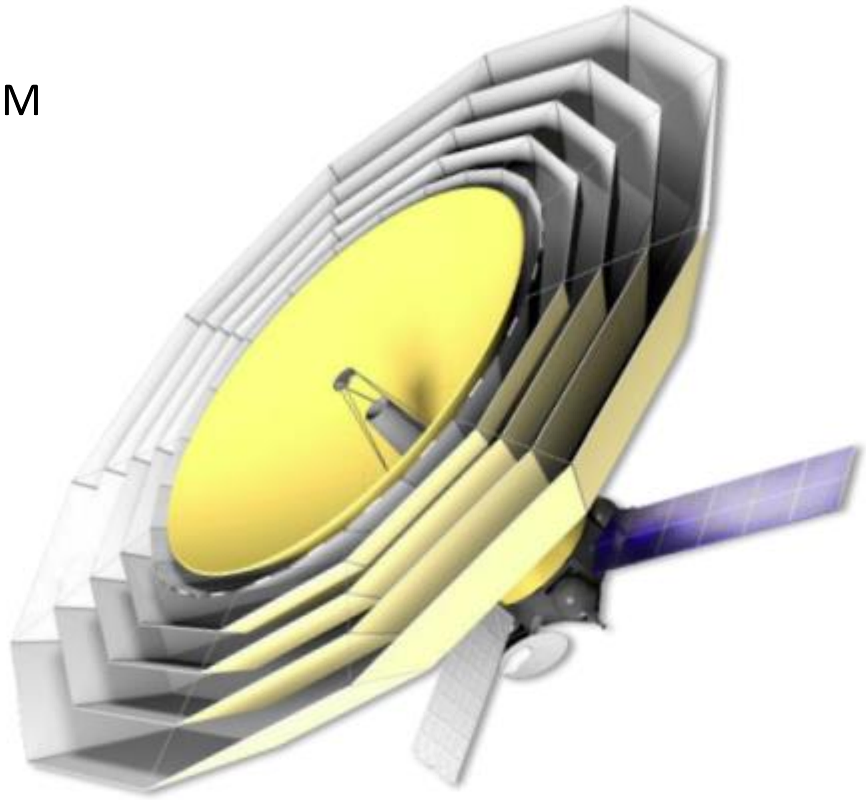
- Step forward with respect to earlier missions
- Sensitivity: 10-22 W/m2 for spectroscopy and 0.5 μJy

for photometry (single dish)

Spacecraft bus and instruments in Phase-A

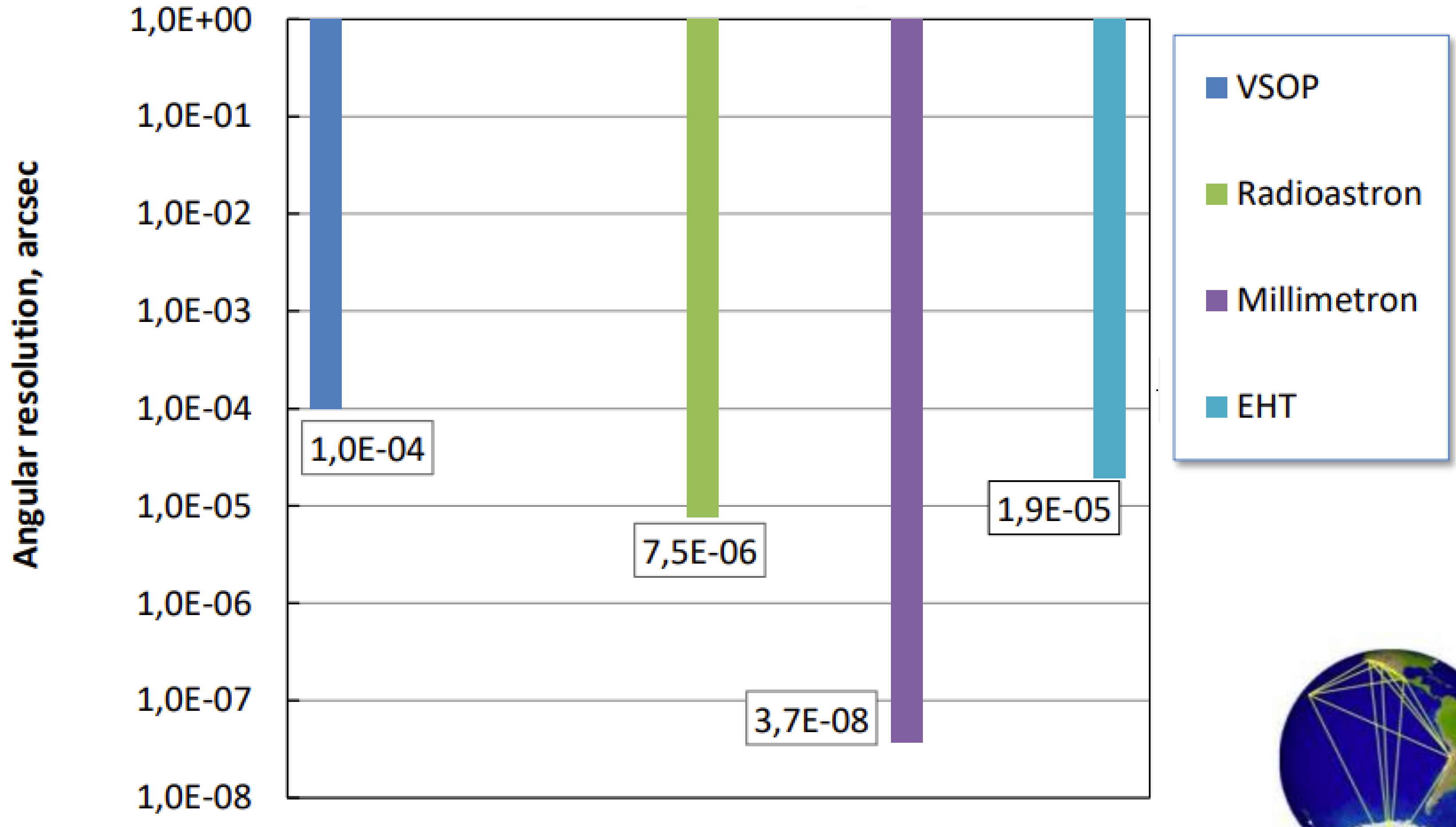
Antenna in Phase-B

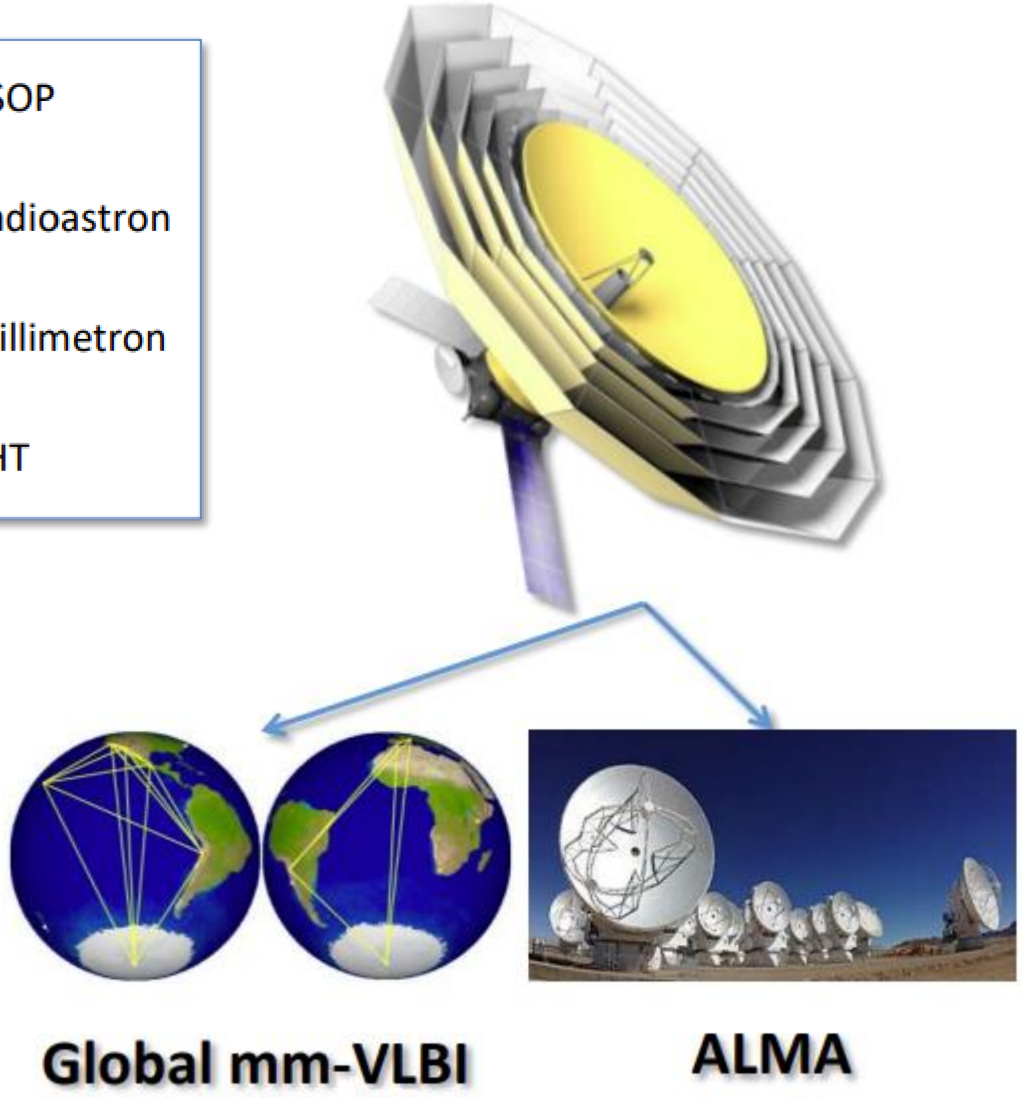
Launch date : 2029



More information: http://millimetron.ru/

Millimetron – A New Step in Angular Resolution



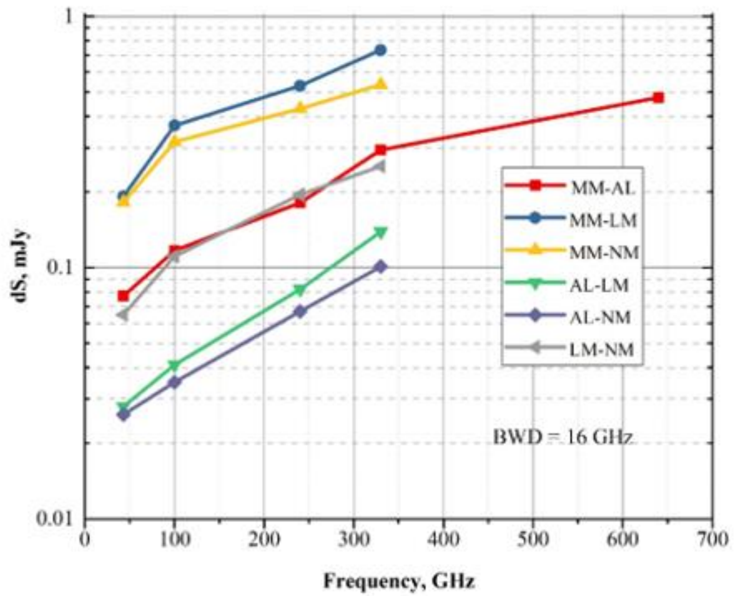


The 10-m telescope working in Space-VLBI mode can increase angular resolution ≈ 10-100 times (≈ 10^{-7} -10^{-8} arcsec).

VLBI Capabilities

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

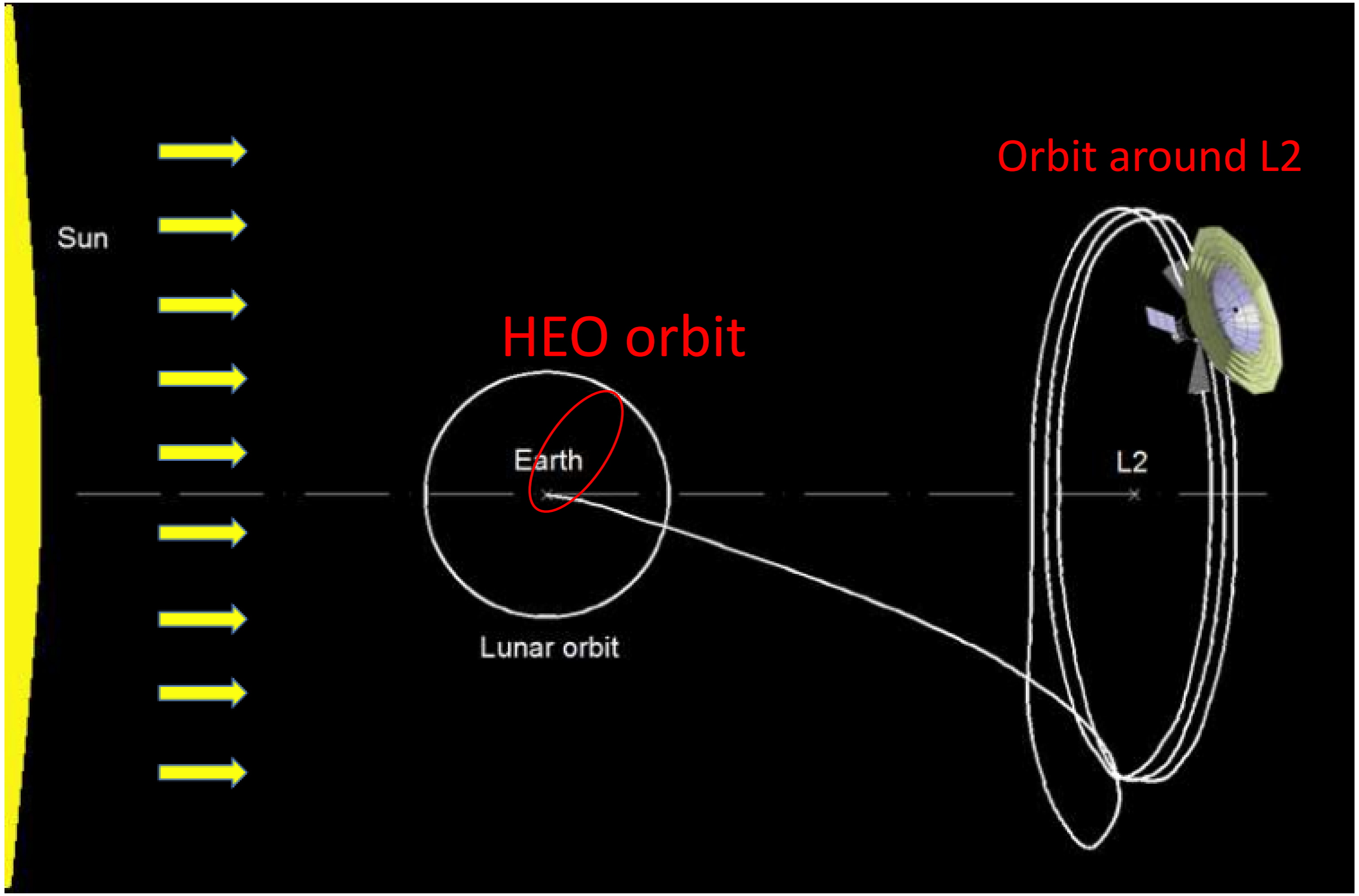
ALMA Band No.	Bandwidth (GHz)	Frequency* (GHz)	$SEFD_{MM}$ (Jy)	$SEFD_{ALMA}$** (Jy)	$SEFD_{MM-ALMA}$ (Jy)
1	31-45	40	1100	14	124
3	84-136	90	2760	42	340
6	211-275	240	5520	58	565
7	275-373	340	7180	70	710



- 2 GHz bandwidth is considered to be increased to 16 GHz
- Memory volume 10 TB is considered to be increased to 100 TB
- Downlink speed 1.2 Gb/s is considered to be increased
- Multifrequency simultaneous observations and frequency phase transfer

- More details in A.G.Rudnitskiy talk

Orbit



<u>L2 orbit</u>

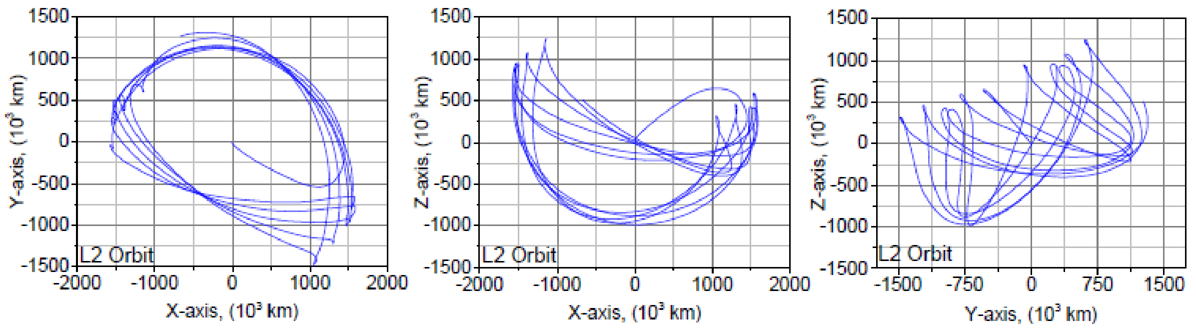
- Halo orbit around L2 point of Sun-Earth system, distance 1.5 million kilometers
- Orbit period – 178 days.
- Baseline – 1 500 000 km, max.
- Time of oscillation around L2 is about half of a year.
- Antenna view angle opening is ± 75° in ecliptic latitude and longitude.

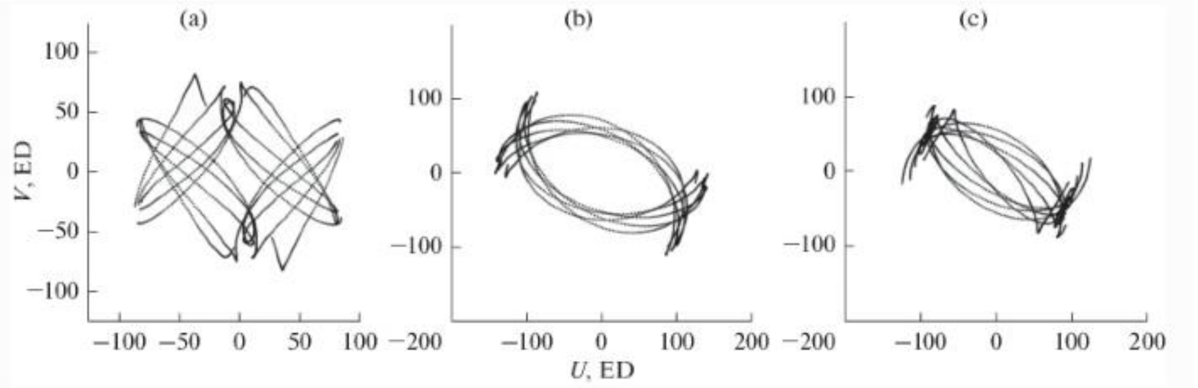
<u>Combined orbit (L2+near-Earth orbit)</u>

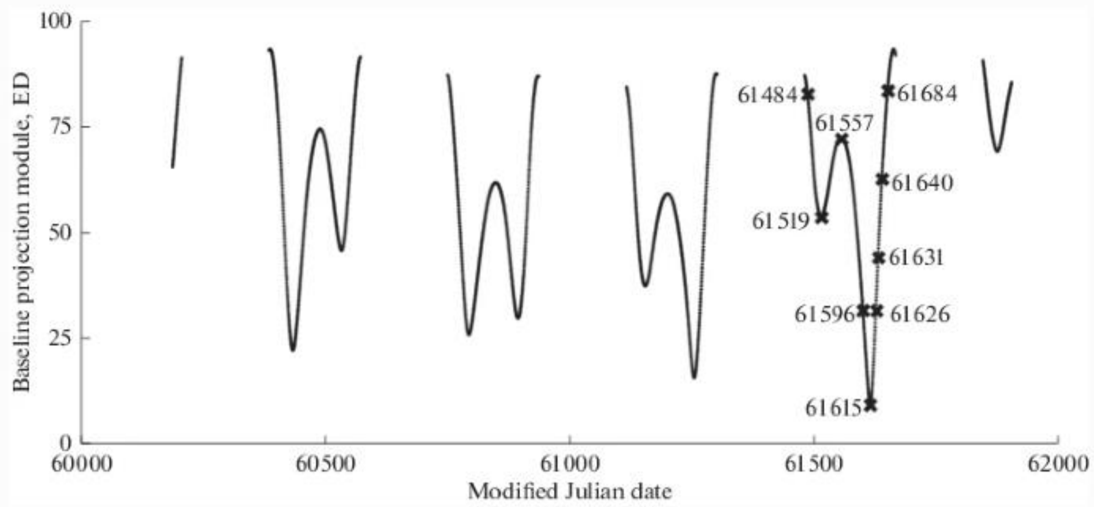
- High elliptical near-Earth orbit (HEO)
- Orbit period – 10 days.
- Baseline – up to 350 000 km, max.
- Possible transition from/to L2 point of Sun-Earth system using the gravitational maneuver near the Moon

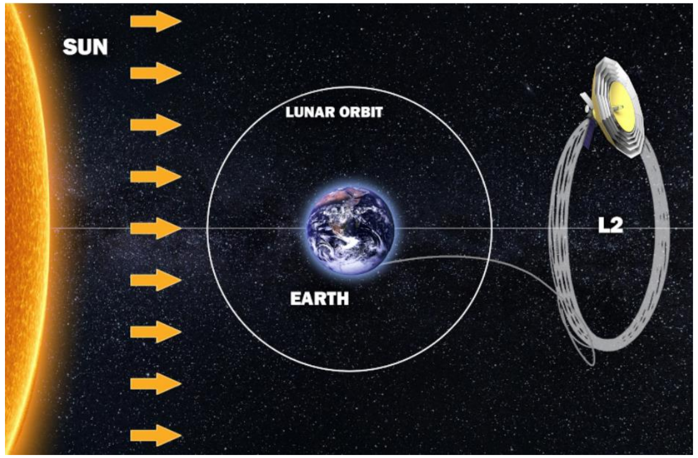
After the warranty period of the mission, it is possible to transition to the high elliptical orbit if necessary (for additional imaging of M87 and Sgr A *)

L2 orbit





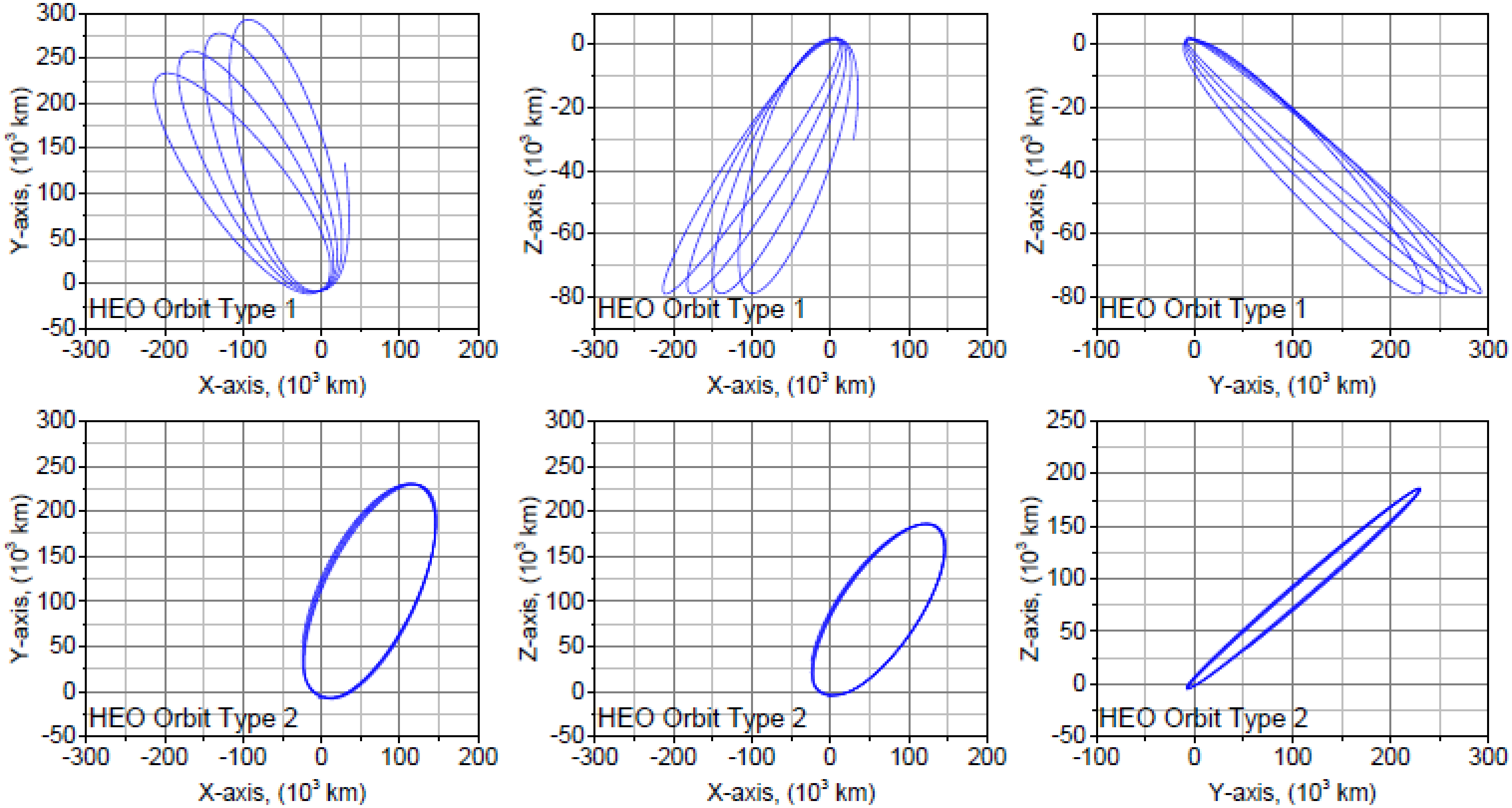




R ~ 1.5 * 10^6 km, P ~ 180 days

- High angular resolution
- It is difficult to obtain the good UV-plane (especially on small baselines) for imaging (but it’s possible)
- The orbit is unstable, with minimal fuel consumption it is possible to go to high elliptical near-Earth orbit

High elliptical near-Earth orbit (HEO)



- Type 1 – UV-coverage is optimized for Sgr A* observation
- Type 2 – UV-coverage is optimized both for Sgr A* and M87 observations
- Transfer from L2 orbit with gravity assist near the Moon.
- Perigee of HEO orbit restriction at least 10,000 km due to thermal constraints

Parameter	Type 1	Type 2
a	165,000 km	165,000 km
e	0.939	0.939
i	20.008	323
Ω	$-3.583°$	$170°$
ω	$-92°$	$-114°$
Period of both orbits is 10		

a – semi-major axis, e – orbit eccentricity, i – inclination, Ω – longitude of the ascending node, ω – argument of periapsis, i. e. the orientation of the ellipse in the orbital plane

UV-coverage for Sgr A* and M87 on HEO orbit

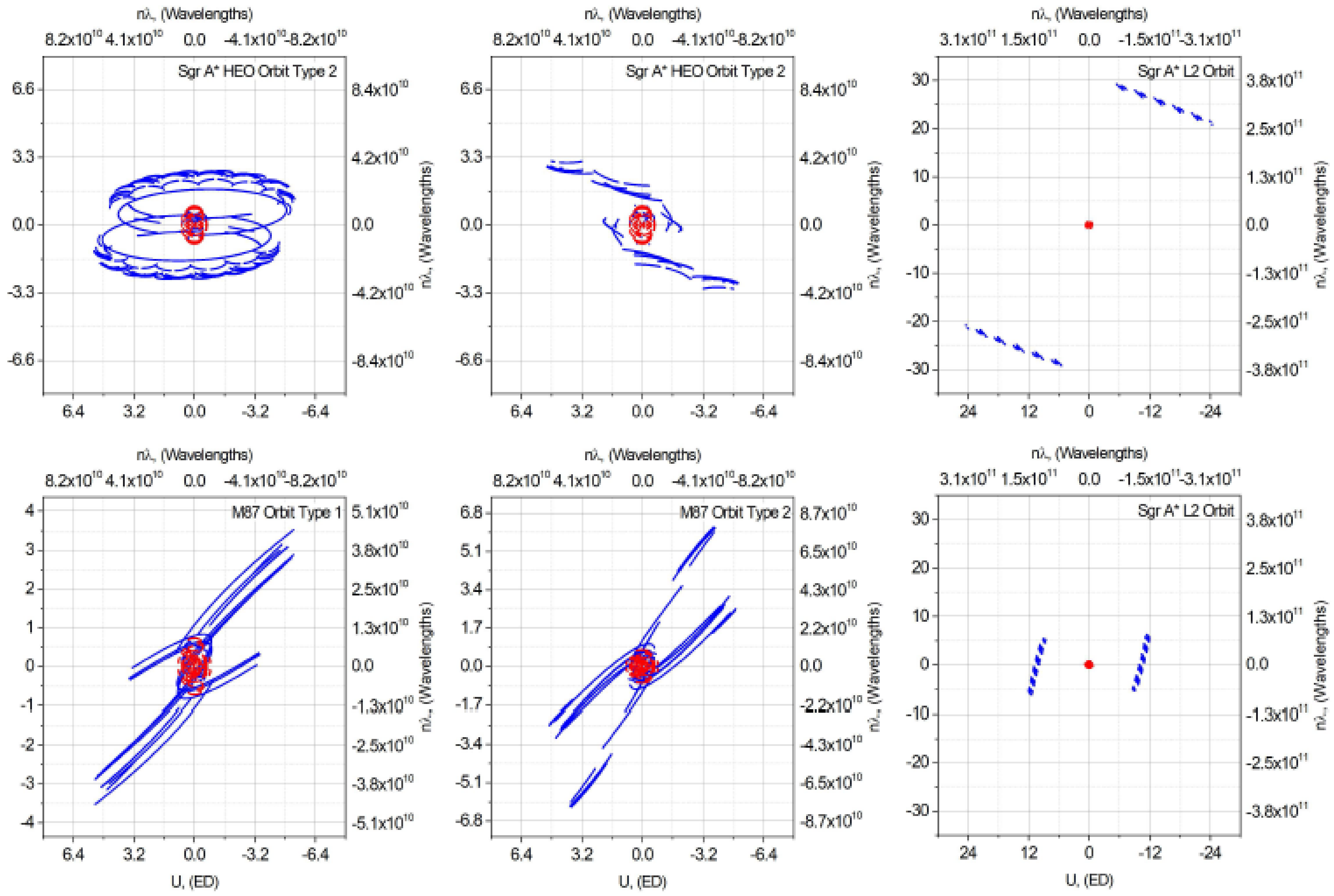


Figure 2. Top: (u, v) coverage for Sgr A* (from left to right: Orbit Type 1, Orbit Type 2 and L2). Bottom: (u, v) coverages for M87 (from left to right: Orbit Type 2 and L2). Coordinates are represented in Earth diameters (bottom-X, left-Y axes) and wavelengths (top-X, right-Y axes). Red dots correspond to EHT ground baselines, blue dots correspond to EHT+MM space-ground baselines

- Top row – UV-coverage for Sgr A*

Observation time is one orbit period (10 days), recording time is 15 hours (with gaps between scans)

- Bottom row - UV-coverage for M87

Observation time 20 hours at the orbit perigee

- Right column – typical UV-coverages for L2 orbit

Modeling parameters, sensitivity

Table 2. Parameters of ground telescopes at 230 GHz (Event Horizon Telescope Collaboration et al. 2019c)

Telescope	X, m	Y, m	Z, m	SEFD, Jy	D, m
Atacama Large Millimeter Array, Atacama, Chile (ALMA)	2225061.164	-5440057.37	-2481681.15	74	73
Atacama Pathfinder Experiment, Atacama, Chile (APEX)	2225039.53	-5441197.63	-2479303.36	4700	12
Greenland Telescope, Greenland (GLT)	1500692.00	-1191735.0	6066409.0	5000	12
IRAM 30-m millimeter radio telescope, Pico Veleta, Spain (PV)	5088967.900	-301681.6000	3825015.8000	1900	30
James Clerk Maxwell Telescope, Hawaii (JCMT)	-5464584.68	-2493001.17	2150653.98	10500	15
Large Millimeter Telescope, Mexico (LMT)	-768713.9637	-5988541.7982	2063275.9472	4500	50
Submillimeter Telescope, Arizona, United States (SMT)	-1828796.200	-5054406.800	3427865.200	17100	10
Submillimeter Array, Hawaii, (SMA)	-5464523.400	-2493147.080	2150611.750	6200	14.7
Kitt Peak National Observatory, Arizona, United States, (KP)[2020]	-1995678.840	-5037317.697	3357328.025	13000	12
Northern Extended Millimeter Array, Plateau de Bure, France (NOEMA)[2020]	4523998.40	468045.240	4460309.760	700	52

[2020] - telescopes to be added to the EHT in 2020.

- Telescope parameters (SEFD) correspond to the current state of the EHT (2020).
- Observation frequency 230 GHz, bandwidth 2 GHz
- For modeling was used the software developed at the ASC LPI Astro Space Locator (CLEAN imaging method)
- EHT Imager software (MEM imaging method) was also used - the results are similar

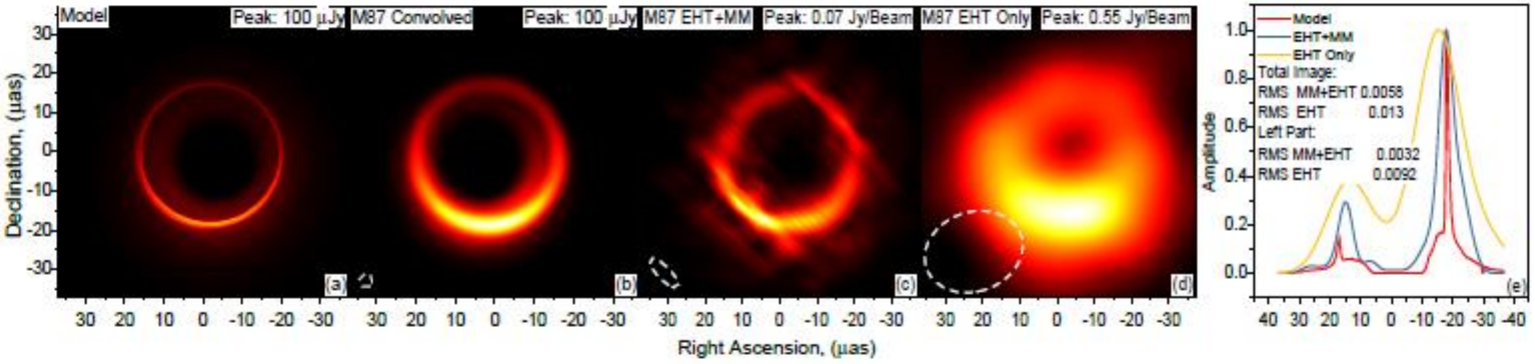
Astro Space Locator:

- paper: S.F.Likhachev, et al., Astro Space Locator — A software package for VLBI data processing and reduction, Astronomy and Computing, Volume 33, 100426 (2020)

-download: ftp://www.asc.rssi.ru/ASL_10

M87 imaging on the high elliptical orbit

Model Convolved model EHT+MM EHT only X-axis section



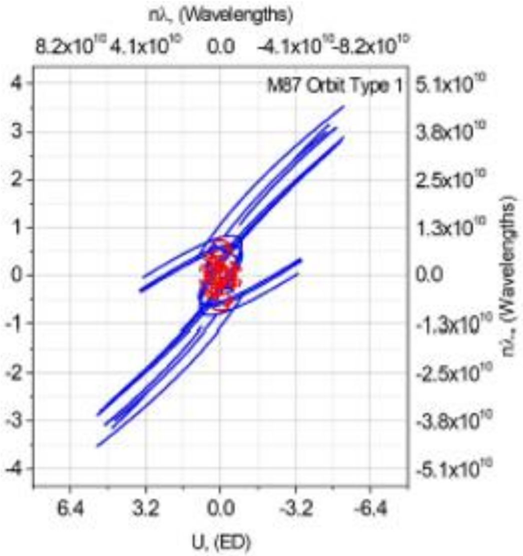
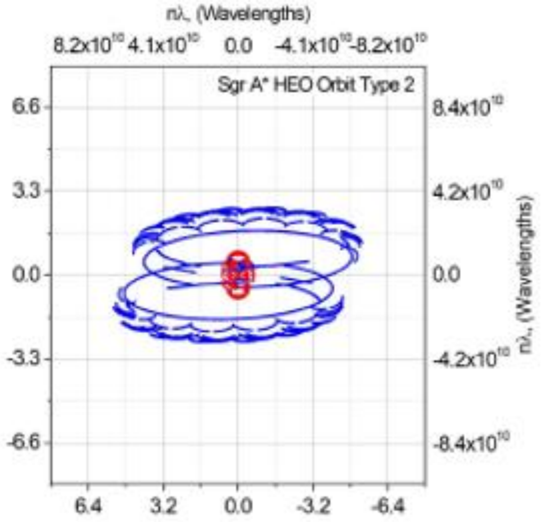


Table 6. Normalized Fidelity and SSIM for images of M87

Model	Convolved	Millimetron + EHT	EHT
		Normalized Fidelity	
Model	9.79	12.56	2.25
Convolved	∞	22.40	2.55
		SSIM	
Model	0.286	0.345	0.012
Convolved	1	0.93	0.126

- From left to right: model, model convolved with Gaussian beam, MM + EHT image, EHT only image, X-axis section
- Frequency 240 GHz
- Observation time 20 hours
- Fidelity, RMS and SSIM metrics gives the best scores in case of MM+EHT

Sgr A* imaging on the high elliptical orbit

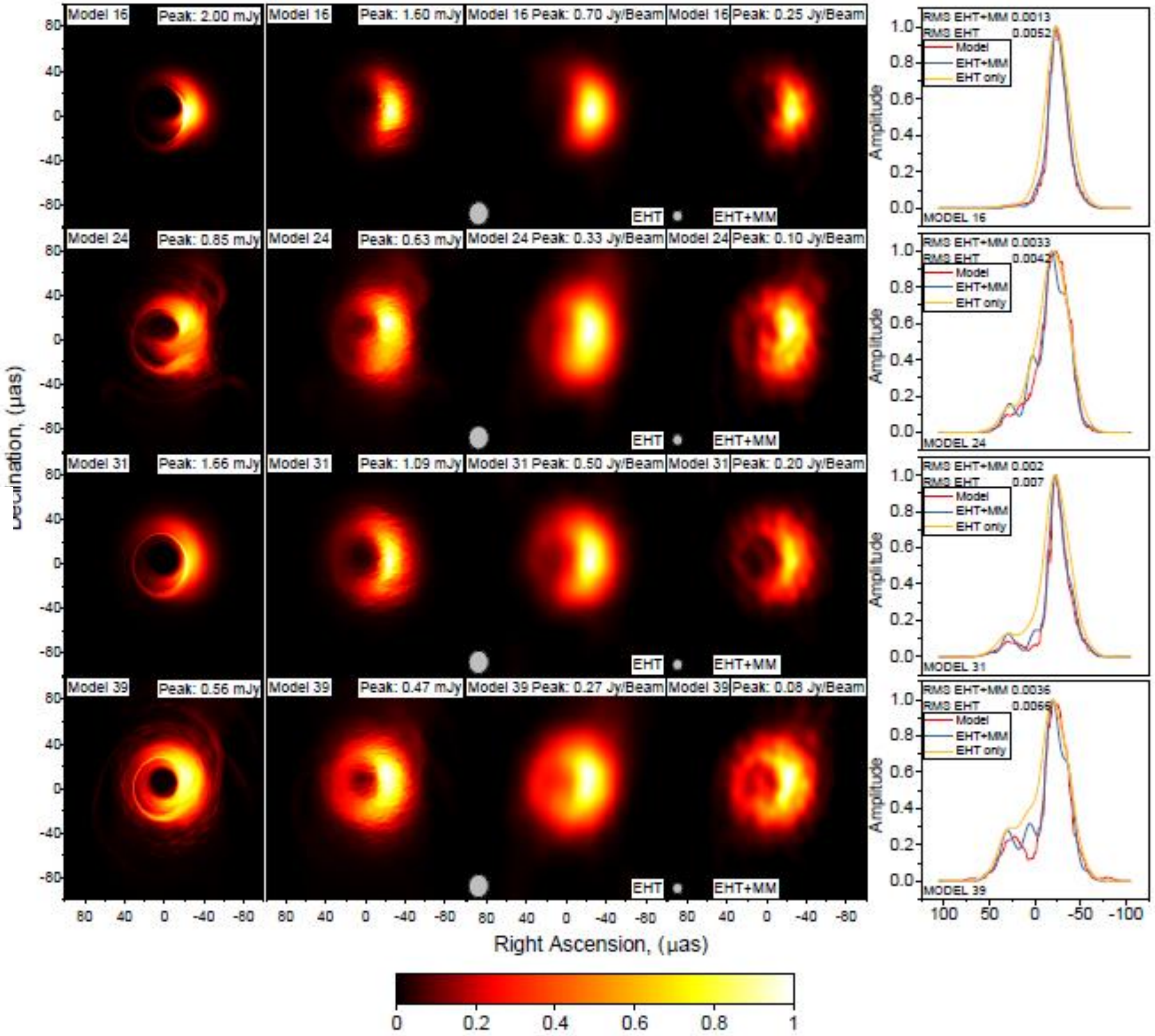


List of EHT models used for S-E VLBI simulations.

#	i	$\Theta_{e,\mathrm{J}}$	$(T_p/T_e)_{\mathrm{d}}$	$\dot{M}$ ($M_\odot$ yr^{-1})
16	60°	10	5	3.9×10^{-9}
24	60°	20	20	4.2×10^{-8}
31	30°	10	5	5.6×10^{-9}
39	30°	20	20	4.1×10^{-8}

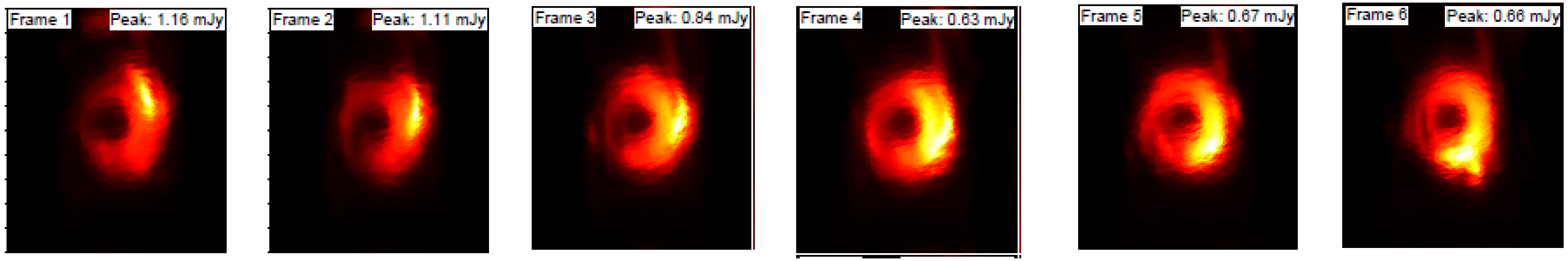
Fidelity of obtained images for Sgr A*.

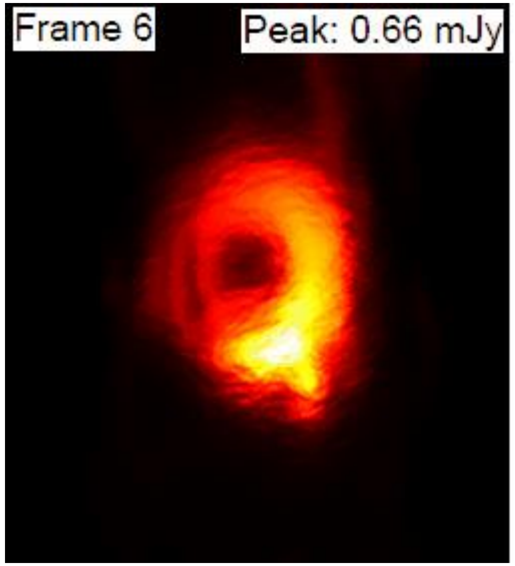
Sgr A* Model	16	24	31	39
MM+EHT	61.39	49.49	54.18	41.2
EHT only	32.53	34.65	31.52	29.1



- Observation time 10 days (with gaps)
- Left to right: GRMHD model, scattered model (thin screen), EHT only image, EHT+MM image
- Top to bottom: GRMHD models with different parameters
- Fidelity and RMS metrics gives the best scores in case of MM+EHT for all GRMHD models

Is it correct to use averaged model for Sgr A*?





- Sgr A* has fast variability
- Between frames 220 seconds
- Full turnover period of a bright spot in the disk ~ 1000 seconds
- The observation time is ~ 10 days
- (for M87 there is no such problem - the characteristic period is 1000 times longer, and the observation time is ~ 1 day)

Is it correct to use averaged model for Sgr A*?

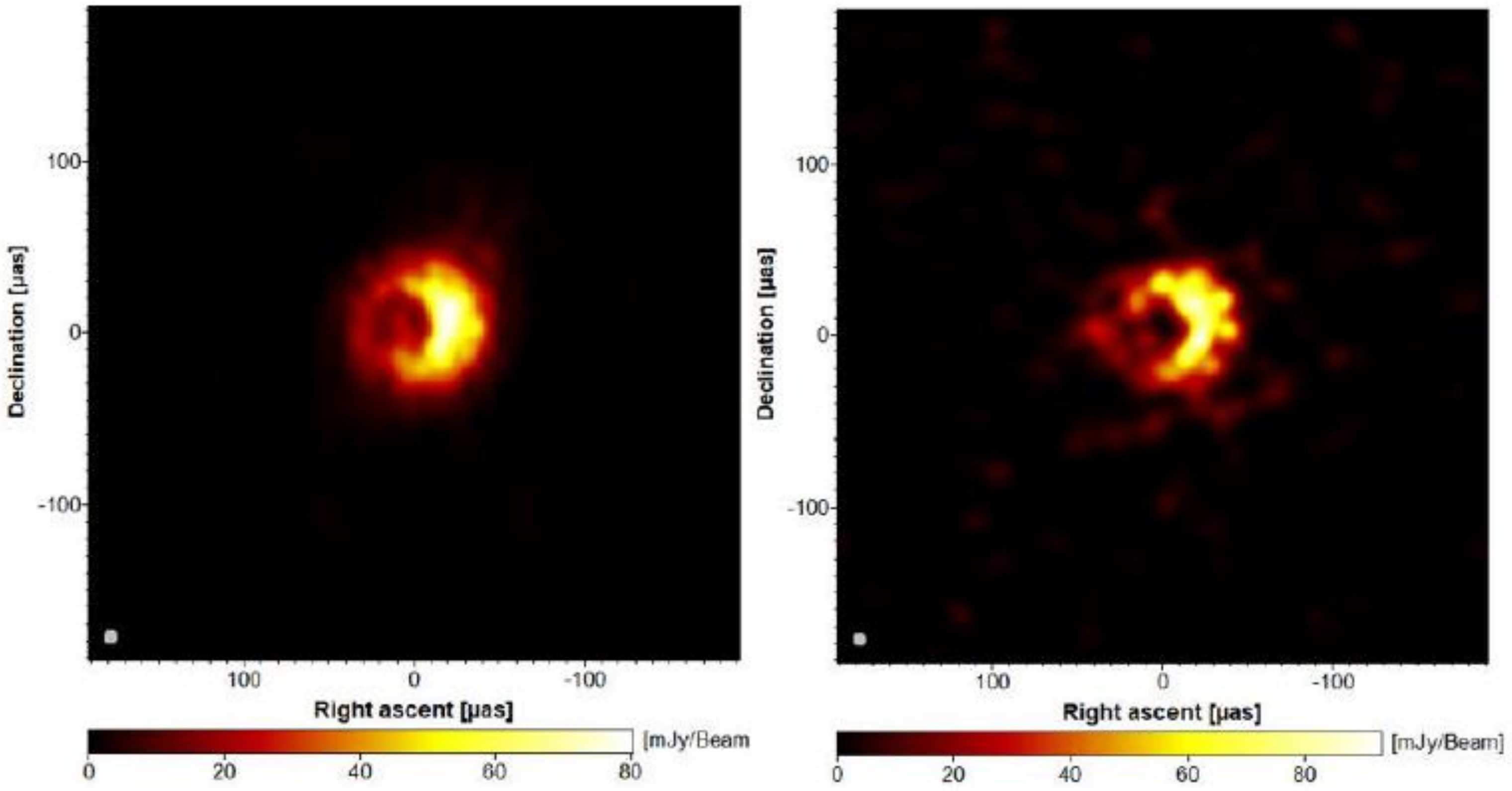


Figure 5. Left plot corresponds to imaging with Sgr A* # 39 model (averaged), right plot corresponds to imaging with Sgr A* # 39 dynamic model (cycled 80 different frames with time separation 221 s, and the concerted (u,v)-plane).

- Left plot – imaging with averaged model
- Right plot – imaging with dynamic model (cycled 80 different frames with time separation 221 s applied to the concerted UV-plane)
- It can be seen that the operations are not equivalent, but the images are similar.
- This approximation can be used for Sgr A* imaging
- In the left case it is also much easier to estimate the formal closeness between the reconstructed image and the original model

Video of Sgr A*

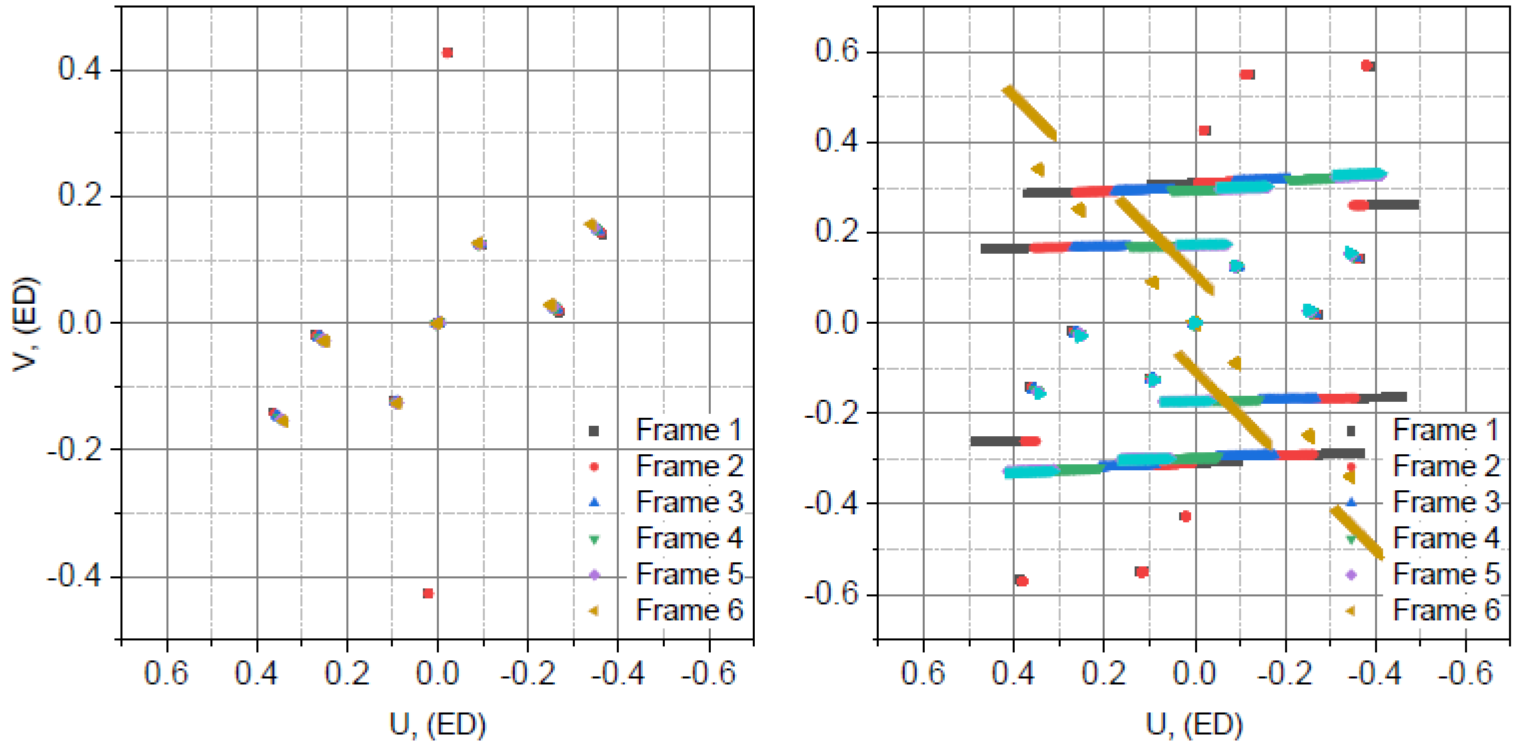
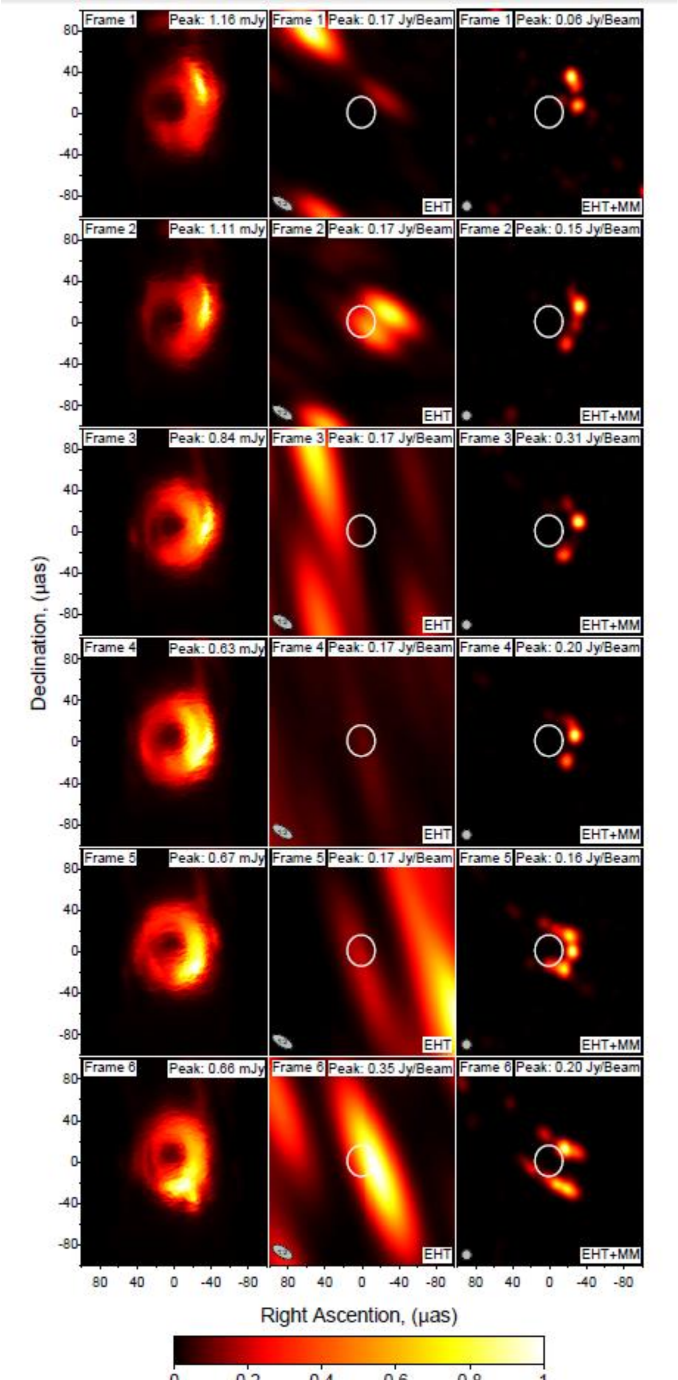
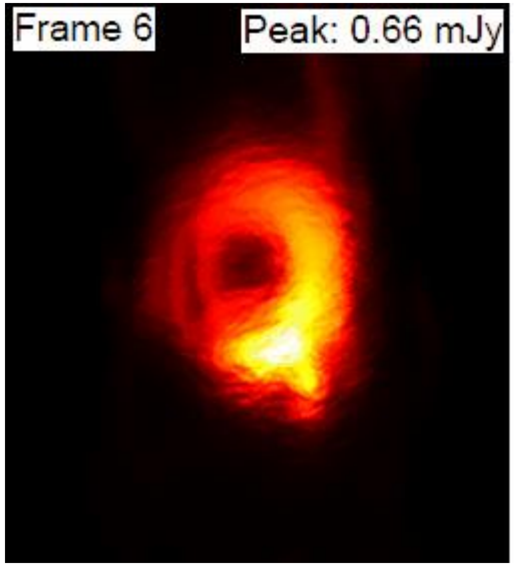


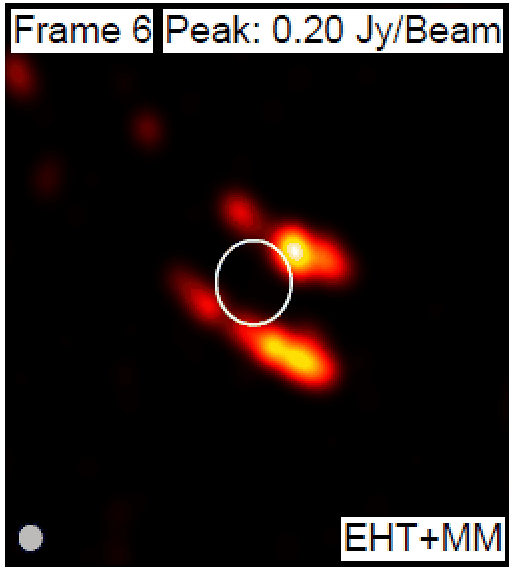
Figure 3. (u, v) coverage for Sgr A* dynamic simulations: EHT only (left) and Millimetron+EHT (right, Orbit Type 1) dynamic frames. Coordinates are represented in Earth diameters. The total snapshot integration time is 1326 s (221 s per frame).

- The HEO orbit provides a high perigee velocity. This provide enough UV-plane filling to recover the image in each 221-seconds frame.
- This makes it possible for the first time to obtain video from VLBI observations of Sgr A *.

Sgr A*, изображение в динамике (видео)

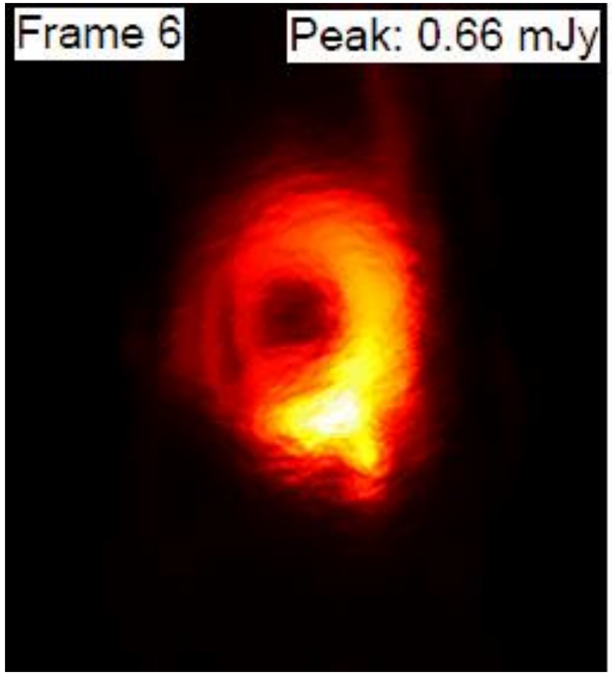




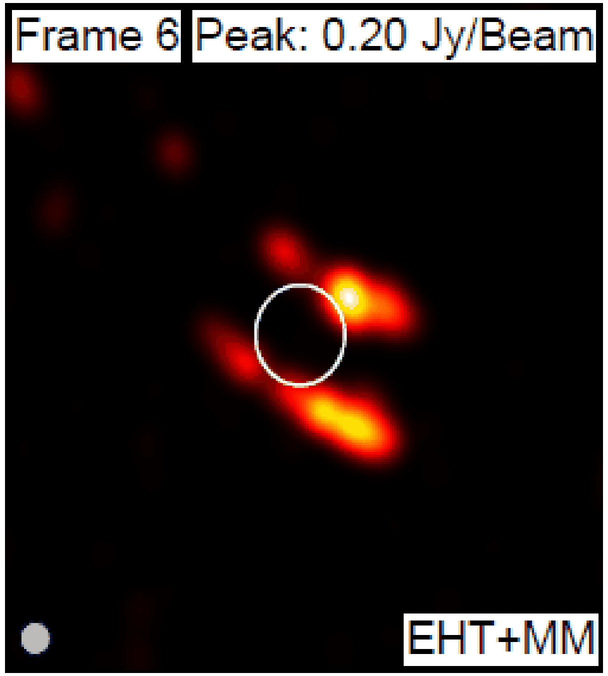


- Left column – model, middle column – reconstructed EHT image, right plot – reconstructed EHT+MM image
- Frame duration 221 s
- Total duration of observations at perigee 22 min
- Video can be done each orbit period, i.e. every 10 days

Video of Sgr A*



Model



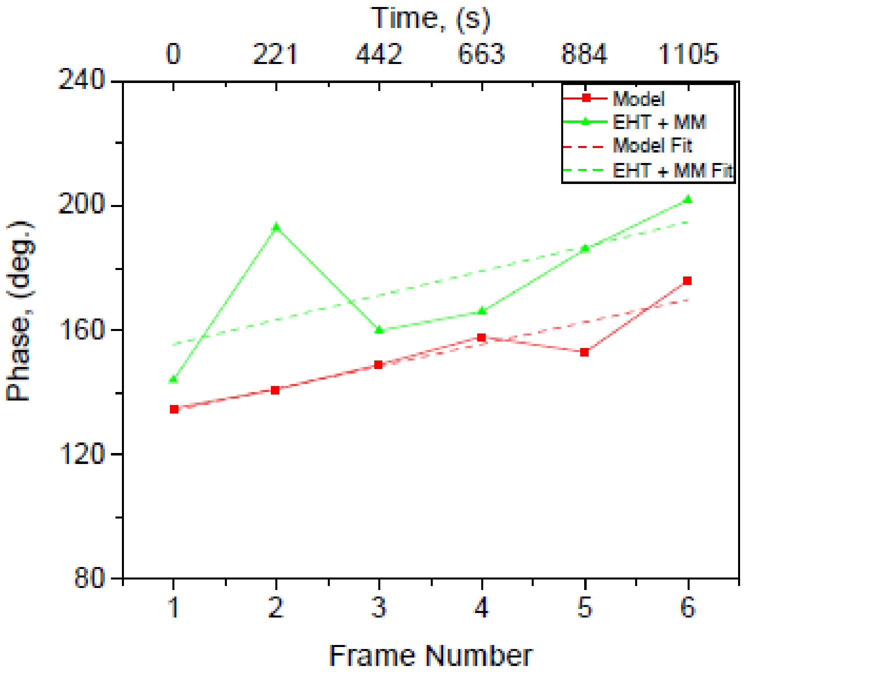
Reconstructed image

$$X_{cm} = \frac{\sum_{i=1}^{N} I_i \cdot x_i}{\sum_{i=1}^{N} I_i}$$

$$Y_{cm} = \frac{\sum_{i=1}^{N} I_i \cdot y_i}{\sum_{i=1}^{N} I_i}$$

$$R_{cm} = \sqrt{X_{cm}^2 + Y_{cm}^2}$$

$$\varphi_{cm} = \arctan\left(Y_{cm}/X_{cm}\right)$$



Position of the center of mass of the image in time (along the angular coordinate)

Model	EHT only	EHT + Millimetron
5.6 ± 1.1	-1.0 ± 30.0	6.2 ± 3.5

Angular velocity of a bright spot rotation in the Sgr A model ($10^{-4} s^{-1}$)

- Frame duration 221 s
- Total duration of observations at perigee 22 min
- Video can be done each orbit period, i.e. every 10 days
- The video allows to determine the angular velocity of the brightest feature in the accretion disk

Conclusions

- Transition from L2 orbit to a highly elliptical orbit is possible
- HEO orbit allows M87 and Sgr A * imaging sessions frequently, once every 10 days
- Resolution and image quality of black hole shadows in M87 and Sgr A* using EHT + Millimetron is several times better that EHT only
- HEO orbit will allow to receive video Sgr A * for the first time.

Thanks for your attention!