The VSOP Mission

By HISASHI HIRABAYASHI

ISAS, Yoshinodai 3-1-1, Sagamihara, Kanagawa 229-8510, Japan

The radio-astronomy satellite HALCA was launched on 12 February 1997, and the VLBI Space Observatory Programme (VSOP) mission has since made over 500 observations of active galactic nuclei (AGN). A brief review of the project and its contributions to AGN science are given.

1. Introduction

The Institute of Space and Astronautical Science (ISAS) launched the first space VLBI satellite, HALCA, on 1997 February 12. After completing a series of engineering experiments, the first VLBI fringes and images were obtained in May and June 1997, respectively. If historical remarks are allowed at such a scientific meeting, the year of HALCA's launch was half a century after the first detection by the cliff-top interferometer in Sydney (Bolton and Stanley 1948), and 30 years after the first VLBI experiments in 1967. The first space VLBI experiment with TDRSS was made in 1986 (Levy et al. 1986), paving the way for dedicated imaging space VLBI to come 10 years later. HALCA is being operated for science observations at 1.6 and 5 GHz for the VSOP (VLBI Space Observatory Programme) project in cooperation with many organizations and radio telescopes around the world. HALCA's status earlier in the mission has been reviewed by Hirabayashi (1998), Hirabayashi et al. (1998), and Hirabayashi and Hirosawa (2000).

2. The HALCA Satellite, Performance and In-Orbit-Checkout

HALCA's orbit has an apogee height of 21,400 km, perigee height of 560 km, inclination angle of 31°, and orbital period of 6.3 hours. The 8 m main reflector and the sub-reflector supporting structure were deployed in orbit. An artist's impression of the deployed satellite observing in concert with a number of ground telescopes in shown in Figure 1.

The on-board radio astronomy subsystem is composed of low-noise amplifiers for three frequency bands, 1.60–1.73 GHz, 4.7–5.0 GHz and 22.0–22.3 GHz, down-converters, two video converters, two high speed samplers, a formatter, two frequency-synthesizers, and a calibration signal generator (Hirosawa and Hirabayashi 1997, Kobayashi et al. 2000a).

The HALCA radio-telescope has typical system temperatures of 75 K at 1.6 GHz and 95 K at 5 GHz, with an antenna aperture efficiency of about 30% at 1.6 GHz. The 22 GHz system temperature is unexpectedly high, and it is thought that the 22 GHz waveguide connecting the feed horn and the front-end may have been impaired during launch.

After a series of experiments as an engineering satellite — deployment of the 8 meter antenna, precise attitude control of spacecraft with a large antenna, transfer of phase reference signal, high data rate telemetry, etc. — the Usuda 64 m antenna and HALCA, via Usuda 10m tracking antenna, observed the quasar PKS 1519−273 at 1.6 GHz on 1997 May 7. The tapes were processed with the VSOP correlator at the National Astronomical Observatory (NAO), Mitaka, and the first HALCA-ground fringes were found on May 13. Subsequent three station interferometry with HALCA, the Usuda 64 m antenna and the Kashima 34 m showed stable closure phases.

In mid-June 1997, the first 1.6 GHz images were generated and in July the first 5 GHz images were produced at the VLBA (Very Long Baseline Array) correlator and an angular resolution of $\sim$0.3 mas achieved.

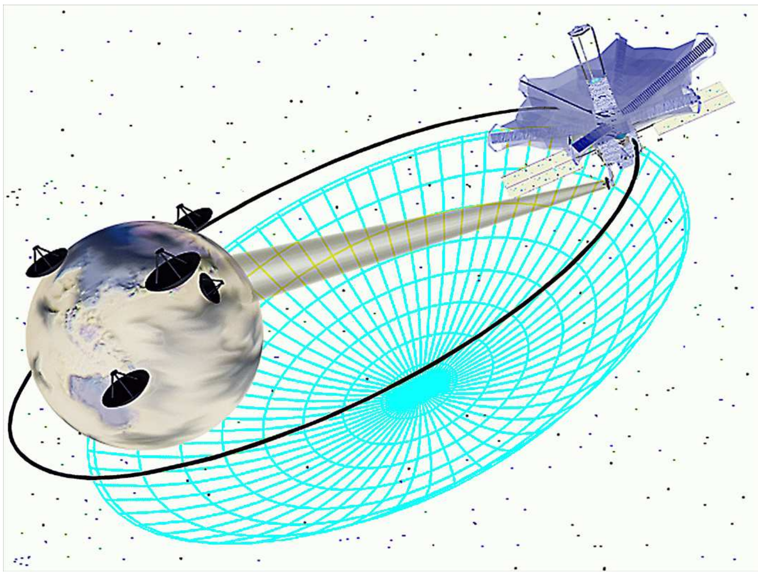

Figure 1. The HALCA satellite co-observing (via a real-time two-way link with a tracking station) with ground radio telescopes for VLBI Space Observatory Programme (VSOP) observations.

In April 1998, 22 GHz fringes to HALCA were first detected at Socorro for the bursting water maser in Orion-KL (Kobayashi et al. 2000b). HALCA has had some operational problems resulting in a observing being stopped because of telemetry signal loss, attitude control loss, etc. However, as far as electric power is concerned, it seems HALCA will be able to operate for at least five years from launch.

3. VSOP International Operation

HALCA is commanded from the Sagamihara Operations Center at ISAS by 2.1 GHz telemetry through the Kagoshima Space Center. For VLBI observations real-time two-way telemetry support with phase-transfer uplink at 15.3 GHz and data downlink at 14.2 GHz at 128 Mbps is required, and so, five 15 GHz-band tracking stations are employed: at Usuda (Japan), operated by ISAS; Goldstone (USA), Madrid (Spain), and Tidbinbilla (Australia) operated by NASA/JPL; and Green Bank (USA), operated by NRAO. Range-rate data from this ground telemetry network is also used for ISAS and JPL orbit determination (Hirabayashi et al. 2000).

A number of ground radio telescopes have committed time for simultaneous observations with VSOP. The commitments of ground radio telescopes have been negotiated through the Global VLBI Working Group (GVWG), formed under URSI Commission J. Participating telescopes include those of the European VLBI Network (EVN), the Very Long Baseline Array (VLBA), and individual telescopes.

The recording format of the VLBI data is dependent upon the ground facilities involved. Three different tape formats are used: S2, VSOPT and VLBA/MkIV. Depending on the participating ground telescopes, VSOP observations are correlated at the 10-station VSOP correlator in Mitaka, the 20-station VLBA correlator in Socorro, the 6-station S2 correlator in Penticton. Experiments involving two or more formats require conversion of some tapes at Mitaka, which has two S2/VSOPT and two VLBA/VSOPT bi-directional copiers.

Year	GOT observations	Survey observations	Test observations	Total
1997	49	20	25	94
1998	109	65	9	183
1999	183	45	9	237
Total	341	130	43	514

TABLE 1. Summary of VSOP Observations to January 2000

4. Overall Science Activities of VSOP

Scientific observations are classified into two categories; the peer reviewed General Observing Time Program and the mission-led Survey Program. The Survey Program deals with a statistical sample of nearly 300 sources, observed at 5 GHz with ~3 ground telescopes over ~6 hours, and is described in more detail by Fomalont et al. (2000) Moellenbrock et al. (2000) and Lovell et al. (2000a).

Scientific observations are being routinely undertaken at 1.6 and 5 GHz. A summary of VSOP observing to January 2000 is given in Table 1. About fifty Survey Program observations have been extracted from GOT observations, and so the grand total of observed Survey sources is now 180 sources (Fomalont et al. 2000). Of the GOT observations, 131.5 were made at 1.6 GHz and and 209.5 at 5 GHz (with one observation conducted simultaneously at 1.6 and 5 GHz).

5. AGN Continuum Results from the VSOP Mission

In this section, results of VSOP observations of AGN phenomena are presented.

VSOP observations of M87 will be able to quantify how the jet sub-structure evolves with time. The first VSOP image at 1.6 GHz shows a helical structure (Reid et al. 2000). A more recent 1.6 GHz observation made in March 2000 (Reid et al. private communication) shows limb-brightened structure of the jet. VSOP monitoring observations at 5 GHz do not show the $6c$ movement which is seen in the outer jets by HST (Junor et al. 2000). It is worth mentioning that the VSOP beam at 5 GHz is 300 times the Schwarzschild radius of suspected super-massive black hole revealed by the HST spectral observation.

HALCA receives only LHCP, but with dual polarisation ground observations VSOP can make polarisation observations to provide a unique opportunity to better resolve spatial variations in magnetic field structures. VSOP polarization observations (Gabuzda et al. 1999) revealed a twisted jet in the AGN 1803+784, with the magnetic field remaining perpendicular to the jet direction all along the bent structure.

VSOP has the same resolution with the ground VLBI with 3 times higher frequency. Spectral mapping with matched resolution allows information on the optical thickness, spectral aging, etc. to be determined. The sources studied with this technique include 3C 279 (Piner et al. 2000), 3C 84 (Asada et al. 2000) and Mkn 501 (Edwards et al. 2000). Free-free absorption of radiation from the counter-jet of NGC 4261 in the sub-parsec accretion disk was clearly seen with the use of a 4.9 GHz VSOP image and ground-based VLBI images (Jones et al. 2000). Similar studies have been made of a number of GPS sources also (Snellen et al. 2000; Kameno et al. 2000).

It is now known that synchrotron photons at radio wavelengths are related to X- and gamma-rays by the inverse-Compton effect. A second-epoch VSOP observation of

PKS 0637−752 was made in August 1999, coordinated with the calibration observation of Chandra soon after its launch. Chandra astonishingly discovered a jet consistent with the ATCA radio image (see Figure 2), and the second-epoch VSOP observations was used to confirm the $\sim 11c$ super-luminal motion in the parsec-scale jet inferred after the first-epoch VSOP observation (Tingay et al. 2000, Lovell et al. 2000b).

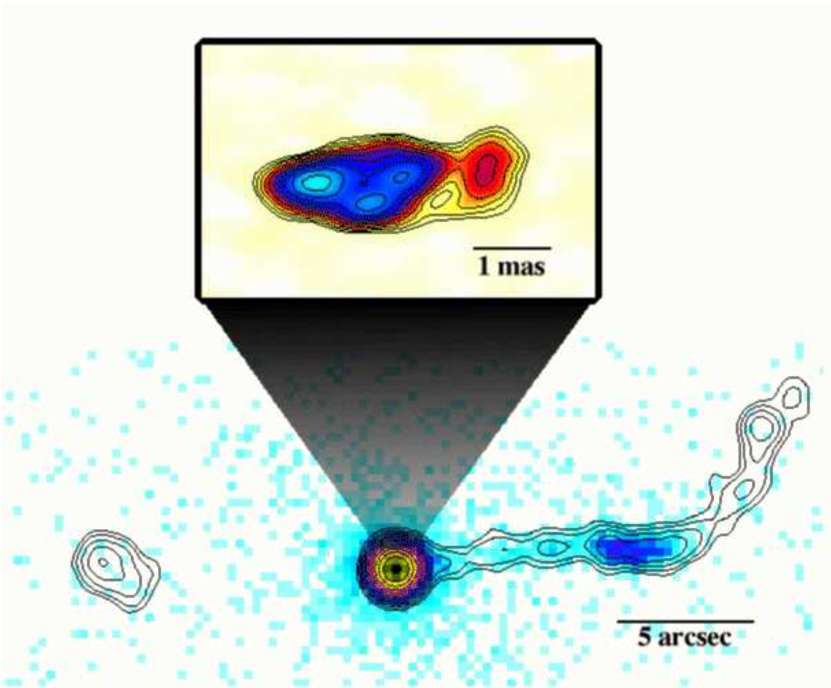

FIGURE 2. Chandra (pixels), ATCA (contours) and VSOP (inset) images of PKS 0637−752 (Lovell et al. 2000).

Mrk 421 is known to emit TeV gamma-rays. Piner et al. (1999) used an EVN+HALCA observation and ground-based VLBI observations to show that the motion of the components in the radio jet is subluminal, implying that there has been rapid jet deceleration between the regions where the TeV photons and radio photons are being emitted.

Imaging of high-redshift quasars at the VSOP frequencies of 1.6 and 5 GHz enables their milli-arcsecond radio structures to be studied at emitted frequencies of 6.5–8.0 and 20–27 GHz respectively. Of the 44 accepted VSOP observations of high-z quasars, over 20 have been conducted to date. Highlights include the detection of extremely violent bending in the quasar 1351-017 (z=3.71) and the discovery of the most distant rich "core-jet" structure in the quasar 2215+020 at z=3.55 (Gurvits et al. 2000).

There is a brightness temperature limit of $\sim 10^{12}$ K for incoherent synchrotron emission in the rest frame of the emitting plasma due to inverse Compton scattering loss of the emitting particles (Kellermann and Pauliny-Toth 1969). The brightness temperature observed in our reference frame differs from its value in the emitted frame by the factor $\delta/(1+z)$, where δ is the Doppler factor of the component in the rest frame of the radio source core. VSOP is a unique instrument for the measurement of brightness temperature, as the brightness temperature is directly proportional to the maximum baseline length sampled in the observation. Brightness temperatures in excess of 10^{12} K have been measured for a number of sources (e.g., Bower & Backer 1998, Shen et al. 1999) implying Doppler boosting factors of up to $\sim$10 for material in the jets.

Similar results have been obtained from a program of VSOP observations of the Pearson-Readhead sample of sources, with the derived brightness temperature distribution of bright core-dominated radio sources extending well beyond the Inverse Compton limit (Preston et al. 2000). Also, there appear to be no differences between the brightness temperature distribution of gamma-ray loud and gamma-ray quiet AGN, contrary to previous claims.

The VSOP Survey Program is providing a large complete sample of homogeneous data on sub–milli-arcsecond radio structures, which is essential for studying cosmology and statistics of AGN, planning future VLBI observations, and for designing future Space VLBI missions (Lovell et al. 2000a).

A good summary of the mission at the epoch of January 2000 can be seen in the VSOP Symposium Proceedings "Astrophysical Phenomena Revealed by Space VLBI", edited by H. Hirabayashi, P.G. Edwards and D.W. Murphy.

6. The Future of Space VLBI

The VSOP mission proved the instrumental and scientific capability of space-VLBI, and this is not the end. The VSOP mission, if it were more sensitive to lower brightness sources, could do more science for gravitationally lensed objects, galactic super-luminal or sub-luminal sources, flare stars, late-type stars, continuum AGN cores with rotating H_2O maser disks, etc. H_2O maser and continuum observations at 22 GHz were planned as one of the most important goals for the VSOP mission in terms of AGN and maser physics, but have been unable to be carried out. There are many frontiers or possible directions for future space-VLBI; longer baseline for higher angular resolution, shorter observing wavelength, better sensitivity, lower brightness detection limit, etc. Multiple space element interferometry is also very attractive.

A Japanese successor to VSOP, currently dubbed VSOP-2, with a 10 m class antenna in a slightly higher orbit than HALCA and a range of frequencies up to 43 GHz is being considered as a near-future mission with the potential launch of 2007 (Hirabayashi 2000; see also http://www.vsop.isas.ac.jp/vsop2.html). This model has 20 micro-arcsecond resolution at 43 GHz, and the sensitivity increase over the VSOP mission is one order of magnitude, allowing a wider scientific area and a larger number of observable sources. The ARISE mission is considering the use of a 25 m inflatable antenna for observations up to 86 GHz, as a bigger mission further into the future (Ulvestad and Linfield 1998; see also http://arise.jpl.nasa.gov).

The angular resolution with a HALCA-type orbit at 43 GHz and 86 GHz is 20 and 10 micro-arcseconds, respectively. This is only 10 and 5 times that of the suspected Schwarzschild radius of M87. ASCA's discovery of MCG–6-30-15 type phenomena seen by Fe-line spectroscopy seems to be taking place in the region only several times that of the event horizon (Tanaka et al. 1995). Space-VLBI in future will see the region with comparable physical resolution with real imaging capability.

The VSOP Project is led by the Japanese Institute of Space and Astronautical Science, with significant contributions from National Astronomical Observatory of Japan, the Jet Propulsion Laboratory, the U.S. National Radio Astronomy Observatory, the Canadian Dominion Radio Astrophysical Observatory, the Australia Telescope National Facility, the European VLBI Network, the Joint Institute for VLBI in Europe, and the directors and staff of many of the world's radio observatories. The author would like to express his sincere thanks to a large number of international members of the VSOP team for the collaborations on the VSOP for long years. Philip Edwards is thanked for his help in the preparation of this paper.

REFERENCES

Asada, K., Kameno, S., Inoue, M. et al. 2000 in *Astrophysical Phenomena Revealed by Space VLBI* p. 51.

Bolton, J.G. & Stanley, G.J. 1948 *Nature* **161**, 312.

Bower, G.C. & Backer, D.C. 1998 *ApJ* **507**, L117.

Edwards, P.G., Giovannini, G., Cotton, W.D. et al. 2000 *PASJ* in press.

Fomalont, E.B., Hirabayashi, H. Murata, Y. et al. 2000 in *Astrophysical Phenomena Revealed by Space VLBI* p. 167.

Gabuzda, D. 1999 *New Astronomy Reviews* 43, 691.

Gurvits, L.I., Frey, S., Schilizzi, R.T. et al. 2000 *Adv. Sp. Res.* **26**, 719.

Hirabayashi, H. 1998 *IAU Coll. 164: ASP Conf. Ser.* **144**, 11.

Hirabayashi, H. 2000 *Adv. Sp. Res.* **26**, 751.

Hirabayashi, H., Hirosawa, H., Kobayashi, H., et al. 1998 *Science* **281**, 1825 and erratum **282**, 1995.

Hirabayashi, H. & Hirosawa, H. 2000 *Adv. Sp. Res.* **26**, 589.

Hirabayashi, H., Hirosawa, H., Kobayashi, H. et al. 2000 *PASJ* in press.

Hirosawa, H. & Hirabayashi, H. 1997 *Advances in the Astronautical Sciences* **96**, 229.

Jones, D.L., Wehrle, A.E., Piner, B.G. et al. 2000 in *Astrophysical Phenomena Revealed by Space VLBI* p. 71.

Junor, W., Biretta, J.A., Owen, F.N. & Begelman, M.C. 2000 in *Astrophysical Phenomena Revealed by Space VLBI* p. 13.

Kameno, S., Sawada-Satoh, S., Shibata, K.M. et al. 2000 in *Astrophysical Phenomena Revealed by Space VLBI* p. 87.

Kellermann, K.I. & Pauliny-Toth, I.I.K. 1969 *ApJ* **155**, L71.

Kobayashi, H., Wajima, K., Hirabayashi, H. et al. 2000a *PASJ* in press.

Kobayashi, H., Murata, Y., Diamond, P.J. et al. 2000b *PASJ* in press.

Levy, G.S., Linfield, R.P., Ulvestad, J.S. et al. 1986 *Science* **234**, 187.

Lovell, J.E.J., Horiuchi, S. Moellenbrock, G.A. et al. 2000a in *Astrophysical Phenomena Revealed by Space VLBI* p. 183.

Lovell, J.E.J., Tingay, S.J., Piner, B.G. et al. 2000b in *Astrophysical Phenomena Revealed by Space VLBI* p. 215.

Moellenbrock, G.A., Lovell, J.E.J., Horiuchi, S. et al. 2000 in *Astrophysical Phenomena Revealed by Space VLBI* p. 177.

Piner, B.G., Unwin, S.C., Wehrle, A.E. et al. 1999 *ApJ* **525**, 176.

Piner, B.G., Edwards, P.G., Wehrle, A.E. et al. 2000 *ApJ* **537**, 91.

Preston, R.A., Lister, M.L., Tingay, S.J. et al. 2000 in *Astrophysical Phenomena Revealed by Space VLBI* p. 199.

Reid, M. et al. 2000 *in preparation.*

Shen, Z.-Q., Edwards, P.G., Lovell, J.E.J. et al. 1999 *PASJ* **51**, 513.

Snellen, I., Tschager, W., Schilizzi, R. et al. 2000 in *Astrophysical Phenomena Revealed by Space VLBI* p. 79.

Tanaka, Y., Nandra, K., Fabian, A.C. et al. 1995 *Nature* **375**, 659.

Tingay, S.J., Jauncey, D.L., Reynolds, J.E. et al. 2000 *Adv. Sp. Res.* **26**, 677.

Ulvestad, J.S. & Linfield, R.P. 1998 *IAU Colloquium 164, ASP Conf. Series* **144**, 397.