Hisashi Hirabayashi et al.: The VSOP-2 Space VLBI Mission, IVS 2002 General Meeting Proceedings, p.171–174
http://ivscc.gsfc.nasa.gov/publications/gm2002/hirabayashi

The VSOP-2 Space VLBI Mission

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Abstract

Following the success of the VLBI Space Observatory Programme (VSOP), a next generation space VLBI mission, VSOP-2, is currently being planned. Higher observing frequencies, cooled receivers, increased bandwidths and larger telescope diameters will result in gains in resolution and interferometer sensitivity by factors of ∼10 over the VSOP mission. The use of phase-referencing by fast switching between a calibrator source and the target source is now being studied as this technique allows sources 50–150 times weaker to be observed depending on the frequency band. Such a capability would greatly enhance the VSOP-2 mission. Several other enhancements to the VSOP-2 mission are also presently under investigation including the VSOP-2 spacecraft operating at the same time as a U.S. spacecraft to form what has come to be known as the iARISE (international ARISE) mission.

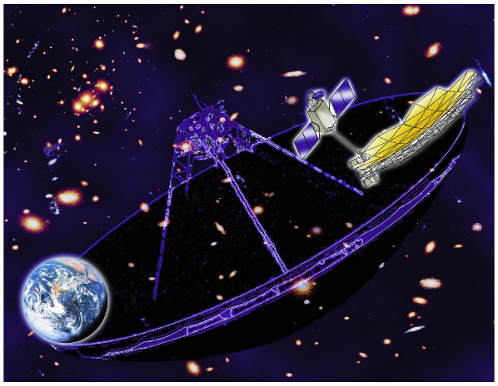

Figure 1. Artist's conception of the VSOP-2 mission illustrating how a spacecraft in orbit can create a synthetic aperture several Earth diameters in size.

1. Introduction to Next Generation Space-VLBI Mission VSOP-2

Space VLBI synthesizes a telescope larger than the Earth as illustrated in Figure 1 for the case of the VSOP-2 mission. ISAS's launch of the HALCA satellite in 1997, as part of the VLBI Space Observatory Programme (VSOP), has allowed sub-milli-arcsecond–scale imaging at 1.6 GHz and 5 GHz ([1],[2]). In addition, successful detection of space-ground fringes at 22 GHz confirmed that there will be no major problems extending space VLBI to shorter wavelengths in the future. Planning for a next generation space VLBI mission, currently designated as VSOP-2, is well underway ([3]). The VSOP-2 spacecraft will have a 10m-class antenna with cryogenically cooled low-noise receivers and a downlink data rate of at least 1 Gbps, resulting in an improvement of an order of magnitude in interferometer sensitivity over the VSOP mission. Observing frequencies up to 43 GHz will allow high angular resolution observations of the optically thin emission in many AGN cores. An angular resolution of ~25 micro-arcseconds at 43 GHz will be achievable, corresponding to ~10 Schwarzschild radii at the distance of M87.

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 the success of VSOP-2. Submission of the VSOP-2 proposal to ISAS will take place within the next year and consequently launch on an ISAS M-V rocket could be as early as 2009.

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; and the highest resolution studies of spectral line masers and mega-masers, and circum-nuclear disks.

3. VSOP-2 Phase-Referencing Capability

Phase-referencing observations remove atmospheric phase fluctuations and consequently can increase the coherence time and hence allow weaker sources to be detected. Although this capability was not considered in the ordinal VSOP mission design nevertheless successful ‘in-beam’ phase-referencing observations have been carried out with the quasar pair 1342+662/1342+663 separated by $4.8'$ ([4],[5]). Furthermore the VERA array of the National Astronomical Observatory of Japan, which consists of four 20 m antennas with dual beam systems will enable phase-referencing technique to be explored in great depth. It is therefore very desirable that the VSOP-2 spacecraft have such a capability at all observing bands as this will greatly enhance the science return from the mission and make it more exciting to the wider astronomical community as it will allow a wider range of astrophysical phenomena to be observed and for astrometric experiments to be undertaken.

Table 1. Comparison of VSOP-2 Detection Limits with and without Phase-Referencing

Frequency (GHz)	Coherence Time (τ_c) (min)	No Phase-Referencing 5-σ Detection Limit (mJy)	Phase-Referencing 3-σ Image Noise Level (mJy/beam)
5	10	2.8	0.06
8	6	4.7	0.08
22	2	19.0	0.18
43	1	47.0	0.31

A rough estimate of the atmospheric coherence times and the VSOP-2 detection thresholds (without phase-referencing) are shown in the second and third columns of Table 1. The use of water vapor radiometers to measure directly the short term changes in the tropospheric path length may help extend the coherence time considerably and hence lower the detection thresholds. Combining radio source count data and information from the VSOP 5 GHz survey on the source visibility function on ground-space baselines, we have estimated, as shown in the fourth column of Table 1, the image noise level in a 12-hour phase-referencing observation with the VLBA. By using phase-referencing techniques we not only increase the effective coherence time but we coherently use data from all baselines to detect the target source. These two effects combined reduce the detection threshold by the factor $\approx 150/\sqrt{\tau_c}(\mathrm{min})$ compared to non phase-referencing observations. Phase-referencing is easier at lower frequencies because the separation between target and calibrator sources are typically only a few primary beam widths or a few degrees. With the nominal VSOP-2 parameters, phase-referencing is feasible at 22 GHz and below but becomes challenging at 43 GHz.

4. Current VSOP-2 Spacecraft Design Parameters

The VSOP-2 spacecraft will be three-axis stabilized, and will probably employ a 10–12 m diameter off-axis paraboloid antenna. The observing bands will be 5 or 8, 22, and 43 GHz, with the highest frequency placing stringent requirements on the surface accuracy on the mesh surface of the antenna (≈0.3 mm RMS). The VSOP-2 satellite will be placed in an elliptical orbit with an apogee height of ∼30,000 km and a perigee height of ∼1,000 km, resulting in a period of ∼8 hours. Unlike HALCA, the VSOP-2 satellite will detect both LCP and RCP, and use cryogenic coolers to reduce the system temperature. Observing requires a two-way link between the satellite and a tracking tracking station. The link frequency bands that will be used are the 37–38 GHz band for the wideband down link at 1 Gbps or more, and 40 GHz for the uplink used to transfer a ground-generated ultra-stable reference signal. Currently studies are being undertaken into the antenna design and the high speed backend digital electronics ([6]).

One method of implementing phase-referencing observations is the nodding of the whole spacecraft quickly between the calibrator and target sources. Such fast slewing of the spacecraft may be possible with the use of 4 large momentum reaction wheels (RWs), and the addition of two Control Moment Gyroscopes (CMGs). This configuration does not impose too much of a penalty on the mass and power budgets but does require more complicated attitude control logic.

5. Current Ground Support System Design Parameters

VSOP observations are supported by a network of five tracking stations ([1]), however as only one of these is located in the southern hemisphere, significantly less tracking coverage was available when HALCA's apogee is in the south. Potential solutions for VSOP-2 include the addition of an ESA tracking station in Malindi, Kenya, or a tracking station near the ALMA site in Chile.

Over 25 ground telescopes and arrays from over 12 countries have participated in VSOP observations ([2]). By the time of the launch of the VSOP-2 spacecraft a number of new arrays and telescopes will also be in operation, with 1 Gbps and higher recording widely available. VSOP data is being correlated at the VSOP correlator (Japan), the VLBA correlator (USA) and the S2 correlator (Canada). Upgrades to all three will be required for the correlation of VSOP-2 data. In addition, the JIVE MkIV correlator (the Netherlands) may also be upgraded to handle space VLBI data.

6. Orbit Accuracy Requirements

For phase-referencing observations orbit accuracies of $\approx$ 120 cm (5 GHz), 50 cm (8 GHz), 6.5 cm (22 GHz) and 1.8 cm (43 GHz) are required, and to detect H_2O maser proper motions in AGN requires a 2 cm accuracy. With HALCA, using 2-way Doppler tracking, 3–10 m orbit accuracy has been achieved but this may be the limit of this technique. However, better orbit determination accuracy can be achieved by adding GPS receivers and a high precision accelerometer, even though the GPS coverage is limited for the VSOP-2 orbit. Simulations performed at JPL for the VSOP-2 orbit show that a $\approx$ 2 cm orbit accuracy can be realized by installing a JPL-developed GPS receiver package (2.5 kg, 20 W) which includes a 3-dimensional accelerometer (20 kg, 8 W) with 0.1 mm s^{-2} accuracy.

7. A Two Spacecraft Mission?

Apart from phase-referencing another way to greatly enhance any space VLBI mission is to use more than one spacecraft. A 2-spacecraft mission (named iARISE) has recently been studied in the U.S. ([6]) and offers several advantages over a single spacecraft mission. The primary advantage being that high resolution observations over the whole sky can be obtained at all epochs. One realization of the iARISE 2-spacecraft concept is that the VSOP-2 spacecraft would be one spacecraft of the i-ARISE pair with the other being provided by non-Japanese space agency such as NASA. Alternatively, VSOP-2 might be a precursor which fully demonstrates the techniques, such a phase-referencing, which the iARISE mission needs.

8. Acknowledgments

VSOP-2 is a collaborative project led by ISAS involving many institutions in many countries and the authors gratefully acknowledge the work undertaken by many people in preparing for the VSOP-2 mission.

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