Vol. 48 No. 1 | Journal of the Communications Research Laboratory Printed in Tokyo, Japan | March 2001 pp. 41–46

2.6 Space VLBI Mission: VSOP

By

Yasuhiro MURATA, Hisashi HIRABAYASHI, Hideyuki KOBAYASHI,
Katsunori SHIBATA, Tomofumi UMEMOTO, and P.G. EDWARDS

ABSTRACT

We have successfully performed space VLBI observations using the HALCA satellite of the VLBI Space Observatory Programme (VSOP) launched in February 1997 by the M-V-1 rocket developed by the Institute of Space and Astronautical Science (ISAS). The mission is led by ISAS and the National Astronomical Observatory (NAO) in collaboration with the Communications Research Laboratory (CRL), National Aeronautics and Space Administration (NASA), National Radio Astronomy Observatory (NRAO), and other institutes and observatories in Europe, Australia, Canada, South Africa, and China. Through the course of this mission, we have made a large number of observations revealing new features of active galaxies, cosmic jets, and other astronomical objects.

Keywords: VSOP, Space VLBI, Active galaxy

1. Introduction

Ever since the invention of the interferometer type of radio telescope, baselines have never been long enough for astronomers involved in observations of this type. With the success of Very Long Baseline Interferometry (VLBI) experiments, baselines reached a length comparable to the size of the Earth, and in an attempt to achieve even longer baselines, a space VLBI experiment was conducted using the Tracking & Data Relay Satellite System (TDRSS) satellite[1]. In this experiment, observations were planned and executed by researchers in the United States and Australia in collaboration with the National Astronomical Observatory (NAO), Institute of Space and Astronautical Science (ISAS), and Radio Research Laboratory (the present Communications Research Laboratory (CRL)) in Japan. The Kashima 26-m antenna of the Radio Research Laboratory and the Usuda 64-m antenna of ISAS were used in these observations to pair up with the TDRSS satellite, and fringes were detected by correlation processing using the correlators at Haystack in the U.S. and Kashima in Japan. The success of this experiment led to the beginning of the VLBI Space Observatory Programme (VSOP) project and to its eventual success.

2. VSOP

As the name implies, the VLBI Space Observatory Programme or "VSOP" is a space-oriented VLBI observation project. It uses the HALCA space VLBI satellite launched on February 12, 1997 and having an elliptical orbit with a perigee height of 560 km and an apogee height of 21,600 km. With HALCA, baselines of about 30,000 km can be achieved for interferometry. After launch, HALCA was first used to confirm various engineering-related technical objectives, and once this was accomplished, VSOP observations began in earnest[2],[3]. HALCA was designed to perform observations in the 1.6 GHz, 5 GHz and 22 GHz frequency bands, but as a large drop in sensitivity occurred in the 22 GHz observation system early on[4], that band was used for observing only one celestial body[5]. The 1.6 and 5 GHz bands, however, have been successfully used to achieve a variety of astronomical results as described below.

Command transmission and telemetry reception are performed at S-band using the 20-m antenna system at the Kagoshima Space Center (KSC) of ISAS. On the other hand, tracking for phase transmission and reception of observation data are performed at Ku-band by a total of five tracking stations. These are the Usuda 10-m antenna of ISAS, the Canberra, Goldstone, and Madrid stations of the Deep Space Network (DSN), and the Greenbank station of the National Radio Astronomy Observatory (NRAO) in the United States. A high data transfer rate of 128 Mbps is used for the data downlink.

In addition to the satellite, VSOP observations require ground telescopes and correlation stations. There are three correlators that perform VSOP correlation processing: the Socorro correlator of NRAO in the United States, the Penticton correlator of the Dominion Radio Astrophysical Observatory in Canada, and the Mitaka correlator of NAO in Japan. The NAO correlator at Mitaka was developed using VLBI-correlator construction technology from the Radio Research Laboratory.

To organize a network of ground telescopes and oversee the smooth execution of space VLBI observations, the Global VLBI Working Group (GVWG) was formed. This organization determines how much time each telescope can provide to space VLBI observations, and performs scheduling on the basis of these resources. Each telescope provides from several percent to about ten percent of total observation time. In addition, each telescope station decides on its own the amount of time that it can provide to survey observations, an important part of the VSOP mission. Table 1 lists main ground telescopes participating in VSOP observations. Those from Japan are the Kashima, Nobeyama, and Usuda telescopes. In the case of Nobeyama, however, the only band that its 45-m

Table 1 Ground Telescopes

Telescope Name	Code	Location	Array	Aperture	Recording Format	Band
Effelsberg	EB	Germany	EVN	100	MK4, VLBA	L, C, K
Jodrell Bank	MK76	U.K.	EVN	76	MK4, VLBA	L
Jodrell Mark II	JB26	U.K.	EVN	26	MK4, VLBA	C, K
Medicina	MC	Italy	EVN	32	MK4	L, C, K
Metsaehovi	MH	Finland	EVN	14	VLBA	K
Noto	NT	Italy	EVN	32	MK4, S2	L, C, K
Onsala	ON	Sweden	EVN	26	MK4	L, C
Shanghai	SH	China	EVN	25	VLBA, S2	L, C
Torun	TR	Poland	EVN	32	VLBA	L, C
Urumuqi	UR	China	EVN	25	MK4	L, C, K
Westerbork	WB	Netherlands	EVN	25	MK4	L, C
Goldstone	GO	United States	DSN	70	MK4	L, K
Robledo	RO	Spain	DSN	70	MK4	L, K
Tidbinbilla	TI	Australia	DSN	70	MK4, S2	L, K
Hartebeesthoek	HH	South Africa	SHEVE	26	MK4, S2	L, C
Hobart	HO	Australia	SHEVE	26	S2	L, C, K
Mopra	MP	Australia	SHEVE	22	S2	L, C, K
Ceduna	CD	Australia	SHEVE	30	S2	C
ATCA	AT	Australia	SHEVE	54[1]	S2	L, C, K
Kashima	KA	Japan	JAPAN	34	VSOP, (S2)	L, C, K
Nobeyama	NO	Japan	JAPAN	45	VSOP	K
Usuda	UD	Japan	JAPAN	64	VLBA, VSOP, S2*	L, C
Pie Town	PT	United States	VLBA	25	VLBA	L, C, K
Kitt Peak	KP	United States	VLBA	25	VLBA	L, C, K
Los Alamos	LA	United States	VLBA	25	VLBA	L, C, K
Brewster	BR	United States	VLBA	25	VLBA	L, C, K
Fort Davis	FD	United States	VLBA	25	VLBA	L, C, K
Saint Croix	SC	United States	VLBA	25	VLBA	L, C, K
North Liberty	NL	United States	VLBA	25	VLBA	L, C, K
Owens Valley	OV	United States	VLBA	25	VLBA	L, C, K
Mauna Kea	MK	United States	VLBA	25	VLBA	L, C, K
Hancock	HN	United States	VLBA	25	VLBA	L, C, K
VLA-27	Y	United States	NRAO	129[1]	VLBA	L, C, K
Greenbank	GB	United States	NRAO	43	VLBA, S2	L, C, K
Arecibo	AR	Puerto Rico	NAIC	305	S2*, VLBA	L, C
Bear Lakes	BL	Russia	RUSSIA	64	S2	L
Kalyazin	KL	Russia	RUSSIA	64	S2	C

'*': VSOP-format tapes can be copied as VLBA-format tapes.
[1]: Equivalent aperture size.

telescope shares with VSOP is the 22 GHz one, and as a result, this station has not been able to participate to any large extent. Being in the Far East, the other two telescopes in Japan and the telescope in China are considered to be very important to the VSOP mission. The 34-m antenna at Kashima, incidentally, is a VLBI-dedicated antenna in contrast to the 64-m antenna at Usuda. The former antenna therefore has few limitations with respect to VLBI observations and has achieved many observation results especially in the survey observations described below[6].

These ground telescopes were employed for VLBI observations even before the launch of HALCA and have come to use four types of data recording formats: Very Long Baseline Array (VLBA), Mark IV, S2, and VSOP. Apart from the VSOP type, the Mark IV Field System Version 9 (FS9) developed by NASA/GSFC may be employed as the observation field system (observation control software) for these telescopes. The VEX format, moreover, has come to be used for observation schedules. The VLBA observation stations, however, have not adopted FS9 and operate instead under an original field system using an original format for scheduling (crd format). These schedule files can be created by the "sched" program developed at NRAO. Please see Ref. (7) for details on operation flow of this type.

Despite being a huge project spanning 13 countries when including ground telescopes, the operation of VSOP itself has gone rather smoothly thanks to international VLBI cooperative structures, which precede VSOP, and the individual efforts of many collaborators in many countries. The HALCA satellite (the satellite especially designed for VSOP), however, has periods of instability that lowers observation efficiency. Nevertheless, for the three and a half years since its launch, a total of 600 VLBI observations have been performed as of November 2000, about 70% of which have been observations proposed by astronomers from around the world and about 30% survey observations[6]. To date, applications for observations have been accepted four times.

3. Observation Results

At frequencies of 1.6 and 5 GHz, VSOP observations using HALCA can achieve the highest resolutions in the world. Of these two frequencies, the resolution at 5 GHz is the highest, although still inferior to that achieved by VLBA observations at 22 and 43 GHz. However, the state of radiation from a celestial body for frequencies differing by even a multiple of three is quite different, and it is therefore important that maximum resolution be obtained at any one frequency. The following example should make this clear.

Figure 1 shows observation results for 3C84 by Asada et al[8]. Observations by VSOP at 5 GHz are shown on the left and observations by VLBA at 15 GHz are shown on the right. Here, while the baseline length of the former is three times that of the latter, the wavelength of the former is also about three times that of the latter, and as a result, the resolution of both images is about the same. The bright section in the middle is the center of the galaxy above and below which radio radiation was observed. The upper radiation, however, is bright at 15 GHz while the lower radiation is bright at 5 GHz.

There are several possibilities as to why this is, but the group that performed these observations offers the following explanation. A large formation of plasma gas in the shape of a torus exists around the center of the galaxy. The upper radio radiation enters this plasma gas and is consequently absorbed to some extent. Radio radiation at lower frequencies, however, undergoes much more absorption by plasma gas, which means that radio radiation at higher frequencies is brighter in this area. On the other hand, radio radiation on the south side of this structure undergoes no absorption, and as a result, radio radiation at low frequencies is bright. This enables the radio radiation of a cosmic jet to be seen here.

In this way, by showing the difference in radio flux density between frequencies, the HALCA observations succeeded in obtaining at high resolution a radio spectrum, which is an important observation quantity in radio observations.

In addition, when investigating the brightness temperature (brightness per unit area) of an observed body

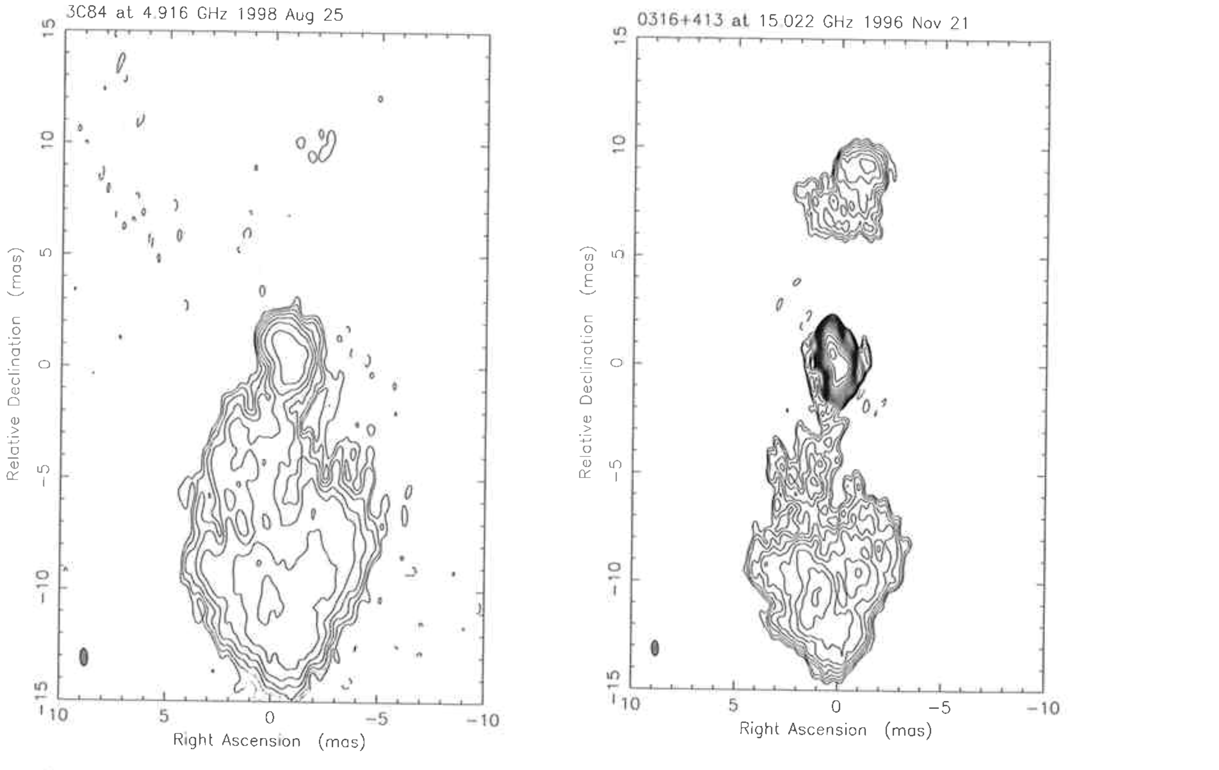

Fig. 1 Images of 3C84 obtained by VSOP observations at 5 GHz[8] and images of the same obtained by VLBA at 16 GHz[14]

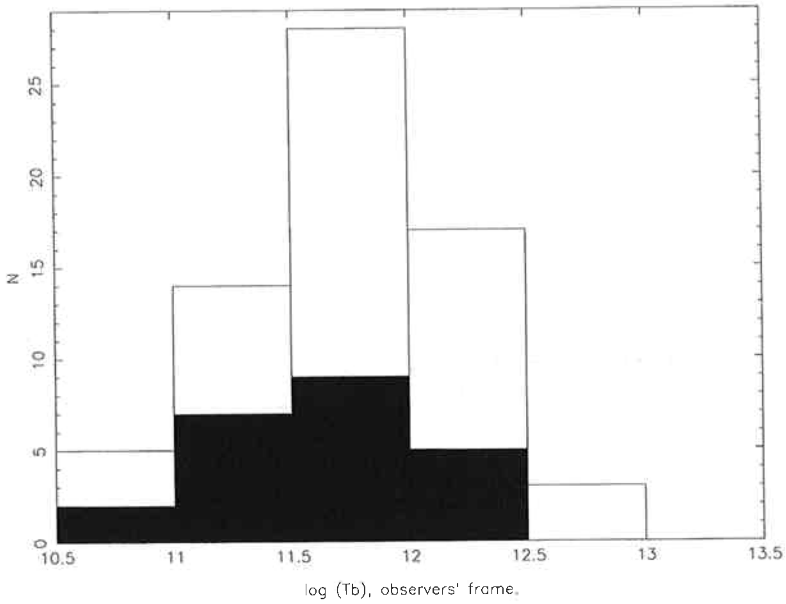

Fig. 2 Brightness-temperature distribution of active galaxies by VSOP survey observations. The image shows the brightness-temperature distribution for 67 celestial bodies in the observers' frame. The filled blocks represent sources where a compact component size was measured, while open blocks represent sources where only an upper limit on size and hence a lower limit on brightness temperature was possible.

on the basis of radio flux density, longer baseline lengths provide better sensitivity for high brightness temperature sources. Making use of this property, survey observations with HALCA were planned, and over 200 celestial bodies were observed at 5 GHz and their brightness temperatures measured[9],[6]. Figure 2 shows the resulting frequency distribution for brightness temperature. Here, in relation to brightness temperature, we point out that if the mechanism behind radio radiation is thermal in nature, radio field intensity will be proportional to the physical temperature of that radiating region. In VLBI observations, however, non-thermal synchrotron radiation is observed, which means that the temperature of this region is not in actuality related to brightness temperature in that way. What happened, however, was that brightness temperature exceeding 10 trillion degrees was discovered, but it is difficult to think that radiation from actual celestial bodies could be as intense as that giving rise to such an extremely high brightness temperature. We consider that a mechanism like Doppler amplification may be at work here.

A variety of achievements in addition to the ones described above came out of VSOP, and these are summarized in several papers[10],[11],[12].

4. Summary

More than three years have passed since the commencement of VSOP observations and many observational achievements have been obtained. Of course, the HALCA satellite, correlators, and other key equipment have played a major role in these achievements, but the project could not have progressed without the collaboration of many people especially those involved in the operation of ground telescopes and satellite tracking stations around the world. Within Japan, project execution centered about the Institute of Space and Astronautical Science and the National Astronomical Observatory, but it can certainly be said that Japan's involvement with VLBI as established by the Communications Research Laboratory expanded into the VSOP project. For the future, discussions have already begun on continuing VSOP in the form of a VSOP-2 project[13]. In this regard, technologies like a shared optical interface to high-sensitivity VLBI and VLBI equipment (VSI) using high-speed data recorders are now being researched at CRL, and we can expect such developments to be applied to VSOP-2 and advanced astronomical observation equipment.

Acknowledgments

The authors would like to extend their deep appreciation to all researchers and operators involved in the original VSOP project.

References

(1) G. S. Levy, R. P. Linfield, C. D. Edwards, J. S. Ulvestad, J. F. Jr. Jordan, S. J. Dinardo, C. S. Christensen, R. A. Preston, L. J. Skjerve, L. R. Stavert, B. F. Burke, A. R. Whitney, R. J. Cappallo, A. E. E. Rogers, K. B. Blaney, M. J. Maher, C. H. Ottenhoff, D. L. Jauncey, W. L. Peters, J. Reynolds, T. Nishimura, T. Hayashi, T. Takano, T. Yamada, H. Hirabayashi, M. Morimoto, M. Inoue, T. Shiomi, N. Kawaguchi, H. Kunimori, M. Tokumaru, and F. Takahashi, "VLBI using a telescope in Earth orbit. I The observations", Astrophys. J., 336, pp.1098-1104, January 1989.

(2) H. Hirabayashi, H. Hirosawa, H. Kobayashi, Y. Murata, P. G. Edwards, E. B. Fomalont, K. Fujisawa, T. Ichikawa, T. Kii, J.E. J. Lovell, G. A. Moellenbrock, R. Okayasu, M. Inoue, N. Kawaguchi, S. Horiuchi, S. Kameno, K. M. Shibata, Y. Asaki, T. Bushimata, S. Enome, T. Miyaji, T. Umemoto, V. Migenes, K. Wajima, J. Nakajima, M. Morimoto, J. Ellis, D. L. Meier, D. W. Murphy, R. A. Preston, J. G. Smith, S. J. Tingay, D. L. Traub, R. D. Wietfeldt, J. M. Benson, M. J. Claussen, C. Flatters, J. D. Ronmey, J. S. Ulvestad, L. R. D'Addario, G. I. Langston, A. H. Minter, B. R. Carlson, P. E. Dewdney, D. L. Jauncey, J. E. Reinolds, A. R. Taylor, P. M. McCulloch, W. H. Cannon, L. I. Gurvits, A. J. Mioduszewski, R. T.Schilizzi, and R. S. Booth, "Overview and Initial Results of the Very Long Baseline Interferometry Space Observatory Programme", Science, 281, pp.1825, September 1998.

(3) H. Hirabayashi, H. Hirosawa, H. Kobayashi, Y. Murata, Y. Asaki, I. M. Avruch, P. G. Edwards, E. B. Fomalont, T.Ichikawa, T. Kii, R. Okayasu, K. Wajima, M. Inoue, N. Kawaguchi, Y. Chikada, T. Bushimata, K. Fujisawa, S. Horiuchi, S. Kameno, T. Miyaji, K. M.Shibata, Z. Q. Shen, T. Umemoto, T. Kasuga, J. Nakajima, Y. Takahashi, S. Enome, M. Morimoto, J. Ellis, D. L. Meier, D. W. Murphy, R. A. Preston, J. G. Smith, R. D. Wietfeldt, J. M. Benson, M. J. Claussen, C. Flatters, G. A. Moellenbrock, J. D. Ronmey, J. S. Ulvestad, G. I. Langston, A. H. Minter, L. R. D'Addario, P. E. Dewdney, S.M. Dougherty, D. L. Jauncey, J. E. J. Lovell, S. J. Tingay, A. K. Tzioumis, A. R. Taylor, W. H. Cannon, L. I. Gurvits, R. T. Schilizzi, R. S. Booth, and M. V. Popov, "The VLBI space observatory programme and the radio-astronomical satellite HA LCA", Publ. Astron. Soc. Japan, 52, pp.955-965, December 2000.

(4) H. Kobayashi, K. Wajima, H. Hirabayashi, Y. Murata, N. Kawaguchi, S. Kameno, K. M. Shibata, K. Fujisawa, M. Inoue, and H. Hirosawa, "HALCA's onboard VLBI observing system", Publ. Astron. Soc. Japan, 52, pp.967-973, December 2000.

(5) H. Kobayashi, T. Shimoikura, T. Omodaka, and P. J. Diamond, "Astrophysical Phenomena Revealed by Space VLBI, Proceedings of the VSOP Symposium", pp.109-112., ISAS, 2000.

(6) H. Hirabayashi, E. B. Fomalont, S. Horiuchi, J. E. J. Lovell, G. A. Moellenbrock, M. Inoue, B. F. Burke, P. E. Dewdney et al. "THE VSOP 5 GHz AGN Survey I. Compilation and Observations", Publ. Astron. Soc. Japan, 52, pp.997-1014, December 2000.

(7) Y. Murata, "VSOP/HALCA International Mission Operation", Advances in Space Research, 26, pp.603-608, 2000

(8) K. Asada, S. Kameno, M. Inoue, Z. Q. Shen, S. Horiuchi, and D. C. Gabuzda, "Astrophysical Phenomena Revealed by Space VLBI, Proceedings of the VSOP Symposium", pp.51-54, ISAS, 2000.

(9) J. E. J. Lovell, S. Horiuchi, G. A. Moellenbrock, H. Hirabayashi, E. B. Fomalont, R. Dodson, S. Dougherty, P. G. Edwards, S. Frey, L. Gurvits, M. Lister, D. W. Murphy, Z. Paragi, B. Piner, W. Scott, Z. Q. Shen, S. Tingay, M. Inoue, Y. Murata, K. Wajima, B. Carlson, K. M. Shibata, J. Quick, M. Costa, A. Tzioumis, C. Trigilio, J. Nakajima, H. Xinyong, and W. Wei, "Astrophysical Phenomena Revealed by Space VLBI, Proceedings of the VSOP Symposium", pp.183-188., ISAS, 2000.

(10) Papers in H. Hirabayashi, R. A. Preston, L. I. Gurvits edited, Advances in Space Research, 26, pp.587-756, 2000

(11) H. Hirabayashi, P. G. Edwards, D. W. Murpy edited, "Astrophysical Phenomena Revealed by Space VLBI, Proceedings of the VSOP Symposium", ISAS, 2000.

(12) Papers in Publ. Astron. Soc. Japan, 52, December, 2000

(13) H. Hirabayashi, D. W. Murphy, Y. Murata, P. G. Edwards, I. M. Avruch, H. Kobayashi, and M. Inoue, "Astrophysical Phenomena Revealed by Space VLBI, Proceedings of the VSOP Symposium", pp.277-280., ISAS, 2000.

(14) T. Venturi, A. C. S. Readhead, M. J. Marr, and D. C. Backer, "Subparsec-scale radio structure in NGC 1275 - Complex structure in the vicinity of the central engine", Astrophys. J., 411, pp.552-564, July 1993.