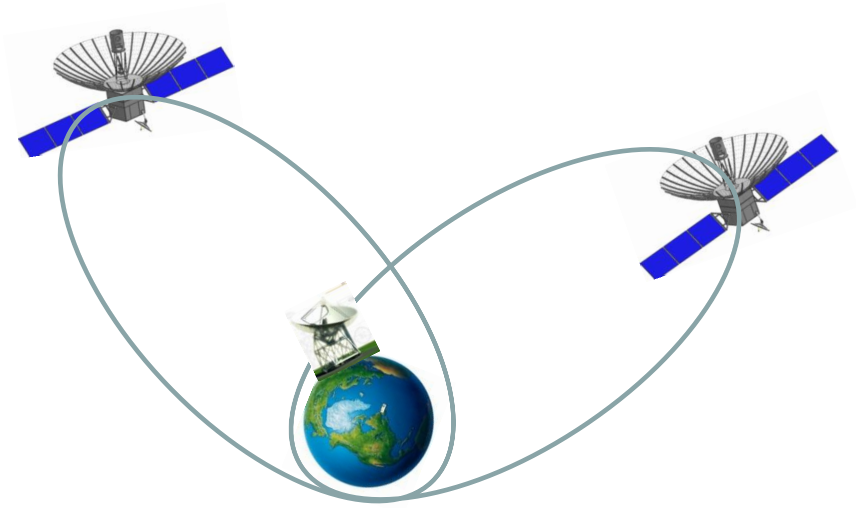
The Chinese Space VLBI Array

Uncovering the Secrets of Supermassive Black Holes and Active Galactic Nuclei



China's prospective Space VLBI Array mission described here is the first of a series of space VLBI projects for imaging Supermassive Black Holes, Active Galactic Nucleic and compact radio sources using long-mm-wavelength VLBI techniques. The planned mission will launch two spacecraft flying in elliptical orbits with apogee altitudes of ~60,000 km, each carrying a 10-m radio telescope, to form very long baselines when working in tandem with other ground-based radio telescopes, thereby realizing a ~20 micro-arcsecond resolution at 43 GHz.

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1 Introduction

The advent of VLBI techniques has allowed astronomers on earth to observe celestial objects with high-resolution details greatly surpassing those of optical telescopes. Exploiting baselines a few thousand km long between the radio telescopes of a ground-based VLBI network, celestial objects and their environs can be imaged as if CCD sensors are used to photograph them through optical lenses. However, the various parts of a celestial object may be viewed in different wavelengths with unequal efficiencies, making it necessary to build diverse types of telescopes (optical, radio, x-ray, infrared, gamma-ray, etc) for observing different astronomical features.

The capabilities of ground-based VLBI networks are generally subject to three serious constraints: baseline length, observing frequency and detection limit (sensitivity). Since the imaging resolution of VLBI is inversely proportional to the baseline length and observing frequency, it is desirable to spread the telescopes of a VLBI network over far-apart locations on earth, and make them operate at the highest possible frequencies suitable for the intended applications. But the baseline lengths of these VLBI networks are still constrained by the size of the earth, while very-high-frequency radiation from radio sources may be absorbed or blocked by the atmosphere. For example, the VLBA network usually operates with baselines shorter than 8,000 km and at frequencies not higher than 86 GHz, resulting in a maximal resolution of ~75 μas.

Hence radio astronomers must try to overcome these limits by moving the telescopes to space and allowing them to fly in high-altitude orbits. But clearly such an approach (known as Space VLBI) is not a panacea as it also creates a plethora of grave problems for the payload, such as cooling (to reduce noise in the receiving amplifier), a highly stable time/frequency standard, high-rate data transfer to ground stations, pointing accuracy of the space antenna, and a highly accurate 8-m or bigger parabolic reflector.

Since the first ground-space VLBI experiment was conducted on the TDRSS satellite in 1986, radio astronomers have been witnessing a series of unremitting attempts—some successful but others ill-fated—to build and operate space VLBI telescopes in tandem with ground stations. Interesting results have been obtained from some early efforts, and more are forthcoming from a current mission (RadioAstron). Here we will present China’s multi-stage roadmap envisioned for the next two decades, and describe its active participation in the exciting field of space VLBI as a natural extension of its ground-based VLBI activities started in the late 1980s.

1.1 Past and present space VLBI missions

The Japanese HALCA satellite in the VSOP project has made history in radio astronomy as the first 8-m space-borne radio telescope working jointly with ground stations to form unprecedented baselines that could be twice as long as the earth’s diameter. It has made some important accomplishments, such as observation of hydroxyl masers at 1.6 GHz, detection of interference fringes, and routine VLBI imaging of quasars and radio galaxies, etc. Unfortunately HALCA could only operate at the maximum frequency of 5 GHz (although it was designed for 22 GHz), and its baseline length was constrained by its apogee altitude of 21,400 km, which resulted in an unimpressive angular resolution and a mediocre (u, v) coverage.

All things considered, VSOP is widely considered as a rather successful mission despite some shortcomings [1]. Its real accomplishment is in demonstrating that high-resolution VLBI observations in a space-ground configuration with baselines longer than the size of the earth are technically feasible and scientifically rewarding; it has also motivated scientists worldwide to explore the possibilities of launching more aggressive space VLBI missions in the future, which will be made possible by a range of advanced electronic, mechanical and aerospace technologies.

VSOP-2 is VSOP's follow-up project planned by the Japanese space agency JAXA as its second-generation space VLBI mission, featuring a maximum observing frequency of 43 GHz, a 10-m on-board antenna, and an apogee altitude of 26,000 km that would offer a greatly improved angular resolution of ~38 μas [2-4]. NASA originally had proposed a space VLBI mission called ARISE which, for budgetary reasons, was later replaced by its potential participation in VSOP-2. But NASA later promoted a dual-satellite mission called iARISE, which featured an apogee altitude of 90,000 km corresponding to a further improved resolution of ~7.5 μas, a 15-m space antenna, and a sensitivity of ~80 mJy at the maximum observing frequency of 86 GHz [5-6]. Unfortunately both iARISE and VSOP-2 were postponed or cancelled.

Russia also has a space VLBI project (RadioAstron) that had been under active planning, design and construction for more than a decade. The satellite (Spektr-R) carrying a 10-m radio telescope was finally launched in July 2011 into a highly elliptical orbit with a maximal apogee altitude of ~350,000 km. Its highest observing frequency is 22 GHz, corresponding to an angular resolution of ~7 μas, and its baseline sensitivity is estimated to be ~13 mJy [7]. Two years after launch, the world's radio astronomy community is now eagerly waiting for reports on its important science findings.

1.2 China's space VLBI vision

China started conceptualizing its VLBI network in the 1970s. Its first radio telescopes were built in Shanghai (25 m) in the 1980s, and then in Urumqi (25 m) in the 1990s. Later in the 2000s, radio telescopes of 50-m and 40-m diameters were built in Beijing and Kunming respectively. Starting in the 2010s, some very large radio telescopes began to emerge, such as the 65-m radio telescope in Shanghai and 500-m FAST in Guizhou.

As radio astronomers in China were accumulating experience in building, operating and using ground-based radio telescopes for VLBI research over the past three decades, they were also gradually shifting their attention from the ground to space. They have drafted a proposal for a future "Space Millimeter VLBI Array," which was selected for pre-study in 2009 by the Space Science Project Committee of the Chinese Academy of Sciences (CAS). The pre-study project was then approved by the CAS in 2012 as a "Background Prototype Research," with the goal of completing the overall design of the first space VLBI array within three years (2012-2015). It should be noted that this project, while technically challenging, must be *science driven* with minimal risk.

There will be a review meeting in 2015 to evaluate the progress made so far, and decide whether or not the space VLBI project should be selected. Below is a tentative roadmap for China's space VLBI activities planned for the next two decades:

- Stage 1 [*possibly* 2015-2020]: Long-mm-wavelength Space VLBI Array
  - Two space telescopes (aperture 10 m)
  - Highest frequency 43 GHz
  - ~20 μas resolution and good (u, v) coverage for *imaging*
- Stage 2 [2021-2025]: Mm-wavelength Space VLBI Array
  - Three space telescopes (12~15 m)
  - Highest frequency 86 GHz

- Stage 3 [after 2026]: Sub-mm-wavelength Space VLBI Array
  - Three to four space telescopes (12~15 m)
  - Sub-mm wavelength

2 Science Goals

The main objective of our prospective Space VLBI Array is to substantially deepen and broaden our understanding of supermassive black holes (SMBHs) and the active galactic nuclei (AGN) in which they lie. Our Space VLBI satellite will operate in tandem with a number of ground radio telescopes in China and abroad to form baselines many times longer than the earth's diameter, thus realizing an angular resolution as fine as 20 μas—about 7.5 times of what can be achieved with ground installations (e.g. VLBA at 43 GHz) alone, or more than 20 times better than the decommissioned VSOP at 5 GHz. Observing at the high frequency of 43 GHz, the proposed Space VLBI Array would be the *only* astronomical tool from 2020 onward which could directly image SMBHs and the hearts of AGN, measure their key physical properties, and even track their evolutions.

2.1 Supermassive Black Hole (SMBH) - M87

The longest baseline (> 60,000 km) between the Space VLBI satellite and collaborating ground stations provides a high angular resolution of ~20 μas (at 43 GHz) that would support:

- *Mapping of the emission structures surrounding SMBHs (mainly M87)*
- *Direct detection and imaging of the shadow (dark region) of M87*

Direct imaging of a black hole is widely considered as a very rewarding endeavor, since its existence has been hitherto based on indirect evidence[1]. But such a mission is also extremely challenging—even if we are only zooming in on the more easily detectable SMBHs—as the task requires state-of-the-art radio receivers, antennas, supporting electronics and cryogenic facilities to work cooperatively in a grand-scale interferometry network offering sufficiently high angular resolution *and* sensitivity. Our prospective Space VLBI Array will be built to achieve this goal.

The most likely candidate is M87, an elliptic galaxy containing one of the nearest extragalactic jets at a distance of 14.7 Mpc. Hubble Space Telescope spectroscopy of its nucleus gave strong evidence for a rapidly rotating ionized gas disk at its center, from which the presence of a central SMBH with ~3.2×10^9 $M_\odot$ was inferred. Its apparent shadow size was estimated to be ~26 μas[2], which is comparable to the angular resolution of the Space VLBI Array, thus making it currently the best candidate for direct black hole imaging. Figure 1 shows two images of M87, one (left panel) obtained by several VLBI ground stations at 43GHz (~150 μas resolution) [8], and the other (right panel) by VSOP in tandem with a ground station at 1.6 GHz (~1.0 mas resolution)[3]. They clearly indicate that the expected higher resolution (~20 μas) of our prospective Space VLBI Array would be sufficient to resolve some interesting, yet-to-be-discovered details about the black hole and its environs. Examples for future study include the innermost portions of the accretion disk, the region in which material leaves the disk and spirals towards the SMBH event horizon, and the acceleration and collimation of ultra-hot plasma[4].

[1] Quoting the strategic plan of NASA's Space Science Enterprise (SSE). See p.1 of [6].
[2] See p. 17 of [4], and [11-12].
[3] See p. 4 of [6].
[4] See p. 3 of [6].

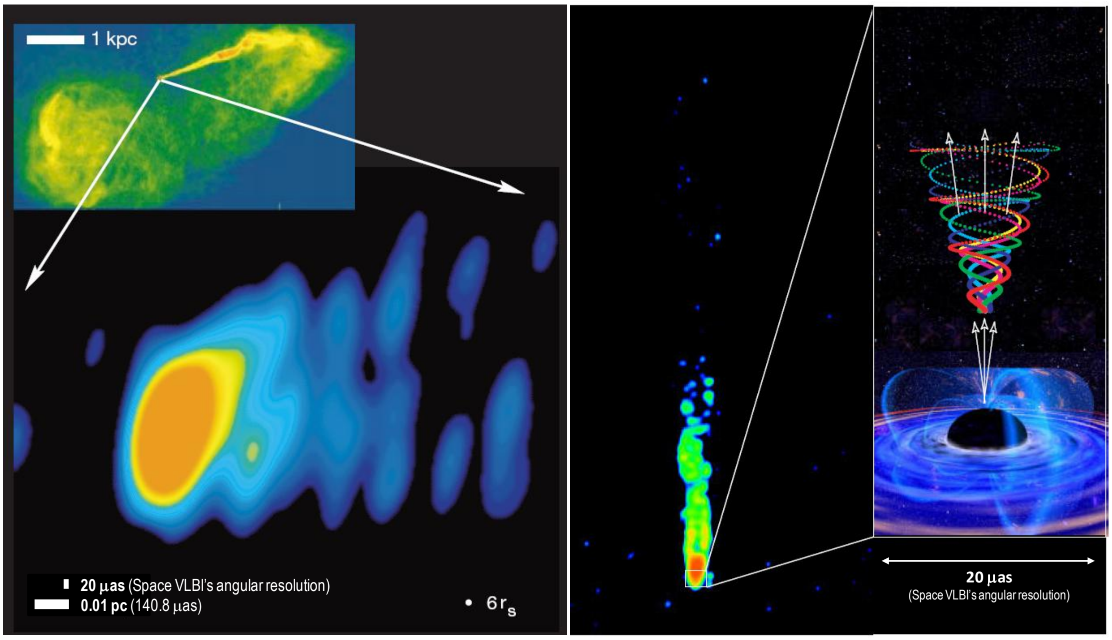

Figure 1. Images of M87 obtained with all-ground VLBI stations (Left) and a VSOP-ground configuration (Right), at very low resolutions in comparison with the 20-µas resolution of the proposed Space VLBI Array.

2.2 Supermassive Black Hole (SMBH) - Megamasers

Through imaging extragalactic water mega-masers that lie in accretion disks orbiting SMBHs with a relatively high ~20 µas resolution (at 43 GHz), the Space VLBI Array would support:

- *Direct mapping of the disk structure and dynamics, and subsequent accurate determination of SMBH masses.*
- *Determination of the Hubble Constant H_0 and related extragalactic distances around the black holes by a proposed "MCP (Mega-maser Cosmology Project) in Space" with sufficiently high resolution, accuracy, and sensitivity (e.g. ~100 mJy in 100 KHz bandwidth at 22 GHz) required by the highly demanding task.*

Besides directly imaging SMBHs (§2.1), another approach to gaining a deeper understanding of black holes is to explore extensively into the accretion disks in AGN as they are the key physical links between SMBHs and their host galaxies, and their proximity to the black holes makes them the best available probes of the deep gravitational wells and black hole environs. VLBI measurements of water maser positions, line-of-sight velocities and proper motions provide unique and direct, well resolved maps of the underlying accretion disks[5]. Since ground-based VLBI networks with relatively poor angular resolutions could only handle the nearest water mega-masers, which are very limited in number, the Space VLBI Array has a definite advantage as it has a much higher angular resolution that could greatly extend the range of observation.

Observations will be carried out over a period of several years to possibly detect the proper motion and centripetal acceleration of mega-masers in several AGN. With these data we could detect rotation of the disks, which would allow us to measure the distances to galaxies geometrically, thus forming a robust basis for calibrating extragalactic distances.

The current MCP at NRAO [9-10] aims to determine the Hubble Constant H_0 with high accuracy (~3%) [9] through measuring the angular-diameter distance to galaxies in the Hubble flow at distances of 50-200 Mpc. Better measurements of H_0, which is related to the current expansion

[5] See p. 5 of [6].

rate of the Universe, would provide critical independent constraints on dark energy, spatial curvature of the Universe, neutrino physics, and validity of general relativity. The MCP will also enable accurate determination of the central black-hole mass in mega-maser galaxies [9]. At present, NRAO uses the GBT, VLBA, VLA, and Effelsberg radio telescopes to conduct the necessary observations. By comparison, the proposed Space VLBI Array is able to provide much longer baselines, hence resulting in higher angular resolutions and better accuracies. However, the real challenge would be to overcome the sensitivity limit of the space-borne low-noise receiver and its cryogenic equipment. Currently the Space VLBI Array is expected to have a sensitivity of about 16.6 mJy (1σ, 512 MHz bandwidth, 60s integration) when working in tandem with a 25-m VLBA telescope.

2.3 Jets in Active Galactic Nuclei (AGN)

- *To conduct a detailed study of the morphology, kinematics, and emission in extragalactic jets through probing a range of angular scales. These observations would help us understand:*
  - *Formation, acceleration, collimation of relativistic jets*
  - *Internal structure of jets*
  - *High brightness temperature sources*
  - *Magnetic field structure*
  - *Origin of the high-energy X-ray and gamma-ray emissions*

Past VSOP observations revealed that AGN jets were extremely relativistic with the bulk Lorentz factors of B ~ 30 [4], but the formation, acceleration, and collimation mechanisms of the jets are still unclear. The high-resolution polarized imaging capability of the proposed Space VLBI Array could enable a detailed study of these problems.

2.4 Formation and Evolution of Massive Stars

- *Observing star-forming accretion disks and outflows traced by masers (H_2O at 22 GHz and S_iO at 43 GHz)*
- *Again, sensitivity is an issue*
- *Deep exploration of maser physics in extreme situations*

With enhanced sensitivity and resolution resulting from better receivers, cryogenic equipment and longer space-ground baselines, the proposed Space VLBI Array will explore the star-forming regions as one of its main scientific goals. On scales of 1-10 AUs, the gas kinematics can be probed by H_2O masers using VLBI. To date, dozens of 22-GHz H_2O masers have been found in locations near the sites where low-mass to massive stars were formed.

On the other hand, since S_iO masers form in the outflows of late-type Asymptotic Giant Branch stars, imaging them allows this important stage of stellar evolution to be traced. Several S_iO masers transitions fall in the 43 GHz observing band supported by the Space VLBI Array, and they are known to be bright and extremely compact. Imaging these sources at 43 GHz allows investigation of a number of key scientific topics in late stellar evolution.

3 Mission Design

Our prospective Space VLBI Array project has been undergoing intensive in-house study and extensive peer reviews in the past few years. So far we have identified some key *mission drivers* that could result in an overall satisfactory project with the "best" returns possible, after making a few necessary compromises to reach some optimal performance tradeoffs.

A key element of the Space VLBI Array mission design is the complementary dual-spacecraft orbit configuration that would give us good (u, v) coverage not only for all sky, but also for specific important targets such as M87. Some possible configurations are presented in Figure 2, which could be further refined in the future with alternative orbit designs. Some simulation results for M87 are shown in Figure 3 [13], showing good (u, v) coverage when the two satellites are working with ground stations worldwide. At present, each satellite orbit has apogee and perigee altitudes of 60,000 km and 1,200 km respectively, with a 28.5° inclination, and the angle between the two orbital planes is ~120°.

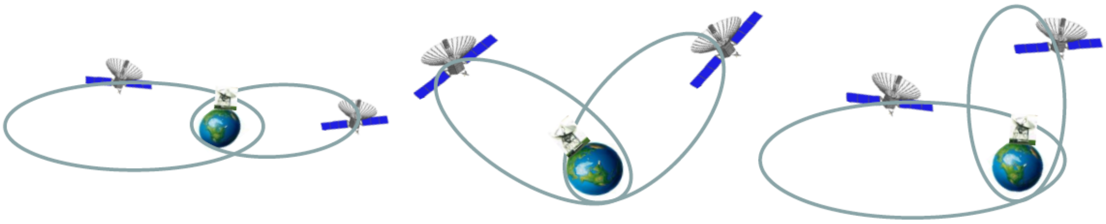

Figure 2. Orbital plane separation between two spacecraft in the Space VLBI Array: 180 deg (Left), 120 deg (Middle) and 90 deg. (Right).

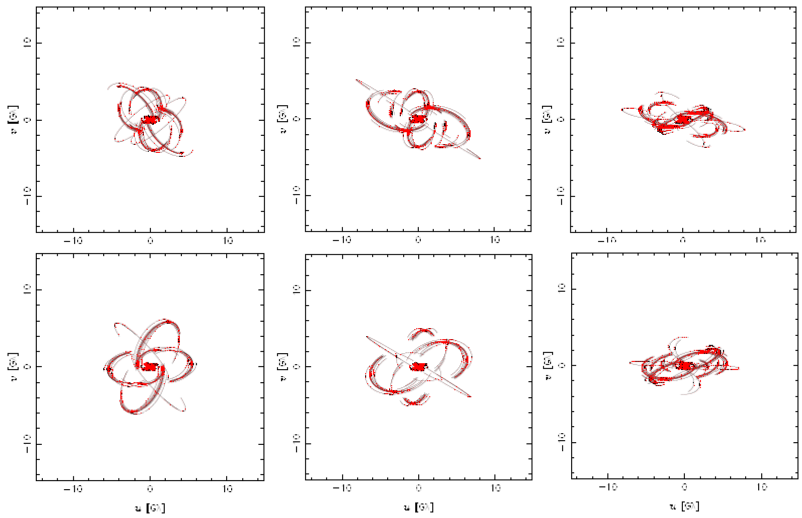

Figure 3. The simulated (u, v) coverage for M87 at six different epochs between the two spacecraft in the Space VLBI Array and some ground stations worldwide. These diagrams show that the multiple tracks (in oval shapes) have filled up many possible "holes" in the (u, v) space to produce good coverage.

4 Key Technologies

The ultimate success of our prospective Space VLBI Array is contingent on a number of key technologies that would enable all the components/subsystems on the satellite and in the ground stations to operate properly together *as a system*, performing the mission's required functions according to strict specifications. At present, after several rounds of initial designs, experimentation, reviews and revisions, we have identified four key technologies (described below) for more focused development in future. However, we must emphasize that this shortlist may likely be refined or substantially changed as we are making more progress in the next few years.

- Space Antenna: The satellite will have a 10-m Cassegrain-type deployable antenna with a total mass ≤ 400 Kg, whose reflector will have a surface error (RMS) ≤ 0.4 mm as required by 43 GHz observation. The antenna when folded should be fitted into a cylinder with a 3.1-m diameter and 5.1-m height. To meet the stringent surface error requirement, special alloys will be used to reduce possible deformation of the mesh structure in the reflector due to significant day/night temperature changes when operating in space, and probably due to dews caused by air humidity during launch as well.

- Astronomical Receiving System: The space antenna will operate in three bands, namely, 6-9 GHz (X) with efficiency ≥ 60%; 20-24 GHz (K) with efficiency ≥ 50%; and 40-46 GHz (Q) with efficiency ≥ 40%. The receiver will support LHCP/RHCP dual polarization, and its low-noise amplifier will be cooled down to about 30K with cryogenic facilities to reduce its background noise when operating at 22/43 GHz.
- Antenna Pointing and Satellite Attitude Control: The space antenna will have a pointing error ≤ 15 μas or 0.0042 °(1σ). Since the antenna is physically tied to the satellite platform, the antenna pointing angle is realized by changing the satellite's attitude. Hence the satellite attitude control should also have a pointing error ≤ 15 μas. (Note: Since phase referencing will not be used to increase the integration times of the captured signals with techniques like quick "nodding," the rate of changing the antenna's pointing angle is not an important issue to consider here.)
- Time and Frequency Standard Subsystem: To support observing at 43 GHz, the time/frequency standard on the satellite should have relatively good short- and long-term stabilities comparable to those of H-masers with the following tentative specifications: 3×10^{-12} (1 sec) and 1×10^{-14} (daily). To meet these requirements, a space-qualified H-maser will be installed on the satellite; on the other hand, a mechanism that will effectively remove frequency shifts due to the satellite's Doppler (with respect to the ground stations) will also be provided to "transfer" the highly stable phase and frequency of an atomic clock on the ground to the satellite, so that an on-board USO (ultra-stable-oscillator) can be "disciplined" to accurately follow the phase and frequency of the ground-based atomic clock. This two-pronged approach may help to reduce the risk of on-board H-maser failures, and also solve—at least partially—the problem of having only a limited number of collaborating up-link tracking stations worldwide.

Other less critical technologies to develop include:

- High-rate data communication from the spacecraft to the ground receiving stations at 1/2 Gbps. For dual-polarization observation, 1 Gbps will only allow a bandwidth of 256 MHz, while 2 Gbps will accommodate a *preferred* 512 MHz bandwidth. Our objective is to provide the highest possible data rates while maintaining acceptable bit-error-rates for given S/N ratios in the data link (under all possible weather conditions) that may be as long as 60,000 km.
- A laser reflector on the satellite may be installed to enable accurate Doppler measurement by ground tracking stations.
- A high-volume mass storage on the satellite may be installed to buffer the captured astronomical data for some periods of time (probably a few hours) when no ground stations are in sight.

5 Conclusions

The Space VLBI Array presented here is the most important first mission of China's current multi-stage roadmap that would ultimately lead to a sub-mm-wavelength space VLBI network enabling high-resolution (micro-arcsecond or better) observation. This mission would also complement other possible space telescopes observing in the x-ray or other bands within the next 20 years.

On the other hand, we believe the risks of the proposed *science-driven* mission could be reduced to a minimum by using advanced but mature technologies that might be further improved in the next few years. If the first satellite of this project could be launched and put into operation around 2020 as planned, it would form the world's *first and only* space VLBI network that could support ~20 μas direct imaging of supermassive black holes, AGN and other compact radio sources at 43 GHz—much higher than VSOP's 5 GHz and RadioAstron's 22 GHz. Hence the returns of this mission would be very high as such *unique* capabilities in astronomical observation could substantially broaden our knowledge and deepen our understanding of the Universe.

References

[1] Hirabayashi, H. VSOP Current Status, in *Astrophysical Phenomena Revealed by Space VLBI*, Hirabayashi H. (*eds.*), 2000.

[2] VSOP-2 计划 提案书 (Japanese version), JAXA, Jan. 2005.

[3] VSOP-2 Proposal (abridged English version), JAXA, Nov. 2005.

[4] VSOP-2 Science Goals, JAXA, April 2007.

[5] Murphy D. et al. iARISE: A Next-Generation Two-Spacecraft Space VLBI Mission Concept. ASP Conference Series, Vol. 340, 2005.

[6] JPL/NRAO. iARISE Zooming in on Black Holes: An International, Two-Spacecraft, Microarcsecond Imaging Mission, JPL/NRAO, Jan. 2002.

[7] RadioAstron User Handbook, Version 2.40, Sep. 2012.

[8] Junor W. et al. Formation of the radio jet in M87 at 100 Schwarzschild radii from the central black hole. Nature, 401 891. Oct. 28, 1999.

[9] MCP Project Overview, NRAO, Aug. 2013.

[10] Lo F. Mega-maser Cosmology Project and NRAO, NRA, Feb. 7, 2013.

[11] Takahashi, R. ApJ, 611, 996, 2004.

[12] Takahashi, R. et al. 2005.

[13] Wajima, K. Tentative Orbit Simulation for the Chinese VLBI Mission., SHAO, July 14, 2013.