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

- 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

**Two operation modes:**

- 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

- 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
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
- 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
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         | 0.930         | 0.930         |
| i         | 20.008        | 320           |
| 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

- 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

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.
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) | 2225.0611.164 | -54.0957.37 | 2381.6811.15 | 74 | 73 |
| Atacama Pathfinder Experiment, Atacama, Chile (APEX) | 2335039.53 | -54.1197.63 | 23542031.36 | 65 | 87 |
| Greenland Telescope, Greenland (GILT) | 150.0092.00 | -119.1735.0 | 606849.99 | 500 | 12 |
| IRAM 30-m millimeter radio telescope, Pico Veleta, Spain (PV) | 5388927.50 | -30.0631.00 | 13527015.80 | 1300 | 20 |
| James Clerk Maxwell Telescope, Hawaii (JCMT) | -5.46453.68 | 240.0900.17 | 21564539.58 | 10500 | 15 |
| Large Millimeter Telescope, Mexico (LMT) | -776813.9637 | -5988541.7982 | 20052973.472 | 4500 | 50 |
| Submillimeter Telescope, Arizona, United States (SMT) | -582979.20 | -505440.880 | 3425785.200 | 1700 | 10 |
| Submillimeter Array, Hawaii, (SMA) | -5864533.408 | 240.0470.00 | 21564539.58 | 9200 | 14.7 |

Kitt Peak National Observatory, Arizona, United States, (KP)\textsuperscript{ad} | -1865678.840 | -503731.697 | 335728.025 | 1800 | 12 |
| Northern Extended Millimeter Array, Plateau de Bure, France (NOEMA)\textsuperscript{ad} | -4529906.490 | -50015.240 | 4403381.960 | 700 | 52 |

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- 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

- 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

- 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*?

- 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*

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

- 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

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

| Frame Number | Model | EHT only | EHT + Millimeter |
|--------------|-------|----------|------------------|
| 1            | 5.6 ± 1.1 | -1.0 ± 3.0 | 6.2 ± 3.5 |
| 2            |         |          |                  |
| 3            |         |          |                  |
| 4            |         |          |                  |
| 5            |         |          |                  |
| 6            |         |          |                  |

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