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SPACE VLBI PROJECT

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ABSTRACT

The first Space-VLBI project, VSOP, started successfully with the launch of the dedicated space-VLBI satellite HALCA in 1997. The project has been in scientific operation in the 1.6 GHz and 5 GHz bands, and studies have been done mainly of the jet phenomena related to active galactic nuclei. A second generation space-VLBI project, VSOP-2, has been planned by the working group formed at ISAS/JAXA with many collaborators. The spacecraft is planned to observe in the 8, 22 and 43 GHz bands with cooled receivers for the two higher bands, and with a maximum angular resolution at 43 GHz (7 mm) of about 40 micro-arcseconds. The VSOP-2 satellite will also have the capability of the phase-reference and full polarization observations, which will produce more powerful results than those of the VSOP project. Far-future space-VLBI projects following VSOP and VSOP-2, have a large potential to achieve enough resolution and sensitivity to satisfy astronomers in future.

Key words : Space mission — VLBI — radio telescope — international collaboration

I. INTRODUCTION

It is clear that there is a limit of the baseline length due to the size of the earth, after the success of the first VLBI (Very Long Baseline Interferometry) experiment in 1967. The extension of the baseline (*e.g.,* the array size) into space requires the space radio-telescope. The first space VLBI experiment with an existing TDRSS satellite (Levy et al. 1986), was successful in 1986.

The success of the TDRSS experiment urged to start the space-VLBI project and the Japanese group with the international collaboration, finally succeeded in accomplishing the first space VLBI project, VSOP. The activities of the space VLBI projects, VSOP, VSOP-2, and other future possibilities are described here.

II. VSOP PROJECT

The Institute of Space and Astronautical Science (ISAS) started the VLBI Space Observatory Programme (VSOP) in 1989, and launched the first space VLBI satellite, HALCA, in 1997. Launch was on the maiden flight of the M-V rocket, with the satellite having a mass of 830 kg. HALCA's typical orbit has an apogee height of 21,400 km, perigee height of 540 km, inclination of 31°, and orbital period of 6.3 hours.

HALCA has an 8 m diameter center-fed Cassegrain mesh antenna suspended by a tension truss supported by six extendible masts. The on-board radio astronomy subsystem is composed of low-noise amplifiers for three frequency bands, 1.6 GHz, 5 GHz and 22 GHz, a calibration signal generator, frequency-synthesizers, down-converters, two video converters, two high speed samplers, a formatter, and a transmitter (Kobayashi et al. 2000a). The 22 GHz system temperature was found to be unexpectedly high, and we mainly made the scientific observations with 1.6 and 5 GHz bands.

For VLBI observations real-time two-way tracking support is required, with phase-transfer uplink at 15.3 GHz and data downlink at 14.2 GHz at 128 Mbps. An international network of 5 tracking stations was formed. Two-way Doppler data from these tracking stations are used for the navigation purpose.

HALCA has been operated for the VSOP project in cooperation with many organizations and radio telescopes around the world. The status of HALCA and VSOP earlier in the project has been reviewed elsewhere (Hirabayashi et al. 1998, 2000a).

The first images were produced at 1.6 GHz in June 1997 and at 5 GHz in July 1997. In April 1998, 22 GHz fringes to HALCA were first detected for the flaring water maser in Orion-KL (Kobayashi et al. 2000b).

Scientific observations are being routinely undertaken at 1.6 and 5 GHz. VSOP project announced the opportunity for submitting the proposal to all astronomers in the world, and many proposals were submitted. The project conducted about 700 observations for 7 years, and produce many papers. The survey project have also conducted.(Hirabayashi et al. 2000b, Lovell et al. 2004, Scott et al. 2004, Horiuchi et al. 2004). VSOP observations are mostly devoted to AGN. Not only jets but the shadow of plasma disks are also visible with VSOP' angular resolution. Hydroxyl (OH) masers, pulsars, and X-ray binaries are amongst other objects observed. All data of VSOP project are

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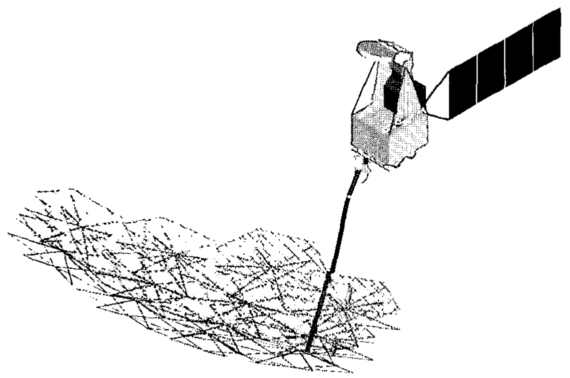

Fig. 1.— Schematic View of the VSOP-2 satellite.

open to any users after 18 months from the correlation.

HALCA has operated for about 8 years, after the launch, which were expected to have the lifetime of 3 – 5 years. Because the long time passed after the launch, some of the instruments are not working properly, and we can not maintain the 3-axis attitude control of HALCA in November, 2004. The satellite continues to be monitored and its orbital evolution tracked.

III. VSOP-2 PROJECT

(a) VSOP-2 Project Outline

A next-generation space VLBI Working Group was formed at ISAS in May 1997 after the detection of fringes in the VSOP project. Following the successes of VSOP, a near-term next generation Japanese space VLBI project, called VSOP-2, is being planned (Hirab -ayashi et al. 2000c, 2001).

The VSOP-2 science goals include: the study of the structure, collimation, magnetic field and acceleration mechanism in the AGN jets; high linear resolution observations of nearby AGN to probe the environment of accretion disks and supermassive black holes; and the highest resolution studies of spectral line masers and mega-masers, and circum-nuclear disks. Jets, masers and magnetospheres of young stellar objects will also be observed. We also expected to observe rather weaker emission sources such as, radio quiet quasars and X-ray binaries, gravitational lenses.

To achieve these scientific goal, and considering conditions imposed the M-V rocket, plans for the VSOP-2 satellite have converged as shown in Table 1, and the schematic view of the satellite is shown in Fig. 1.

Observing frequencies up to 43 GHz will allow high angular resolution observations of the optically thin emission in many AGN cores. An apogee height of 25,000 km will allow an angular resolution of 38 microarcseconds at 43 GHz, which is about 10 times higher resolution than that of VSOP, and corresponding to around 10 Schwarzschild radii at the distance of M87.

VSOP-2 is also possible to achieve about an order higher sensitivity than that of VSOP, with using the cooled low noise amplifiers, dual-polarization detection, and the wideband data transmission. In addition to those upgrades, the capability of the "phase-referencing" observation, to improve sensitivity by extending the coherence time, and to make possible astrometry, is also included in the design of the satellite. New sensitive ground radio telescopes also help to raise the VSOP-2 sensitivity. The comparison of the specifications of the VSOP and VSOP-2 satellites is shown in Table 2.

TABLE 1.
THE VSOP-2 SATELLITE DESCRIPTIONS

Satellite	
Antenna Diameter	9 m
Antenna Type	Offset Cassegrain
Weight	910 kg
Total Power	1,800 W
Attitude Control	3-axis 0-momentum
Mission Life	5 years
Launch	
Launcher	M-V
Launching Place	Uchinoura/Japan
Launch date	2011N
Nominal Orbit	
Apogee	25,000 km
Perigee	1,000 km
Orbit Period	7.5 hours
Inclination	31°
Observation System	
Observing Band	8, 22, 43 GHz
Polarization	LCP and RCP
IF Bandwidth	128 / 256 MHz
Number of IF channels	2
Uplink (phase link)	40 GHz CW
Data downlink	37-38 GHz, OFDM/QPSK
Downlink data rate	1 Gbps
Tracking network	
Command station	Uchinoura (Japan)
Tracking stations	JAXA/NASA/ESA/NRAO

The international cooperation and coordination required for VSOP observations make it one of the most complex space science missions undertaken, and a lot has been learned for future space VLBI missions. A similar level of collaboration will be essential for VSOP-2. It is expected that east Asian telescopes in China, Japan and KVN in Korea will be one of the major arrays that will coobserve with the VSOP-2 satellite, like VLBA, EVN and SHEVE in the VSOP project.

(b) VSOP-2 Instrumental Developments

There are several key instrumental items for space VLBI, and these are outlined in the following subsections.

TABLE 2.

	VSOP	VSOP-2
Ant. Diameter	8m	9m
Apogee Height	21,500 km	25,000km
Period	6.3 hours	7.5 hours
Polarization	LCP	LCP/RCP
Downlink Rate	128 Mbps	1 Gbps
Bands (GHz)	1.6, 5, (22)	8, 22, 43
Resolution	0.3 mas	0.038 mas
Sensitivity (mJy)	140 (5GHz)	23 (8GHz)
		50 (22GHz)
		107 (43GHz)
Phase-reference sensitivity (mJy)		8 (22GHz)
Launch	1997 Feb.	2011 (target)

Comparison of thespecifications of the VSOP and VSOP-2 satellites. Sensitivities are calculated, assumed that 7-σ fringe detection with the VLBA 25 m antenna. These are largely changed with the observing condition. We assumed 1.5 hour integration time is possible by phase-reference observation, and show only VSOP-2 22 GHz case.

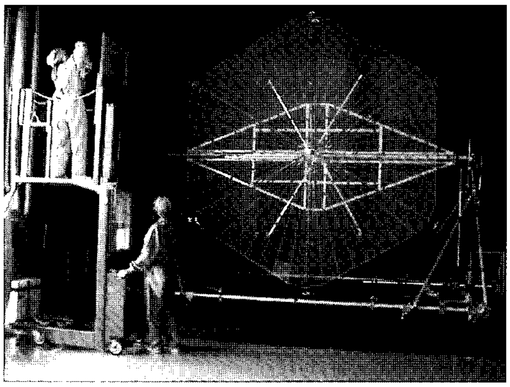

Fig. 2.— A full-scale model of one of seven modules of the projected VSOP-2 antenna. There are 48 radial ribs which help shape the parabolic surface and support the surface mesh with the cable truss. Surface accuracy is measured by taking pictures.

i) High Accuracy Deployable Antenna

The on-board large deployable antenna for radio astronomy at the wavelength of 7 mm, is one of the key parts of the spacecraft. We should make this antenna lighter, smaller and more reliable enough to use in space.

The backup and deployment structure is based on the ETS-VIII project antennas, which are scheduled to be launched by JAXA. VSOP-2 antenna consists of 7 hexagonal modules. The radial ribs structure is newly adopted for the VSOP-2 antenna modules to help to shape a surface accuracy as high as 0.4 mm rms. Both main and sub reflectors have the adjustment mechanism, which allows us to adjust the optics of the antenna after the deployment in the orbit.

The development of the antenna has been in progress over the last four years at ISAS. We made a full-scale model of the rib-type antenna module to confirm that we can achieve the module accurate enough (Fig. 2).

ii) Low Noise Receiver System

VSOP-2 satellite will be operated at 8, 22 and 43 GHz. This is one of the key unit to improve the VSOP-2 sensitivity. Both LHCP and RHCP signals are detected for the polarization observations and to get more sensitivity. Low noise amplifiers and the polarizers in 22 and 43 GHz band will be cooled at the physical temperature of 30 K using the cryogenic coolers, which is developed for ASTRO-F mission.

We have already developed GaAs MMIC LNA possible to use for this system, but we continue to investigate the possibility to use InP MMIC LNA with lower noise figure and lower power consumption.

iii) High Speed Data Sampling in Space

One of the problems for VSOP-2 is how to sample the data on-board, if we follow the same approach as HALCA. We assume a giga-bit rate of data sampling to obtain the desired sensitivity. We tested a 10 Gbps, 1 bit sampler and a 1:16 de-multiplexer, to demonstrate a possible solution for the on-board high speed sampler. We carried out a 1000 krad total dose test and a single event test. We confirmed we can use those LSI's on the VSOP-2 orbit. (Wajima et al. 2002)

iv) Wide Band Data Downlink and Phase Transfer Uplink

The frequency band usable for the 1 Gbps VLBI data link is 37–38 GHz (down-link), and for the (up-link) reference frequency is 40 GHz according to international frequency allocation. We studied the link budget, and found that the condition is more severe than that of HALCA Ku link, but still it is possible. We adopt the OFDM (Orthogonal Frequency Division Multiplex) method with multi-channel QPSK (Quadrature Phase-Shift Keying) modulation, to allow the CMOS type circuit for the modulator, and reduce the emission in the outband of the transmitting band.

By the time of the launch of the VSOP-2 satellite, a number of new arrays and telescopes will also be in operation, with 1 Gbps and higher recording widely available.

v) Requirements for Phase Referencing Observation

VSOP-2 satellite realizes the phase referencing observation with the fast switching observations with nodding of the whole spacecraft quickly between the calibrator and target sources. It is possible with the addition of 2 Control Moment Gyro (CMGs) as a high torque actuator, to the 4 momentum reaction wheels

(RWs), which are used for background 3-axis stabilization and for compensating residual CMG motion while nodding. This complicated momentum control logic, including the soft structure of the large antenna, has been simulated for VSOP-2.

For phase-referencing observations, orbit accuracies of 2-3 cm are required. Orbit determination of a few-cm accuracy could be achieved by adding GPS receivers with a high precision 3-dimensional accelerometer, or by using both GPS and Galileo receivers. Simulations performed at JPL for the VSOP-2 orbit(Wu & Bar-Sever 2001) show that a $\sim$2 cm orbit accuracy can be realized.

vi) Overall Satellite System Design

The satellite system design is also investigated, based on the requirement from the observation. Mass budget, power budget, and thermal condition on the orbit have already studied. Design of the bus system of the satellite is similar to that of HALCA, but newly developed units are introduced in the design. We can move to the detailed design based on the modelling study.

(c) Current Status of the Project

The VSOP-2 project proposal was submitted to ISAS Science Steering Committee in October, 2003. Finally no proposal went to the next step, even though the evaluation committee commented the proposals are good enough. Development funding for 2004 FY will be approved, and we prepared the next proposal for the next evaluation process.

The space VLBI project office for the VSOP-2 project started in NAOJ. NAOJ and ISAS will be the core institute for the VSOP-2 project, as we did in the VSOP project.

IV. VSOP-n (n>2) PROJECTS

We are working very hard with the actual space VLBI project, VSOP-2. The space VLBI project has infinite possibilities. Here we describe the possibilities of the space VLBI (or space array) project in future.

Space–space baseline Both VSOP and VSOP-2 assumed that one of the VLBI radio telescopes is in space, and others are on ground. Multiple space radio telescopes in space, means that we can get the first space-space baseline, which is free from the atmospheric effect. It is also possible to get better UV coverage if we can select better orbit for the UV coverage. We can achieve this in near future, if another space VLBI project goes at the same tile as VSOP-2.

Higher frequency It is natural consideration that to make observation in sub-millimeter wavelength in space, to avoid the atmospheric effect. There is an effort for sub-millimeter VLBI on the ground, but the possible sites for such VLBI observation are very limited on the ground. We should also make effort to have the space sub-millimeter array in parallel.

Higher sensitivity The size of the space antenna is limited by the launcher. However, we can construct the radio telescope in a space factory in the future. We can make a telescope larger than that on the earth, under the non-gravity condition.

Extremely longer baseline We can extend the baseline while the space technology is being developed. Space is almost infinite.

We have presented the current status and the future possibilities about the space VLBI projects. The requirement of the astronomers seems to be infinite. We think the possibility of the space VLBI or the radio interferometry in space is also has the infinite possibility. All current activities for the space VLBI project should be connected larger and more exciting future projects.

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