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On the Near-term Space VLBI Mission VSOP-2

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Abstract. A second generation near-term space VLBI mission, VSOP-2, is being planned for a launch in 2010 or soon after. The scientific objectives are very high angular resolution imaging of astrophysically exotic regions, including the cores, jets, and accretion disks of active galactic nuclei (AGN), water maser emissions, micro-quasars, coronae of young stellar objects, etc. A highest angular resolution of about 40 μas is achieved in the 43 GHz band. Engineering developments are in progress for the deployable antenna, antenna pointing, high data rate transmission, cryogenic receivers, accurate orbit determination, etc., to realize this mission. International collaboration will be as important as it has been for VSOP.

1. Introduction

Following the successes of the VLBI Space Observatory Programme (Hirabayashi et al. 1998, 2000), a near-term next generation Japanese space VLBI mission, currently referred to as VSOP-2 (Hirabayashi et al. 2001; Hirabayashi 2004), is being planned in collaboration with international partners. The VSOP-2 website is http://www.vsop.isas.jaxa.jp/vsop2/ .

2. VSOP-2 Science Goals

The VSOP-2 science goals include: study of emission mechanisms in conjunction with the next generation of X-ray and gamma-ray satellites; full polarization studies of magnetic field orientation and evolution in jets, and measurements of Faraday rotation towards AGN cores; high linear resolution observations of nearby AGN to probe the formation and collimation of jets and the environment around supermassive black holes (e.g., Figure 1); and the highest resolution studies of spectral line masers and mega-masers, and circum-nuclear disks.

The VSOP mission has made important contributions to the study of jets (e.g., Piner et al. 2000; Lobanov & Zensus 2001; Murphy et al. 2003) and plasma torii (Jones et al. 2001; Kameno et al. 2003), but the VSOP-2 mission can pin point the more fundamental inner region by its higher observing frequency and by higher angular resolution. In the nearby AGN M87, the 40μas beam can discern the relative locations of the black hole, accretion disk, and postulated shock regions.

Magnetic field structures of young stellar objects by non-thermal gyro-synchrotron emissions is a new area to be studied in detail (see Figure 2). The X-ray satellites TENMA and GINGA detected hard X-ray emissions from molecular clouds (Koyama 1987, Koyama et al. 1992), and ASCA detected quasi-periodic flare from the proto-star YLW15A (Tsuboi et al. 2000), suggesting reconnection of magnetic fields connecting the star and its accretion disk. Such a new scientific area could be investigated by VSOP-2, for example.

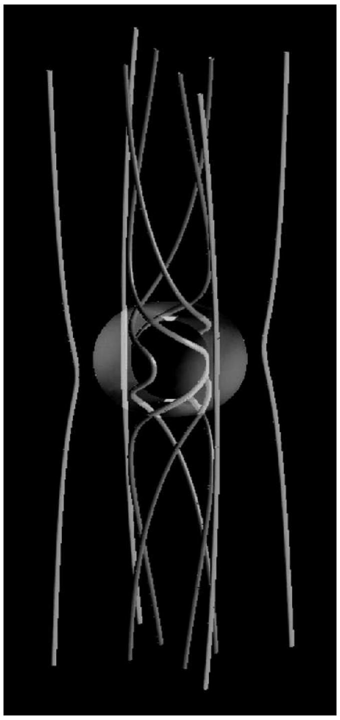

Fig. 1. Magneto-Hydro-Dynamic (MHD) simulation of the magnetic field structure around a black hole (from Koide et al. 2002).

By both the superb angular resolution and magnetic field information, theory and magneto-hydrodynamic simulations can be guided and tested in these astronomical objects.

3. VSOP-2 Instrumental Capabilities

To realize the near-term space-VLBI mission VSOP-2 and make it scientifically valuable, we have three basic improvements over VSOP as follows:

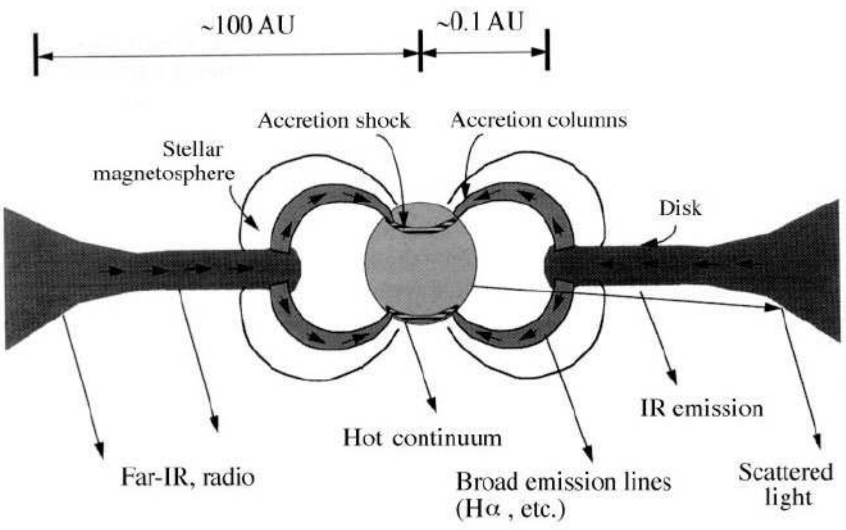

Fig. 2. Schematic diagram of the scales and processes in young stellar objects (from Hartman 1998).

1. an order of magnitude increase in the maximum observing frequency, from 5 GHz to 43 GHz, allowing detailed imaging deeper into the emitting plasma
2. an order of magnitude increase of maximum angular resolution, to $\sim 40\,\mu$as, using the above frequency and a 25,000 km apogee height. This apogee height with 1,000 km perigee height is selected from the consideration of good imaging orbit with the ground array.
3. an order of magnitude increase in interferometer sensitivity for continuum observations. This is accomplished mainly by the 8 times higher bit rate and the lower system noise temperatures.

These are shown quantitatively in Table 1. The observing bands will be 8, 22, and 43 GHz and the receivers for the 22 and 43 GHz bands will be cooled.

VSOP-2 can receive both sense of polarizations (LHCP and RHCP) simultaneously within the limitation of 1 Gbps data transfer. This will enhance polarization mapping capability. HALCA, on the other hand, received and transferred only LHCP, but scientific observations were successfully performed using simultaneous LHCP and RHCP ground observations (e.g., Kemball et al. 2000; Gabuzda & Gómez 2001; Gabuzda 2003).

Observations at 22 GHz were planned with HALCA, but due (most likely) to damage to the wavelguide connection during launch, open scientific observations were not possible. Water vapour maser and mega-maser studies with space VLBI resolution thus remain a new area for VSOP-2.

4. The VSOP-2 Satellite

The VSOP-2 spacecraft will employ a 9 m off-axis paraboloid antenna. It is assumed the VSOP-2 satellite will be launched on a M-V rocket and placed in an elliptical orbit with an apogee height of ~25,000 km and a perigee height of ~1,000 km, resulting in a period of ~7.5 hours. Unlike HALCA, the VSOP-2 satellite will receive both LCP and RCP, and use cryogenic coolers for the two higher frequency bands. Observing requires a two-way link between the satellite and a tracking station, for a wideband down link at 1 Gbps, and with the uplink used to transfer a reference signal. The current spacecraft mass estimate is 910 kg (wet), with a generated power of 1800 W.

5. New Technical Aspects for VSOP-2

The on-board radio astronomy antenna is one of the most critical parts of the spacecraft. The development of an off-axis mesh antenna with a segmented (modular) radial rib design has been in progress over the last four years at ISAS. The backup and deployment structure is based on the ETS-III project antennas, which are scheduled to be launched in 2006. To achieve a surface accuracy as high as 0.4 mm rms, radial ribs will help shape the surface without too much cable structure. HALCA's antenna was designed for use with 22 GHz as the highest observing frequency, and there was no adjustment mechanism in orbit. The VSOP-2 satellite will have in-orbit adjustment mechanism with 3 degrees of freedom for main-reflector and 2 degrees of freedom for the sub-reflector.

The frequency band for the 1 Gbps VLBI data down-link is 37–38 GHz, and the up-link reference frequency is 40 GHz. The use of both senses of polarization will help for the maximum use of the allocated band. Studies and trade-offs have been done taking into account both the quantization loss, circuitry complexity, and down-link power, with the current design employing QPSK modulation with OFDM (orthogonal frequency division multiplexing) frequency synthesis.

Phase-referencing observations remove atmospheric phase fluctuations and consequently can increase the coherence time. Although this capability was not considered in the original VSOP mission design, successful 'in-beam' phase-referencing observations have nevertheless been carried out with the quasar pairs 1308+326 and 1308+328, separated by 14.3′ (Porcas

Table 1. Comparison of VSOP-2, VSOP and VLBA

	$VSOP-2$	$VSOP$	$VLBA$
Antenna diameter	$9m$	$8m$	$25m$
Apogee height	$25000km$	$21500km$	$0km$
Orbital period	$7.5hr$	$6.3hr$	$24hr$
Polarization	LCP/RCP	LCP	LCP/RCP
Data downlink	$1Gbps$	$128Mbps$	$512Mbps$
Observing frequencies (GHz)	$8, 22, 43$	$1.6, 5$	...$1.6, 2, 5, 8, 15, 22, 43, 86$
Highest resolution	$38\mu as$	$360\mu as$	$96\mu as$
Sensitivity (5/8 GHz)	$22mJy$	$158mJy$	$7.9mJy$
Sensitivity (22 GHz)	$39mJy$	...	$23mJy$
Phase-referencing 22 GHz (for a 1.5 hr integration)	$9.1mJy$	...	$5.3mJy$
Launch	$2010(proposed)$	$Feb1997$	...

et al. 2000) and 1342+662 and 1342+663, separated by 4.8′ (Guirado et al. 2001).

Nodding of the whole spacecraft quickly between the calibrator and target sources is possible with the addition of 2 Control Moment Gyroscopes (CMGs) to the 4 momentum reaction wheels (RWs). For such phase-referencing observations, orbit determination accuracy of a few cm is required, and this could be achieved by adding GPS receivers with a high precision 3-dimensional accelerometer, or by using both GPS and Galileo receivers, according to simulations performed at JPL for the VSOP-2 orbit.

6. VSOP-2 Proposal Status

The VSOP-2 proposal was submitted to ISAS in October 2003, at the same time as the hard X-ray mission NeXT. Both missions were highly ranked, but ultimately, due to ISAS' near-term budget profile for the next few years, neither was included in the budget request for the 2005 fiscal year. ISAS is preparing a long-term strategic plan connected with future budget requests. VSOP-2 will be re-submitted in the next proposal round.

7. VSOP-2 International Collaboration

VSOP was realized with large international collaboration in terms of ground telescope arrays and correlators, and with VLBI tracking stations. The same kind of model is assumed for VSOP-2. We had rather small-scale collaboration from Asian countries for VSOP, but the Japanese 4-station VERA (VLBI Exploration of Radio Astrometry) and the 3-station Korean VLBI Network (KVN) will be capable at 8, 22 and 43 GHz before the VSOP-2 launch. The possibility of the Shanghai and Urumqi antennas having higher frequency upgrades is also being considered, and there is a preliminary discussion of part-time east-Asian network in the future (Shen et al. 2004).

Realization of tracking stations network with supports from space agencies is important, and one promising possibility is that a decommissioned European antenna can be modified to work as a tracking station. The ongoing support and assistance from international community will be required for the submission and realization of the project.

After VSOP-2, we can think of far future missions like mm, sub-mm space VLBI, multi-element space mission, etc. VSOP-2 will serve as a precursor for these both from scientific and instrumental point of view. X-ray interferometry mission in space is under consideration (MAXIM), and X-ray fringes have been detected in the laboratory. But radio interferomery is far more advanced, and lots more should be done before an X-ray interferometry mission becomes possible. We hope that we can realize this mission to go further to prove exotic phenomena like strong general relativistic effects around super-massive black holes, and so on.

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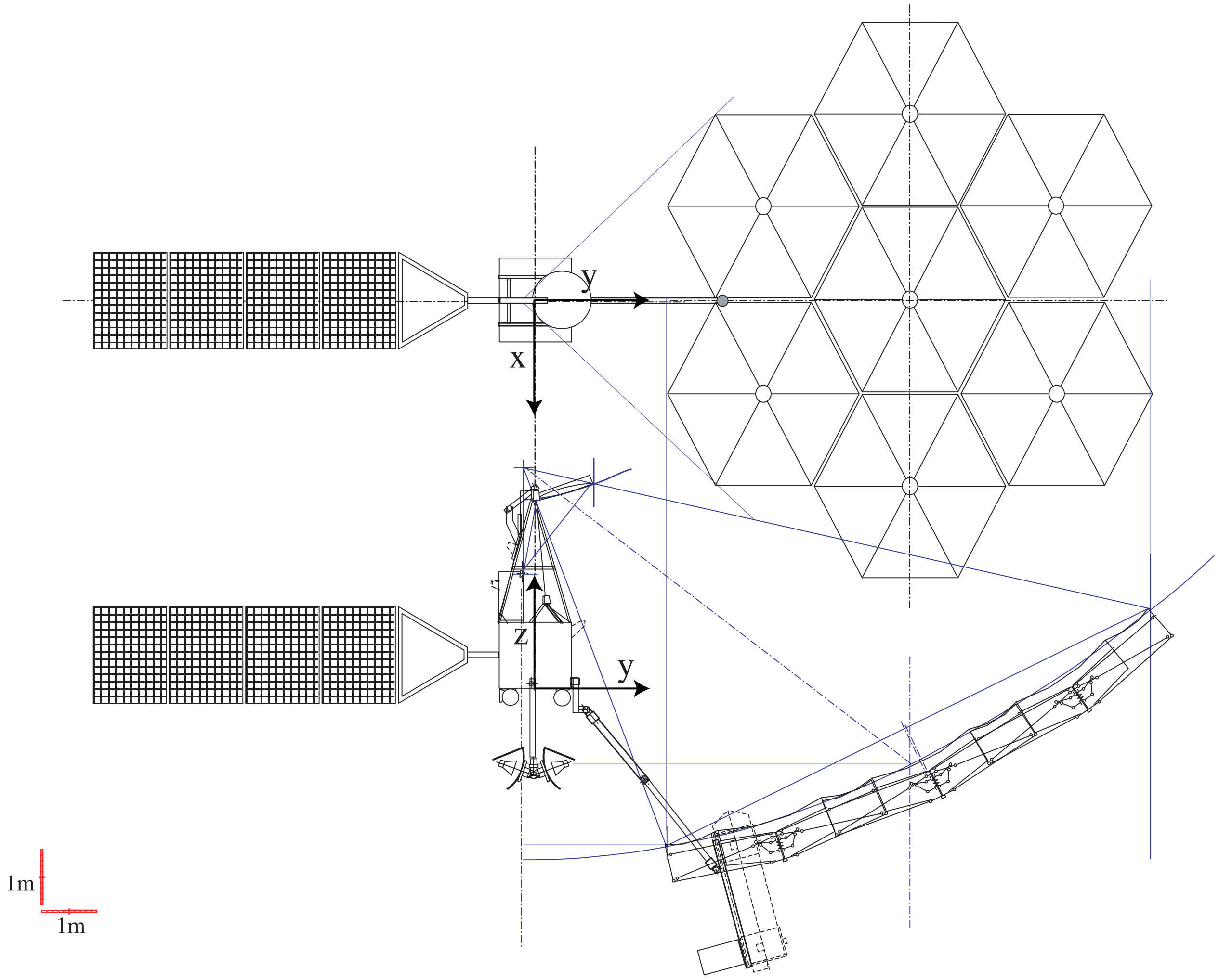

Fig. 3. The present design for the VSOP-2 spacecraft with a 9 m diameter offset Cassegrain antenna of seven hexagonal modules. The *z*-axis is along the antenna boresight direction. The main reflector, sub-reflector, high gain tracking station ("link") antenna, and solar paddle are deployed in orbit. (Two link antennas are shown to illustrate the range of movement of this single antenna.)

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