Status of the Chinese Space Millimeter-Wavelength VLBI Array Planning

---Uncovering the Secrets of Super Massive Black Holes and Active Galactic Nuclei

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1. Brief introduction of the project

- Reported in the 2nd Sino-US workshop and ISSI-BJ workshop

- SHAO: the development of VLBI, and cm radio astronomy;
  - 1970s: VLBI Network Concept
  - 1980s: Shanghai 25m
  - 1990s: Urumqi 25m
    * Join EVN, IVS and VSOP Obs.
  - 2000s: Beijing (60m) and Kunming (40m)
    * (CVN: 5 Ant. + correlator) join the tracking for CE(1.2.3)
    * MK5B, CDAS, eVLBI
  - 2010s: Tianma (65m), FAST (500m)
  - 2020s: ??? 2030 ? ? ?
  - QTT, Space VLBI? Northern hemisphere SKA at cm??
The Chinese Academy of Sciences (CAS) leads the Strategic Pioneer Program to Space science programs. (2011-2015)

- The Hard X-ray Modulation Telescope (HXMT, 2015),
- The Quantum Experiments on Space Scales (QUESS, 2015),
- The Dark Matter Particle Explorer (DAMPE, 2015)
The first batch background research (4 projects) for the next generation of Chinese space science missions, which includes the Space Millimeter VLBI Array (SMVA) was selected for further study in 2011 and start at 2012;

- Magnetosphere – Ionosphere – Thermosphere Coupling Exploration (MIT)
- Solar Polar Orbit Radio Telescope (SPORT)
- X-ray Timing and Polarization mission (XTP)
- Space Millimeter VLBI Array (SMVA)

The second batch (another 4 projects) was selected in 2013 and started in 2014.
1.3 A proposal of SVLBI in China

- We worked out a proposal for China space VLBI
  - **Stage 1:** Long-mm-wavelength Space VLBI Array, with the potential start in 2015 and launch in 2020
    - two 10m space telescopes,
    - highest frequency 43GHz,
    - to realize 20uas resolution and good \((u,v)\) coverage together with ground radio telescopes for imaging
  - **Stage 2:** Mm-wavelength Space VLBI Array (3x12-15m, 86 GHz) in 2021-2025
  - **Stage 3:** submm Space VLBI Array (3-4 12-15m, sub-mm) after 2026
Space Scientific Projects in CAS

- In 2012, the project for pre-study of space VLBI array was approved by the CAS as a “Background Prototype Research”.
- Uncovering the Secrets of Super Massive Black Holes and Active Galactic Nuclei with capability of high resolution for imaging.
- The goal is to complete the overall design of the first space VLBI array. To work out several key engineering and technical problems as well as science cases, from 2012 to 2015.
- There was an interim evaluation in April, 2014.
2. Main concepts of the SVLBI proposal

2.1 Two 10m space antennas

To improve Orbital Design

- Obtain good (uv) coverage for major observing targets
- Preliminary scheme
  Two Satellites (10m antennae)
  - Apogee 60000 km
  - Perigee 1200 km
  - Inclination Angle 28.5 deg
  - Angle between two orbital planes ~120 deg
- Achieve good (uv) coverage at 2-dimension – a critical requirement for imaging
- accomplish imaging within an/ several orbital periods
2. Main concepts of the SVLBI proposal

2.2 The Scientific goals:

- Focusing on some important scientific questions which will help us to understand the Universe better

- Imaging Super massive Black Holes, Active Galactic Nucleic and compact radio sources with high resolution

- **Key Science Goals**
  - Supermassive Black Hole (SMBH) – M87
  - Supermassive Black Hole (SMBH) – Megamasers
  - Jets in Active Galactic Nuclei (AGN)
  - Formation and Evolution of Massive Stars
Key Sciences to be addressed

- **Super-massive Black Hole (SMBH)**
  - Utilizing the space-ground baselines, mapping the emission structure surrounding SMBHs. The elliptical galaxy M87 will be studied in detail.
  - At 43GHz, resolution of 20\(\mu\)as, mapping the closest massive BH in the heart of M87, directly detection and imaging of BH shadow.
<table>
<thead>
<tr>
<th>Name</th>
<th>Other Name</th>
<th>$D$ [Mpc]</th>
<th>$M_{BH}$ [$10^8 M_\odot$]</th>
<th>$\theta_g$ [µas]</th>
<th>$S_{15\text{GHz}}$ [mJy]</th>
<th>Remarks</th>
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<tbody>
<tr>
<td>NGC 3031</td>
<td>M 81</td>
<td>3.63</td>
<td>0.7</td>
<td>0.93</td>
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<td>NGC 3627</td>
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<td>6.6</td>
<td>0.9</td>
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<tr>
<td>NGC 3998</td>
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<td>21.6</td>
<td>5.8</td>
<td>0.53</td>
<td>85</td>
<td>$S$ at 5 GHz</td>
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<tr>
<td>NGC 4143</td>
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<td>17</td>
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<td>NGC 4261</td>
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<td>35.1</td>
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<td>6230</td>
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<td>9.7</td>
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<td>0.57</td>
<td>89.7</td>
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<tr>
<td>NGC 4374</td>
<td>M 84</td>
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<td>16</td>
<td>1.74</td>
<td>183.7</td>
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<tr>
<td><strong>NGC 4486</strong></td>
<td>M 87</td>
<td>16.8</td>
<td>32</td>
<td>3.81</td>
<td><strong>2835.7</strong></td>
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<tr>
<td>NGC 4552</td>
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<td>0.43</td>
<td>58.6</td>
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<tr>
<td>NGC 4594</td>
<td>M 104</td>
<td>20</td>
<td>2.7</td>
<td>0.27</td>
<td>86.6</td>
<td>$S$ at 8.4 GHz</td>
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<tr>
<td>NGC 5128</td>
<td>Cen A</td>
<td>4.2</td>
<td>2.4</td>
<td>2.96</td>
<td>2500</td>
<td>$S$ at 8.4 GHz</td>
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<tr>
<td>IC 1459</td>
<td>PKS 2254 − 367</td>
<td>27</td>
<td>25</td>
<td>1.85</td>
<td>1000</td>
<td>$S$ at 8.4 GHz</td>
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<tr>
<td>Sgr A*</td>
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<td>0.008</td>
<td>0.04</td>
<td>6.50</td>
<td>1030</td>
<td>$S$ at 8.4 GHz</td>
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</table>
Key Sciences to be addressed

- Super-massive Black Hole (SMBH)
  - Imaging extra-galactic water mega-masers which lie in accretion disks orbiting SMBHs to reveal the disk structure and dynamics, and then to determine the SMBH masses.
Key Sciences to be addressed

- Jets in Active Galactic Nuclei (AGN)
  - Probe a range of angular scales, enabling a detailed study of morphology, kinematics, and emission in extragalactic jets.
  - Formation, acceleration, collimation of the relativistic jets
  - Internal structure of jets
  - Polarization structure
Formation & Evolution of Massive Stars

- Observing star-forming accretion disks and outflows traced by masers
  - $\textit{H}_2\textit{O}$ at 22 GHz
    
    \textit{On scales of 1-10 AUs, the gas kinematics can be probed by H2O masers using the Space VLBI Array.}
  - SiO at 43 GHz
    
    \textit{Imaging these bright and compact sources at 43 GHz allows investigation of a number of key scientific topics in late stellar evolution.}

- Again, sensitivity is an issue
- Deep exploration of maser physics in extreme situations
2. Main concepts of the SVLBI proposal

2.3 Frequencies considered:

- The traditional observed bands in ground VLBI: P, L, S, C, X, Ku, K, Q, W,
- VSOP; L, C, K

- Since VSOP and RadioAstron have had good results from L and C band, we are considering other bands (higher frequencies) for new results. So X, K, Q are under considered.
3. The structure of the system

“Space VLBI Array Phase 1”

1. System Designing
   - Sciences
   - Techniques

2. Satellite Platform
   - Designing
   - Pointing
   - Downlink

3. Space antenna
   - 10m
   - 43GHz

4. Astronomical Payload
   - receivers
   - recording sys.
   - time & freq. (H-maser) …
4. Some international meetings
- Learnt a lot from the international colleagues
- Realized such project is a really challenging both at Sciences and technology.
- It should be strongly supported by international collaboration.
- It will be a very expensive project
Two satellite
  apogee 60000 km
  perigee 1200 km
  inclination 28.5 deg

Observation band:
  X (6-9) / K (20-24) GHz
  Q (40-46) GHz
  LCP/RCP
  Cooled receiver (22/43GHz)

Date rate: 1-2 Gbps

Resolution: 20 μarc (43GHz)

Schedule: 2012-2016 key technique study
5. The Progress -- system design

- Strong scientific goal
- Orbiters design with good \((u,v)\) coverage for sciences
- Orbiters determination with USB+VLBI and SLR
  - No phase referencing model is considered this moment, it is possible at low orbit period.
- Down link date rate (1.2 – 2.4 Gbps), need ground station support.
- Time and frequency (Both uplink and Space H masers are considered this moment)
Scientific goals

- SMBHs (e.g., M87);
  - BH shadows?  Challenge
- Masers
  (not many source can be detected)
- Jets in AGN
  - Structure
  - Launching
  - Magnetic structure
  - High Energy connection
  - Jets in x-ray binaries
- Formation and evolution of massive stars
  (the importance and the feasibility?)
Scientific goals

- Suggested to have L band
- Pulsars
- ISM - Intraday variability
- Transients
- Gravity
➢ Developing a software to plot uv for two space antennae.
If the apogees of the two satellites are deferent by 5000km, the uv coverage will much better.

<table>
<thead>
<tr>
<th></th>
<th>Satellite 1</th>
<th>Satellite 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apogee</td>
<td>60000 km</td>
<td>55000 km</td>
</tr>
<tr>
<td>Perigee</td>
<td>1200 km</td>
<td>1200 km</td>
</tr>
<tr>
<td>Inclination Angle</td>
<td>28.5 deg</td>
<td>28.5 deg</td>
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</table>
Satellite Platform

- Pointing is very important
<table>
<thead>
<tr>
<th>payload</th>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space Antenna</td>
<td>Aperture</td>
<td>10m</td>
</tr>
<tr>
<td></td>
<td>Freq./Efficiency</td>
<td>X: 6-9GHz; ≥60%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>K: 20-24GHz; ≥50%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Q: 40-46GHz; ≥40%</td>
</tr>
<tr>
<td></td>
<td>Surface Error</td>
<td>≤0.4mm(RMS)</td>
</tr>
<tr>
<td></td>
<td>Mass</td>
<td>≤400Kg</td>
</tr>
<tr>
<td>Astronomical Receiving System</td>
<td>Type</td>
<td>K/Q: cryogenic, X: room temp.</td>
</tr>
<tr>
<td></td>
<td>Polarization</td>
<td>LCP/RCP</td>
</tr>
<tr>
<td></td>
<td>Bandwidth</td>
<td>512/256/128MHz, 1/2bit</td>
</tr>
<tr>
<td>Time/freq. Standard System</td>
<td>Stability</td>
<td>3×10^{-12} (1s), 3×10^{-13} (10s), 3×10^{-14} (100s)</td>
</tr>
<tr>
<td></td>
<td>Method</td>
<td>Onboard H-maser, Ref. signal trans. System</td>
</tr>
</tbody>
</table>
Payload Consideration

<table>
<thead>
<tr>
<th>payload</th>
<th>Specification</th>
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</thead>
<tbody>
<tr>
<td>High-rate data transmission system</td>
<td>Band: Ka</td>
</tr>
<tr>
<td></td>
<td>Antenna 1.5m</td>
</tr>
<tr>
<td></td>
<td>Modulation: QPSK/8PSK/16APSK</td>
</tr>
<tr>
<td></td>
<td>Coding: RS or LDPC</td>
</tr>
<tr>
<td></td>
<td>Rate: &gt;1.2Gbps</td>
</tr>
<tr>
<td>Laser Reflector</td>
<td>Effective reflection area: 1650 cm²</td>
</tr>
<tr>
<td></td>
<td>Field: ±15°</td>
</tr>
<tr>
<td></td>
<td>Precision of Laser Ranging: 5cm</td>
</tr>
</tbody>
</table>
Technique Requirement

Preliminary consideration: CZ-3C rocket, maximal allowed weight is 3.2 ton,

- Orbit determination accuracy : 200m at apogee, 30m at perigee for engineering
- USB+VLBI; USB+SLR, Satellite tracking accuracy 20 m for sciences.

![Diagram showing Laser reflector and Data transmission antenna]
Key Techniques

Satellite

Astronomical Receiving Sys.

1.2/2.4Gbps

Data transmission

Ground

Receiving & Transmitting

KT 1

KT 2

KT 3

KT 4

10m Antenna

Onboard H-maser

Ref. signal trans. System

H-maser

Onboard H-maser

Ref. signal trans. System
KT1: Satellite configuration and layout

Side view  Top view  Side view
KT2: On-board antenna

24 sectors
inside panel
+outside net.

Double mesh,
and surface can
be adjusted at
6000 points
KT2: On-board antenna

Sunflower Solid surface antenna
KT2: Feed horn

K/Q-band light-wall horn

X-band corrugated horn

Horn test
KT3 Cooler receiver and DBBC

X/K/Q band receiver. Key tech: design of refrigeration and heat insulation under small cold capacity
 KT3 Cooler receiver and DBBC

slot insulation barrel structure

insert additional parts gap, glass fiber insulation tube

simulation results of temperature gradient
KT3 cooler receiver and DBBC

Two-stage stirling cryocooler

20K

80K

Control unit

2W @ 80K
6. Next Step

- Interim evaluation in April,
  - The progress in on the schedule as the plan.
- There is still many challenges for the project.
- Sciences:
  - More simulation studies for the imaging the shadow of M87,
  - Pre-launch VLBI survey for AGN and Maser
- Technology:
  - Antenna (prototype in 2015)
  - Pointing (not a big problem)
  - Receivers (prototype for K band in 2015)
International collaboration

- is very importance for Sciences,
- System Design,
- ground VLBI array
  (VLBA is very important),
- ground station (Down link)
Thank you for your attention!