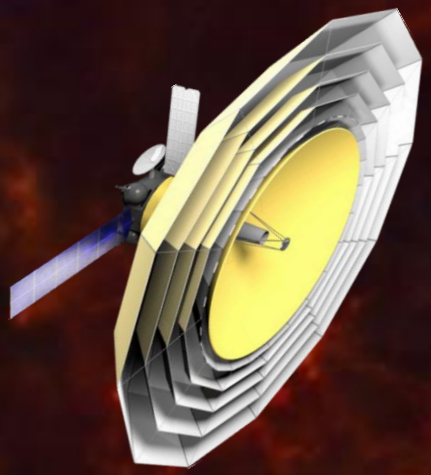


“Millimetron” mission: Space VLBI opportunities and capabilities

Alexey Rudnitskiy, Sergey Likhachev, Vladimir Kostenko, Thijs de Graauw, Andrey Andrianov, Igor Guirin

Astro Space Centre of P.N. Lebedev Institute
of Russian Academy of Sciences

Third International VLBI Technology Workshop, Groningen, 2014

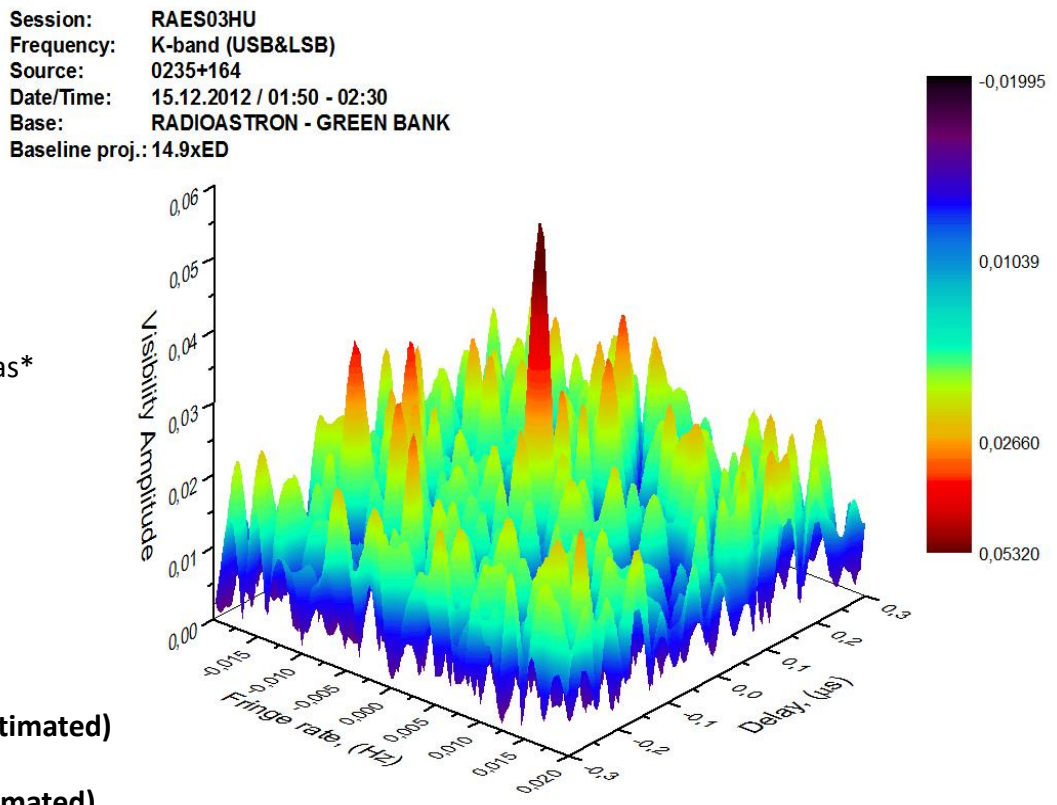
*Rosette Nebula image captured by Herschel telescope

Extremely High Resolutions with SVLBI

Radioastron Preliminary experimental data

Source: 0235+164

RADIOASTRON-GBT: 15xED, 1.3 cm (22GHz): **14 µas**
GMVA result for 0235+164, 3.5 mm (86GHz):~50-70 µas*
Millimetron (expectations): up to 100xED **???**



SEFD:

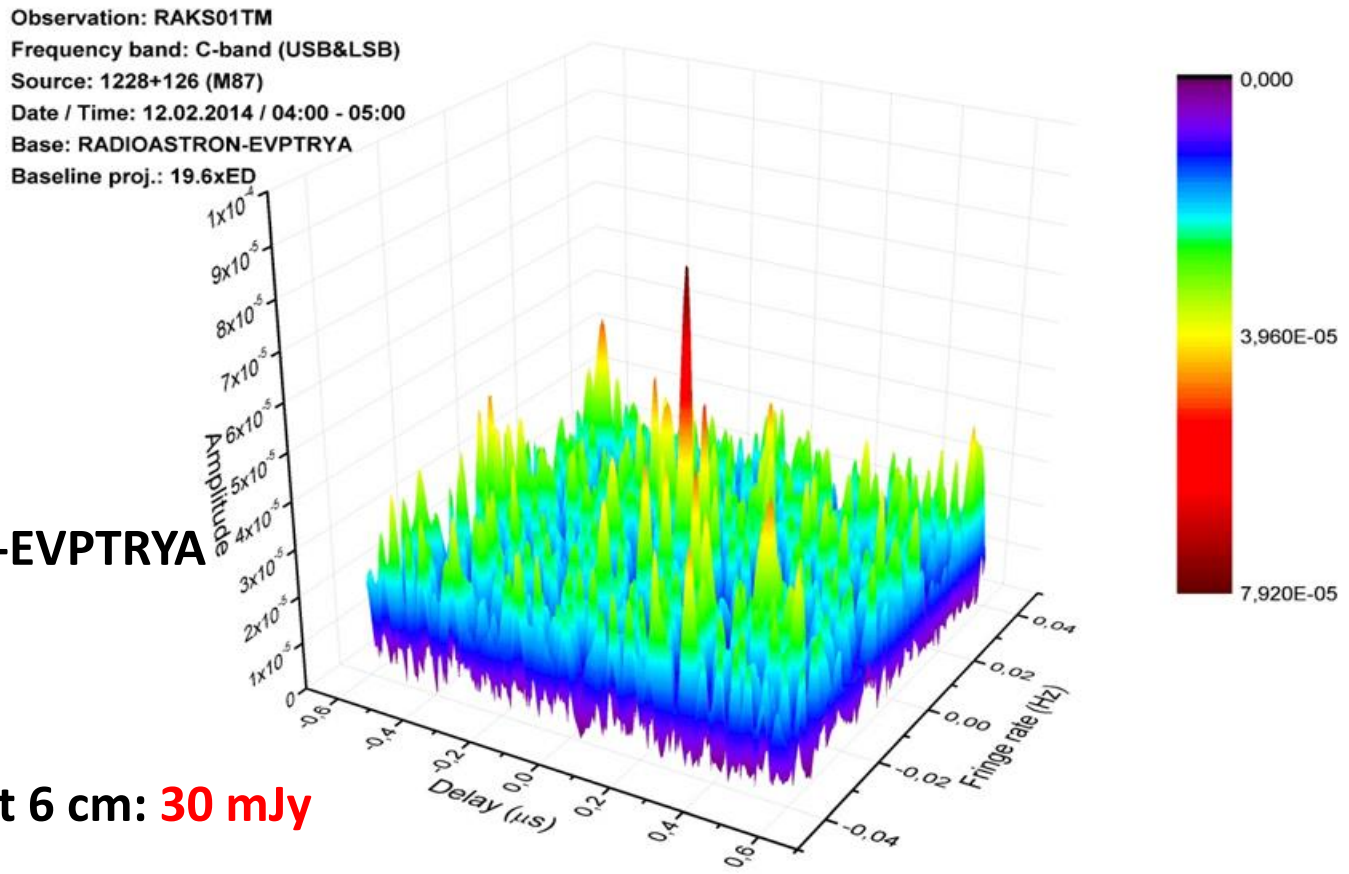
RADIOASTRON	30000 Jy
MMTRON	**712 Jy (estimated)**
RADIOASTRON-GBT	750 Jy
MMTRON-ALMA	**82 Jy (estimated)**

*(Jeffrey A. Hodgson et al., Proc. Of Sci., 11th European VLBI Network Symposium & Users Meeting October 9-12, 2012)

Extremely High Resolutions with SVLBI

Radioastron Preliminary Experimental Data

For the first time correlation found for 1228+126 (M87) at baseline projection of 19.6 Earth diameters at 6 cm wavelength!



Base: RADIOASTRON-EVPTRYA

Baseline: 19.6 ED

φ = 62 μas

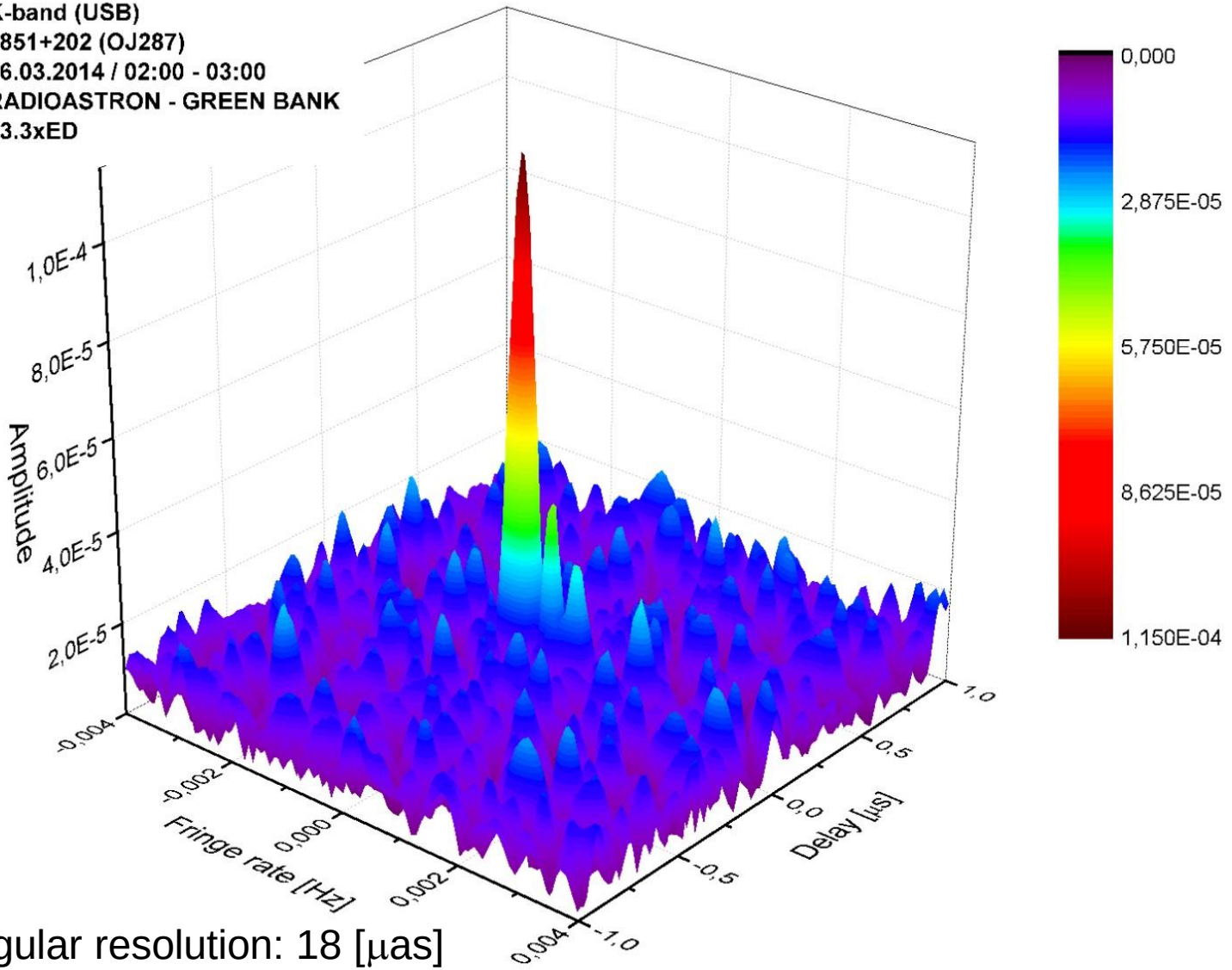
SEFD = 370 Jy

M87 Estimated flux at 6 cm: 30 mJy

Extremely High Resolutions with SVLBI

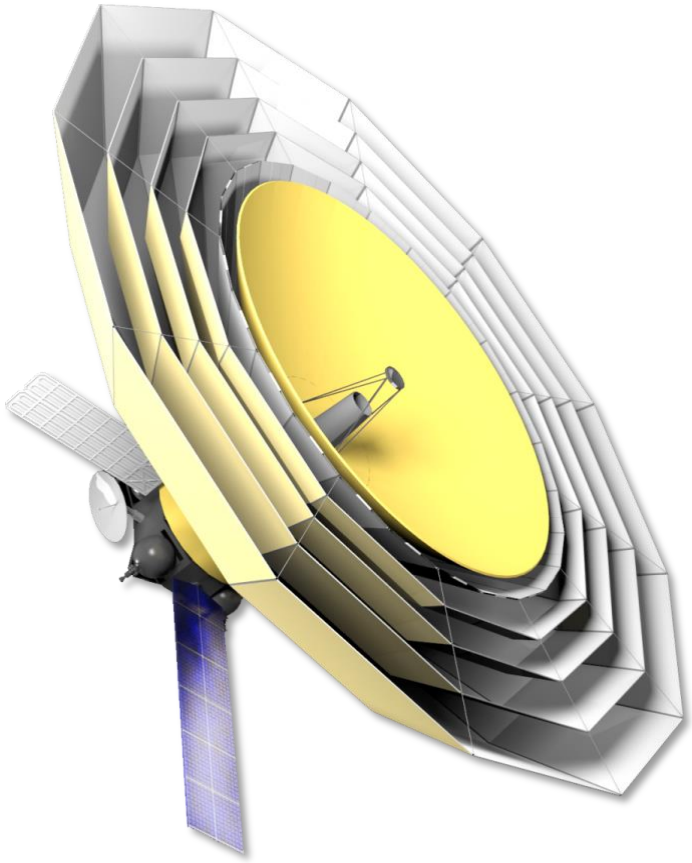
Radioastron Preliminary Experimental Data

Session: RAKS01VT
Frequency: K-band (USB)
Source: 0851+202 (OJ287)
Date/Time: 16.03.2014 / 02:00 - 03:00
Base: RADIOASTRON - GREEN BANK
Baseline proj.: 13.3xED



Estimated angular resolution: 18 [μas]
Estimated flux: 90 mJy

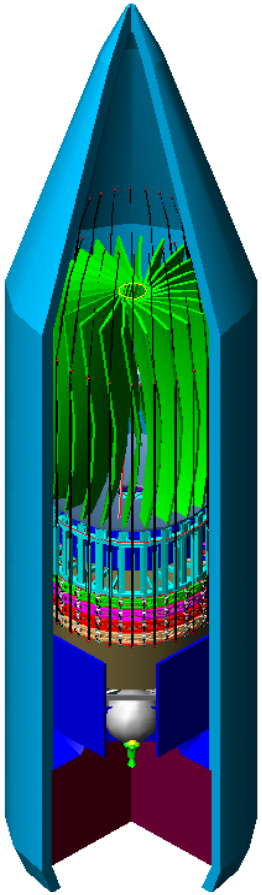
Millimetron Mission



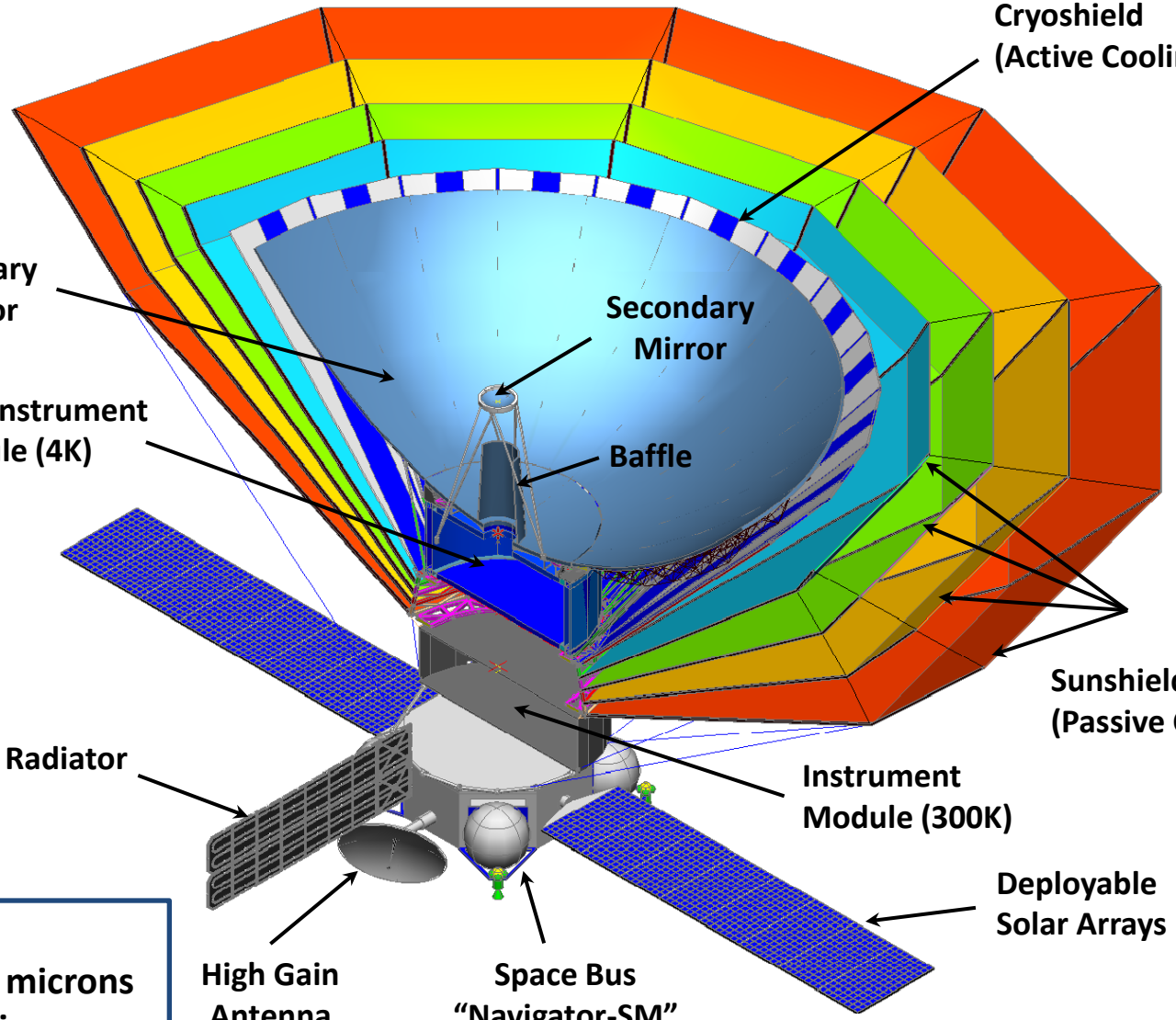
The **Millimetron Mission** has been **approved by Russian Space Agency** and being designed by the Astro Space Centre of P.N. Lebedev Physical Institute of the Russian Academy of Sciences, and Lavochkin Association of Russian Federal Space Agency; in cooperation with Russian institutions.

A goal of the project is to carry out investigations with **a high sensitivity** (single dish mode) and **an unprecedentedly high angular** resolution (**Space-Ground interferometer mode**) at the millimeter and far-infrared wavelength bands.

Millimetron Configuration Overview



The launch packaging in fairing



Surface RMS:
3-meter central part: ~5 microns
10-meter overall: ~10 microns

Millimetron VLBI Receivers

Band	Frequency (GHz)	IFBW (GHz)	Instantaneous bandwidth (GHz)	Polarization	T_{noise} (K)	Comments
1	18 – 26	4-12 (HEMT)	4 (max)	H V	<10	Post cryo capable
2	33 – 50 **ALMA Band 1**	4-12 (HEMT)	4 (max)	H V	<17	Post cryo capable
3	84 – 116 **ALMA Band 3**	4-12 (HEMT)	4 (max)	H V	<37	Post cryo capable
4	211 – 275 **ALMA Band 6**	4-12 (SIS)	4 (max)	H V	<90	Dedicated SIS receiver
5	602-720 **ALMA Band 9**	4-12 (SIS)	4 (max)	H V	<100	Part of HRS*
6	787-950 **ALMA Band 10**	4-12 (SIS)	4 (max)	H V	<150	Part of HRS*

*HRS – High Resolution Spectrometer

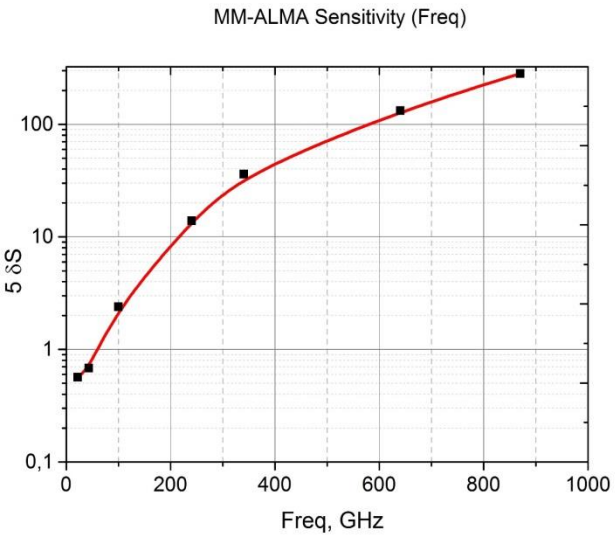
Millimetron Capabilities:

Sensitivity

"MM-ALMA" interferometer. Estimations of integral sensitivity. Forecasts.

Freq,GHz	SEFD ALMA	SEFD MM	SEFD MM-ALMA	Tau, sec	5δS, [mJy]
22	15	1050	125,50	300	0,567
43	16	1190	137,99	250	0,683
100	49	2290	334,98	120	2,393
240	73	6490	688,31	15	13,909
340	164	12990	1459,58	10	36,123
640	810	17570	3772,49	5	132,037
870	1640	23740	6239,68	3	281,939

5δS – minimal detectable flux at a given frequency



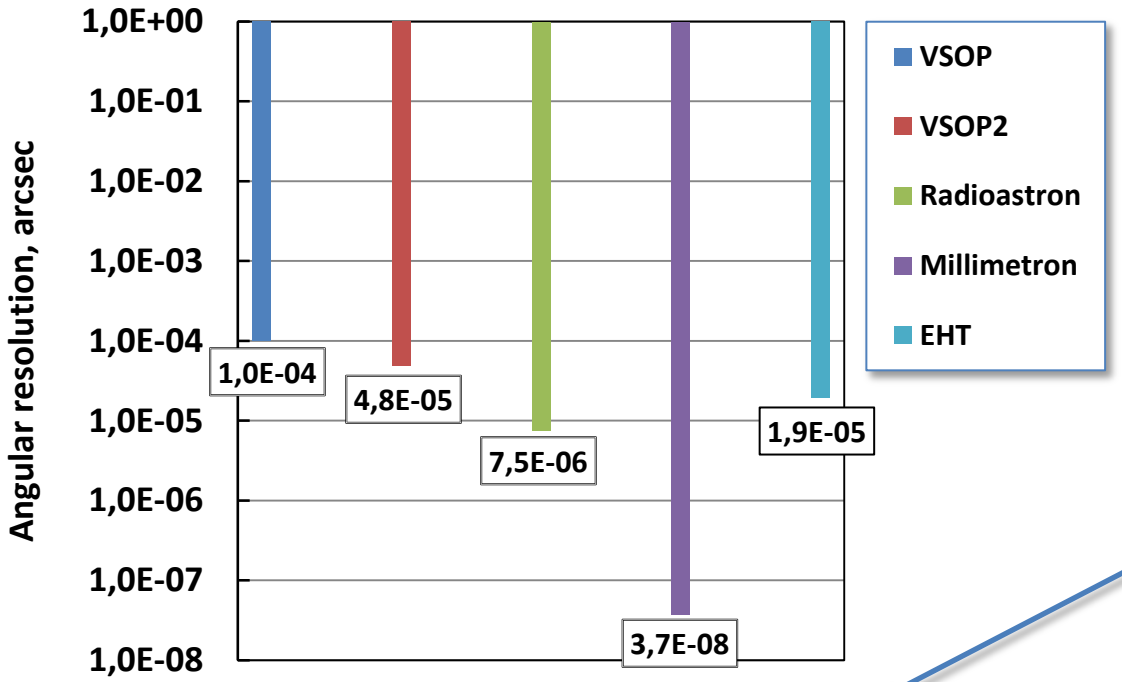
GBT-MM, 22 GHz, Band 18-27.5 GHz

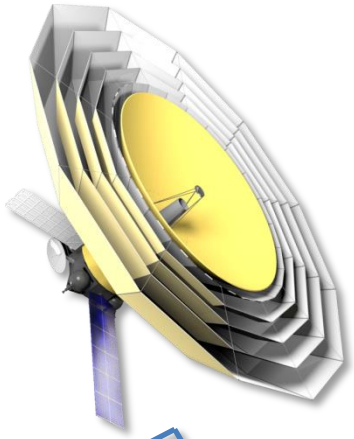
Freq, [GHz]	SEFD GBT, [Jy]	SEFD MM, [Jy]	SEFD MM-GBT, [Jy]	Tau, [sec]	5 δS, [mJy]
22	15	1050	125	300	0.55

SNR = S_{source}/ 5δS

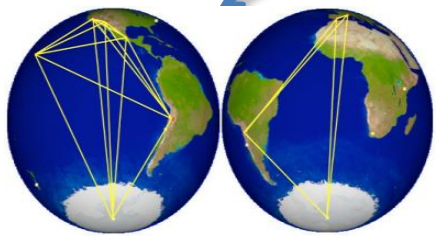
Assumed 4 GHz bandwidth for correlator input

Millimetron Capabilities:
Angular Resolution





The 10-m telescope located at the L2 Lagrange point and working in S-VLBI mode can increase angular resolution ≈ 100 times (up to 10^{-8} arcsec).

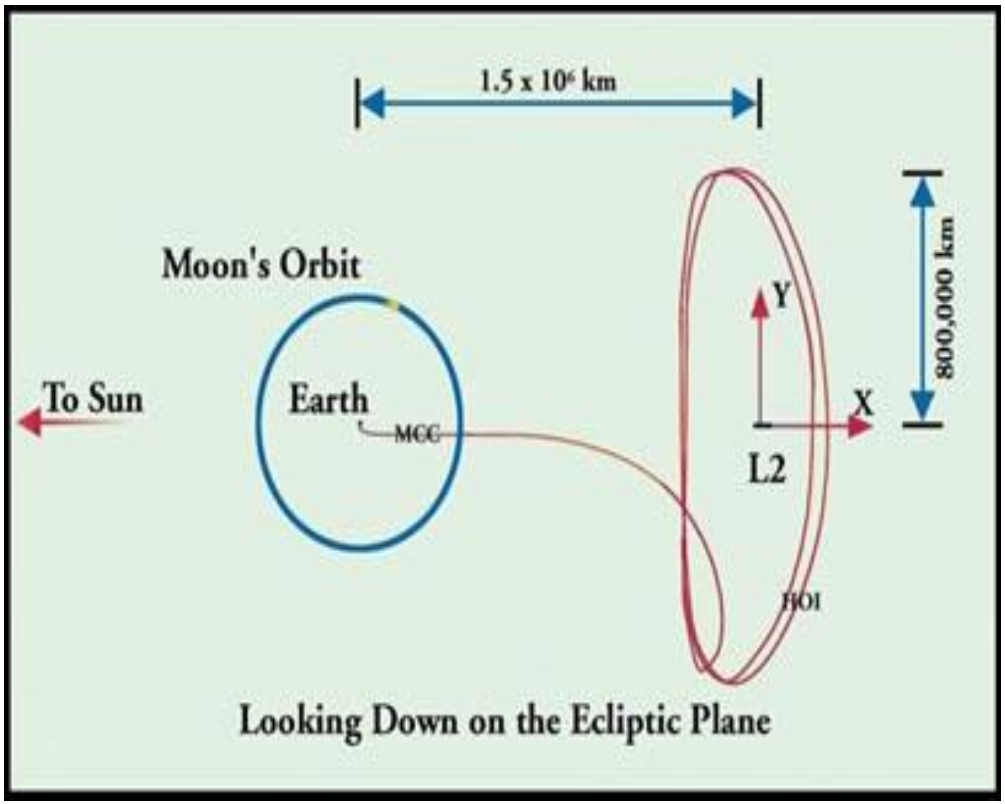


EHT

ALMA

Millimetron Orbit Configuration

- Orbit period – 365 days (L2 point).
- Baseline – 1 500 000 km, max.
- Time of oscillation around L2 is about half of a year.
- MM antenna view angle opening is +/- 75 deg. in ecliptic latitude and longitude.

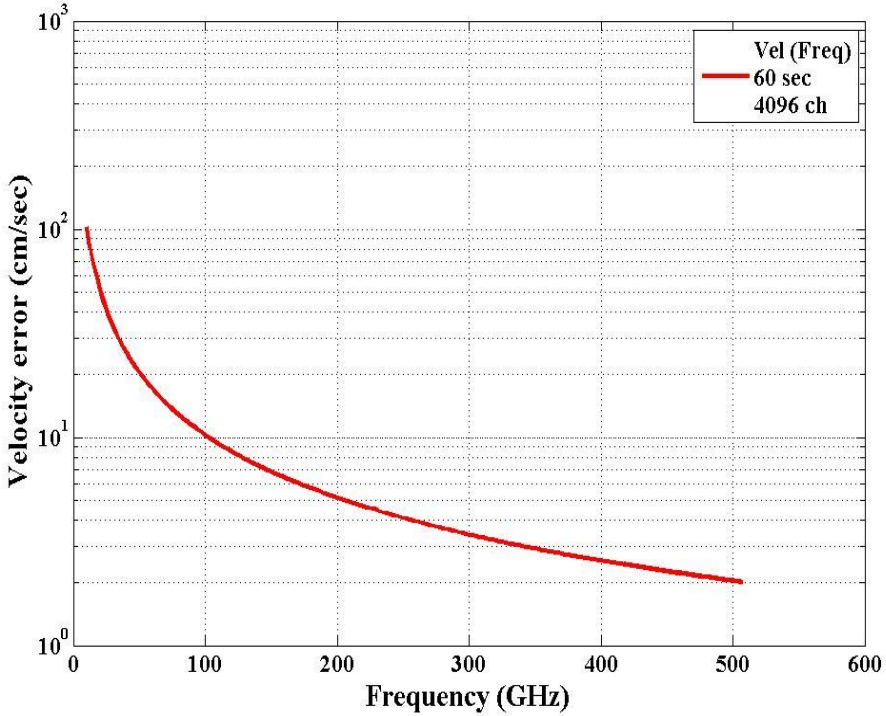


Angular resolution:

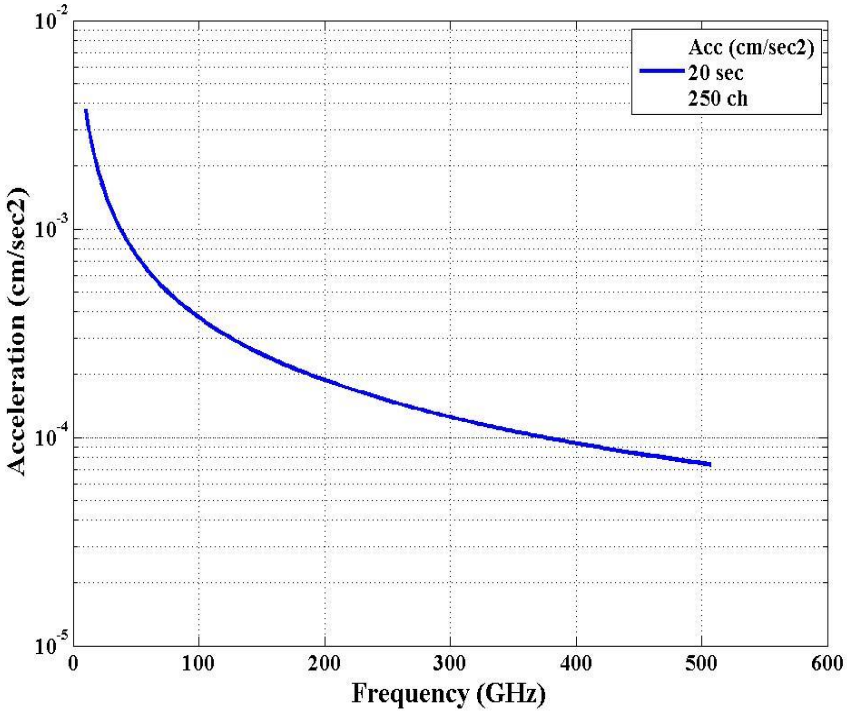
λ = 2 cm λ/D = 2.8 μas
λ = 1 mm λ/D = 0.14 μas

Millimetron: Velocity and Acceleration

Forecast Requirements



V < 3 cm/sec at 320 GHz, $\tau = 60$ sec



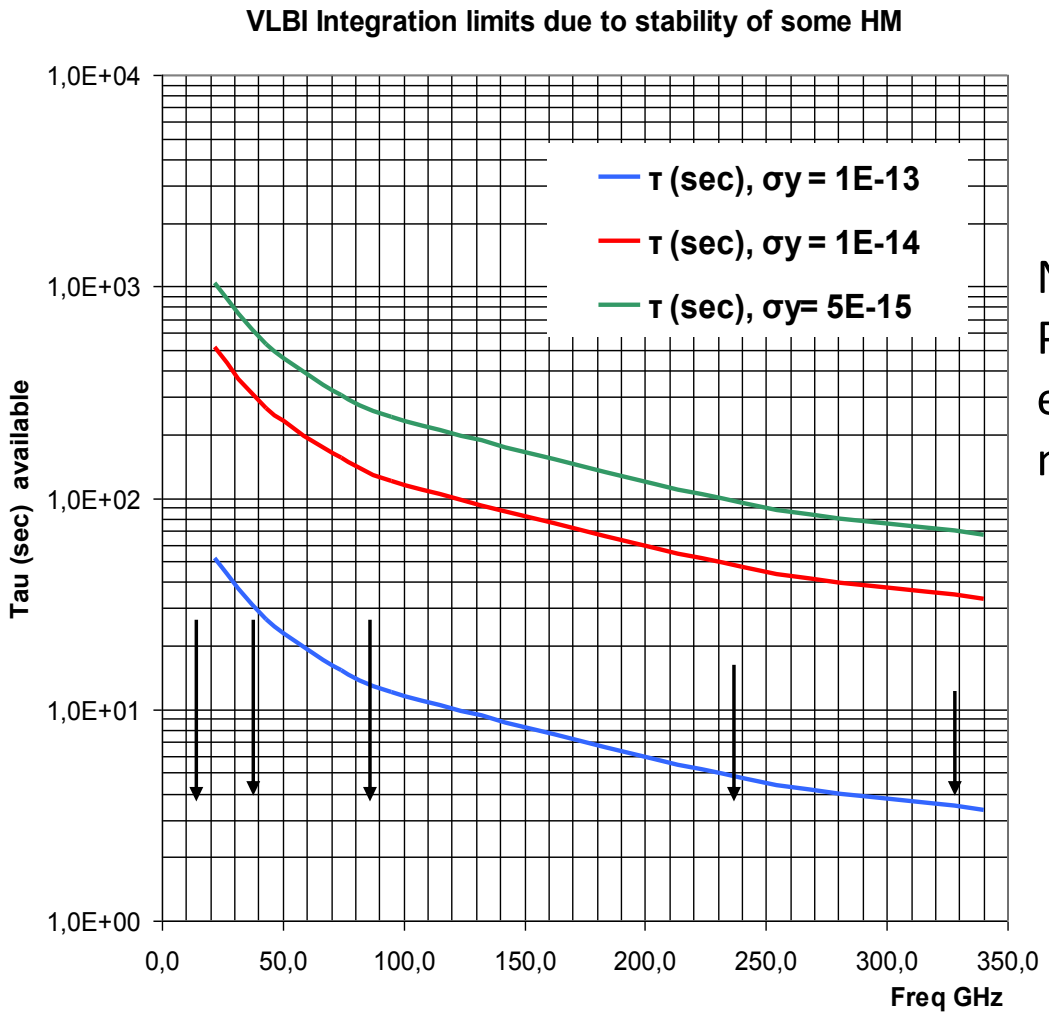
Acc < 1e-4 cm/sec^2 at 320 GHz, $\tau = 20$ sec

$$|ds/dt| < \frac{N_{ch} * c}{2 * \Delta T * f_0},$$

$$|ds/dt^2| < \frac{c}{2 * \Delta T^2 * f_0}$$

N_{ch} – correlator number of channels

H - maser
Integration limits



$$\sigma_y(\tau) - relative\ Allan\ \ deviation$$

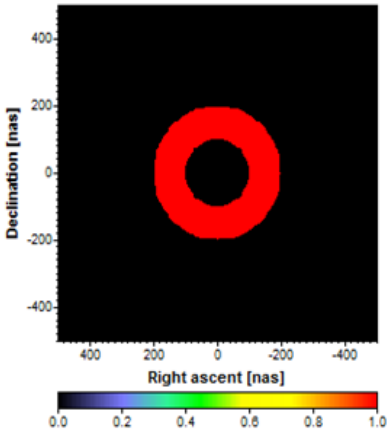
$$Loss = 1 - e^{-(\omega\tau\sigma_y(\tau))^2}$$

$$\omega\tau\sigma_y(\tau) < 1$$

Needs Onboard HM with σ_y **~ 10^{-15}**
Product of "Vremia-CH", a Russian enterprise. Similar onboard H-Maser was made for Radioastron Mission.

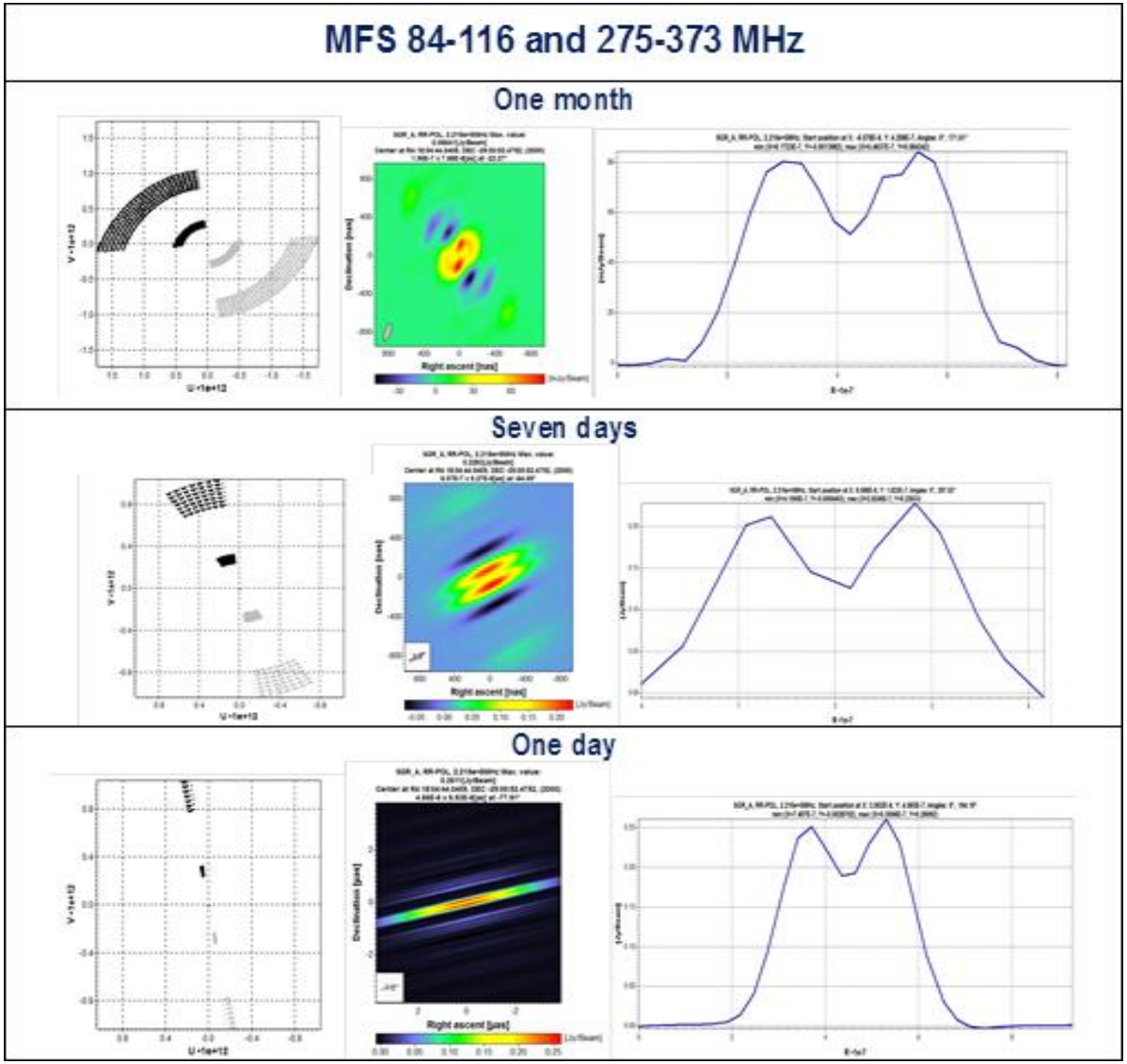
MM-EHT Simulation

“Sgr A”

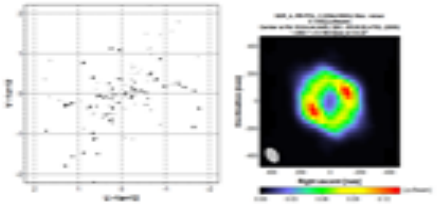
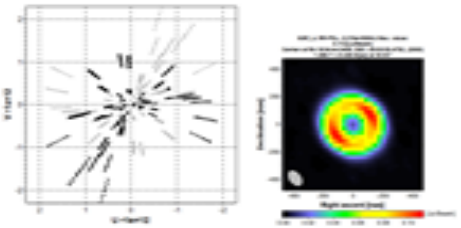
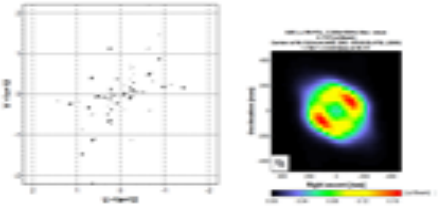
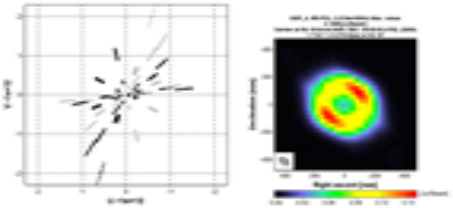


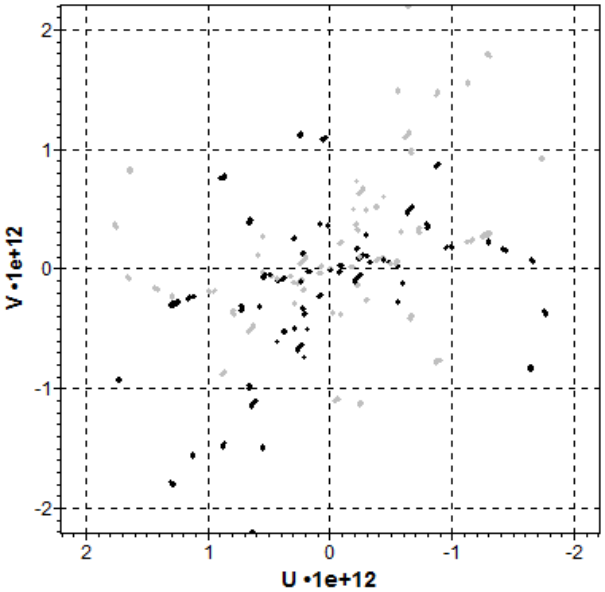
The source size is $4*10^{-7}$ [arcsec]

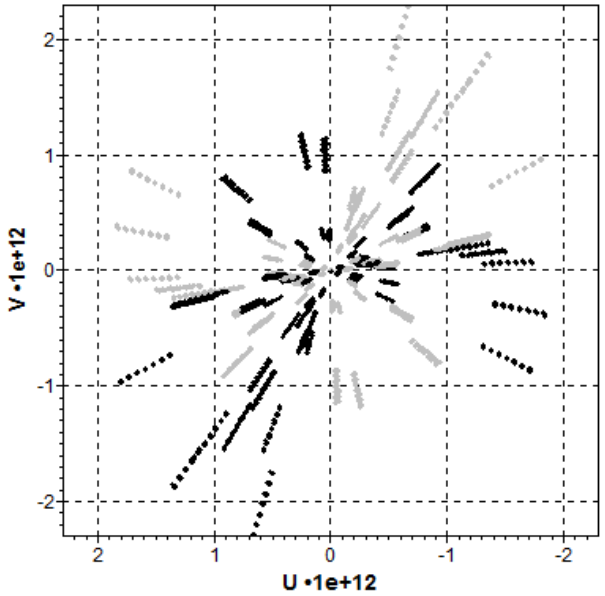
Short-term observations provide opportunities obtaining one dimensional profile of the source.



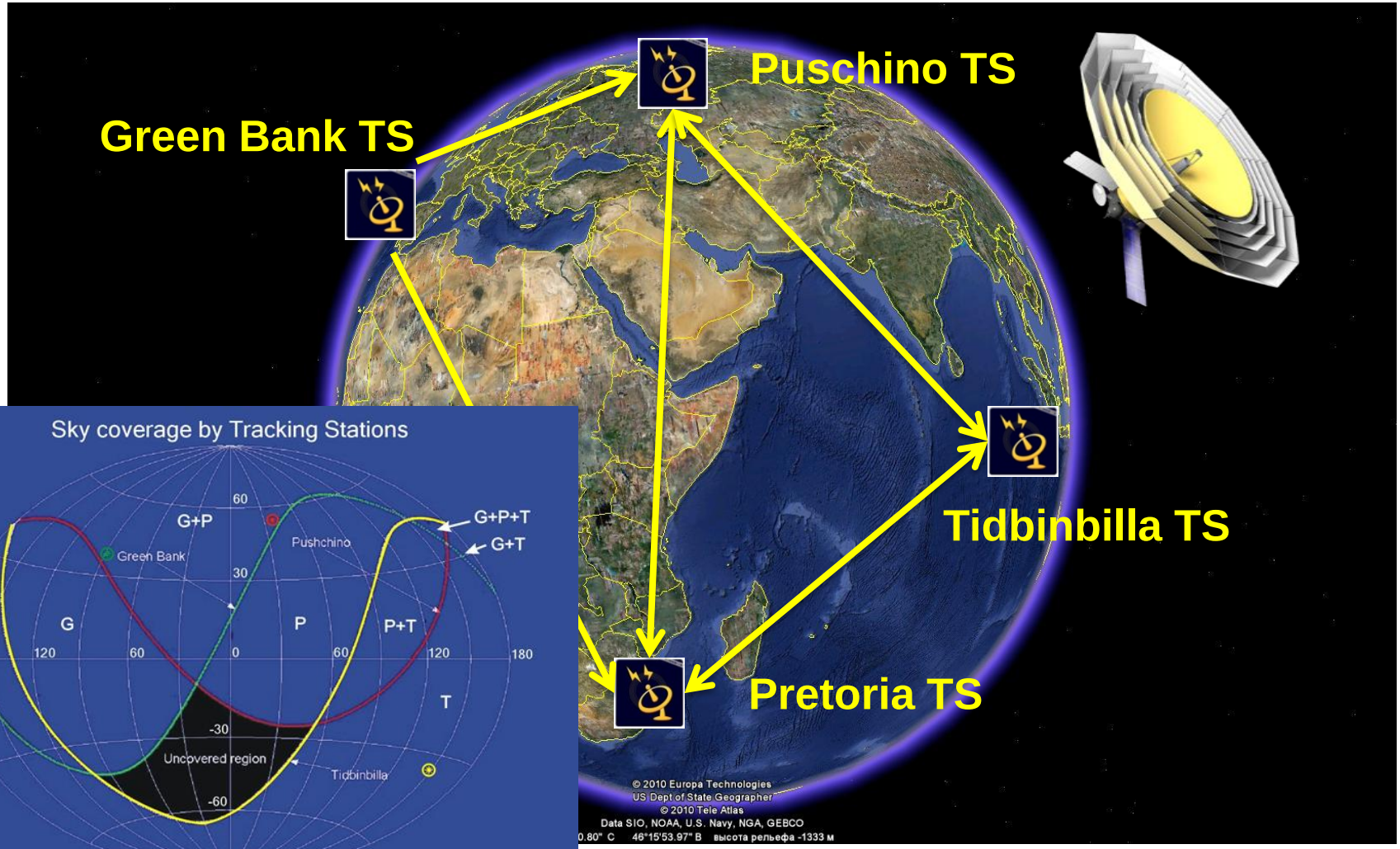
MM-EHT Simulation Snapshots.

345 and 116 MHz	MFS 84-116 and 275-373 MHz
3 years 1 time per 50 days + small baselines (no MFS) 	3 years 1 time per 50 days + small baselines (MFS) 
Small baselines (15 days during 3 years). No MFS. 	Small baselines (15 days during 3 years). MFS. 

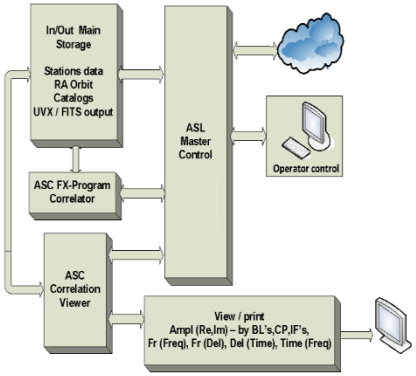




Millimetron Tracking Stations



Millimetron Data Center



- A Millimetron Data Processing Center (DPC) will be organized as a Data-Center.
- Main objectives of DPC are collecting, processing, and archiving of all the observation data and organizing information exchange among mission's participants.
- Volume of data around 100 PB is expected.
- 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.

Millimetron Correlator Preliminary Requirements

- VLBI baseline number − not less than **4** (including space baselines);
- Integration time − programming (starting from **0.001 s**);
- Correlation modes − autocorrelation, cross-correlation, Millimetron single dish mode data processing;
- Polarization/Video band channels number − **2/2 (totally 4);**
- Data rate per channel, maximal − **2048 Mbit/s**;
- Video channel bandwidth, maximal − **1024 MHz**;
- Input data format − **VLBA, RDR-XX, VDIF, Mark-XX, LBA**;
- Maximal data flow − **8192 Mbit/s**;
- Quantization **– 1 or 2 bits**;
- Delay window, maximal − **± 128 microseconds**;
- Fringe rate window − **± 30 Hz**;
- One frequency channel resolution − **62.5 KHz**, i.e. **16384 channels at 1024 MHz video band** (corresponds to resolution of the radial velocity about **0.075 km/s** at the observation frequency about **250 GHz** or **1 km/s** will occupy **840 KHz** bandwidth).

Outcomes

- In spite of the complexity of the Millimetron SVLBI-mode it shows favorable results in competing with the ground based VLBI of Sgr A* Galactic BH and some of SMBH in AGN (more compact than Sgr A and M87) at a wavelength of ~ 1 mm (the angular resolution range can be from $2*10^{-6}$ to $2*10^{-8}$ arc sec for bands 100-340 GHz). According to MM-EHT, MM-ALMA preliminary SVLBI-mode simulations.

- Simulations MM-EHT interferometer show possibility of reliable observations of SMBH at a wavelength of ~1 mm.

- SVLBI Millimetron is a very good instrument to obtain momentary 1D images of very compact sources.

Thank you for your attention!

Critical Issues

Geometry

- **Accuracy of the orbit determination. Possible solution:** permanent laser ranging utilization with active onboard laser and selective VLBI tracking of the spacecraft with onboard ”radio-lighthouse” at 22Ghz (both modes need extra onboard energy resources);
- **On-board Accelerometer and clock** (according to the requirements for acceleration and velocity).
- **Choice of the baseline vector projection to avoid “gaps” on the (u,v)-plane**. **Possible solution:** accurate (**sophisticated!**) scheduling of the mission. It’s possible that successive scientific targets will be rare enough.

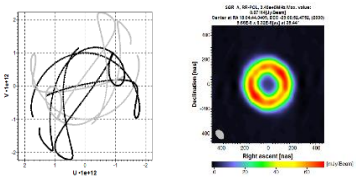
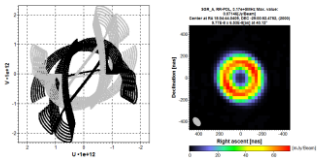
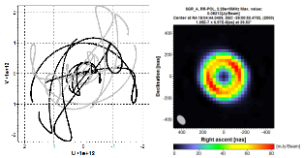
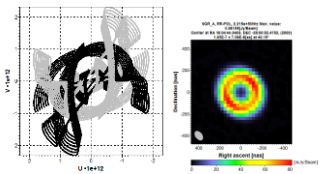
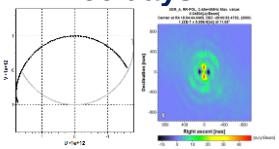
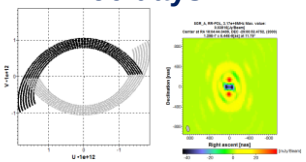
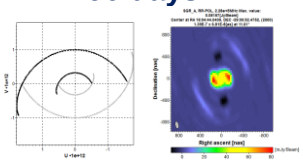
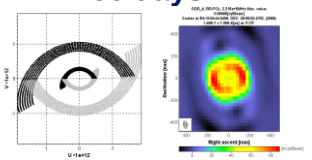
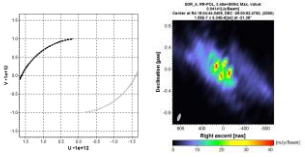
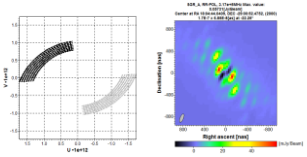
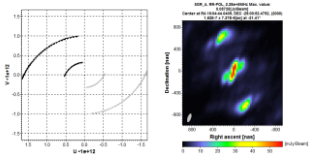
Sensitivity

- **On-board maser stability (not worse than 10^{-15} s). Possible solution:** can be provided by Russia (Nizhnij Novgorod, “Vremia Che”). Currently it has Phase-A stage;
- **Provide acceptable sensitivity on the frequencies higher than 340 GHz**. **Possible solution**: to produce heterodyne receivers with maximal bandwidth.

Scientific efficiency

- **Lack of the MFS experience technology utilization. Possible solution**: to begin use current MFS capabilities of the Radioastron mission**. ASAP!**
- **High bandwidth downlink supply (not worse than 2 Gbit/s). Possible solution:** consider a possibility of current modern design (JPL? Optical Payload for Lasercomm Science (OPALS)?).

Millimetron-EHT Simulations

345 GHz	MFS 275-373 GHz	345 and 116 MHz	MFS 84-116 and 275-373 MHz
3 years 	3 years 	3 years 	3 years 
90 days 	90 days 	90 days 	90 days 
30 days 	30 days 	30 days 	30 days