Astrophysical Phenomena Revealed by Space VLBI
H. Hirabayashi, P.G. Edwards and D.W. Murphy (eds.)

The VSOP Survey I: Description and Participation

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Abstract

The VSOP mission is a Japanese-led project to image radio sources with sub-milliarcsec resolution by correlating the signal from the orbiting 8-m telescope, HALCA, with a global array of telescopes. Twenty-five percent of the scientific time of this mission is devoted to a survey of the 400 brightest, small-diameter extra-galactic radio sources at 5 GHz. The major goals of the VSOP survey are statistical in nature: to determine the brightness temperature and approximate structure; to provide a source list for use with future VLBI space missions; and to compare radio properties with other data throughout the EM spectrum. This paper describes: The compilation of the entire source list; the selection of sources to be observed with VSOP; the extensive ground resources; and the status of the observations as of March 2000. In these proceedings Paper II describes the reduction methods and Paper III gives initial statistical results.

1 Introduction

On February 12, 1997 the Institute of Space and Astronautical Science (ISAS) launched an 8-m radio telescope, called HALCA, into orbit as one element of a global array of radio telescopes. With an apogee height of 22,000 km and an orbital period of six hours, radio sources at 1.6 and 5 GHz can be imaged with a linear resolution three times greater than with ground arrays at these frequencies (Hirabayashi et al. 1998). One of the main scientific goals of the mission is the study the radio properties of AGN at sub-milliarcsec resolution, corresponding to brightness temperatures near 10^{12}K.

The majority of HALCA observing time is given to peer-reviewed proposals which are solicited from the world-wide astronomical community and designated as GOT (General Observing Time) proposals. Most of these projects study the source properties by obtaining high-quality images, often at several epochs separated by days to years. However, with a detection sensitivity of 0.1 Jy, hundreds of radio sources, many of which are not in the GOT proposals, can be detected with HALCA to provide a systematic study of a large sample of sources. This project was undertaken, under Japanese leadership with H. Hirabayashi as the Principle Investigator (PI), and it is called the VSOP Survey Program.

This paper concentrates on the following aspects of the VSOP Survey Program: (1) the compilation of the all-sky 5-GHz sample; (2) the

selection of sources observed with HALCA; (3) the listing of the ground resources used for the survey; and (4) the description of a typical experiment and the observational progress to date. Two additional papers in these proceedings describe the data reduction techniques (Moellenbrock et al. 2000) and results from an analysis of the sample (Lovell et al. 2000). A more complete description of the VSOP survey and the full source list will be given elsewhere (Hirabayashi et al. 2000).

2 The VSOP All-Sky 5 GHz Sample

The VSOP survey sample was defined to include all cataloged extra-galactic radio sources in the sky with: a total cataloged flux density at 5 GHz $S > 0.95$ Jy; a spectral index $\alpha > -0.45$ (where $S \propto \nu^{\alpha}$); a galactic latitude $|b| > 10^{\circ}$. Such a sample definition is relatively unbiased. The sample also included *all* extra-galactic sources with $S > 5$ Jy, regardless of spectral index and galactic latitude.

The existing surveys from which the 5-GHz sample were compiled were the Green Bank *GB6 Catalog* (Gregory et al. 1996) and the Parkes-MIT-NRAO *PMN Survey* (Lawrence et al. 1986, Griffith & Wright 1993). These surveys were observed with several large telescopes and covered most of the sky to a flux density level of < 0.3 Jy. Spectral information was determined from the above catalogs or from other, more recent observations, as needed. The NASA/IPAC Extra-galactic Database (NED; http://nedwww.ipac.caltech.edu) provided the most convenient location for additional information. Additional sources were found in the *S5 survey* near the North Galactic Pole (Kühr et al. 1981), and from the VLA calibrator list.

Since the survey observations used to compile the VSOP sample spanned a period between 1985 and 1996, source variability clearly affected the source membership in the sample. The only way to avoid such ambiguities would be to observe approximately the brightest 1000 sources in the sky at several frequencies within a short period of time: this effort was not possible. A source was included in the sample if the flux density at 5 GHz for *any* of the finding survey was > 0.95 Jy, or there was indication from other VLBI observations of a flat radio spectrum component within the source.

The VSOP 5 GHz survey sample, compiled as described above, contains 404 sources. This number accounts for about 60% of all sources above 1 Jy (Kühr et al. 1981). The source list is available from the

VSOP website (http://www.vsop.isas.ac.jp, click on VSOP Survey Program). The original plan for the VSOP survey was to observe all 404 sources at 5 GHz, the highest frequency and resolution of VSOP. If time permitted, an additional observation at 5 GHz or one at 1.6 GHz would be considered.

3 The VSOP Survey Observing Sample

In order to maximize the return from the HALCA observations, those sources with correlated flux density < 0.32 Jy at 5 GHz on the largest earth baselines were not included in the observing list. These sources would be very resolved with space baselines and many would likely be undetected. This filtering was accomplished in 1996 with a pre-launch 5 GHz VLBA snap-shot survey of all sources in the complete catalog north of declination $-43°$. A detailed presentation of these results are given elsewhere (Fomalont et al. 2000). Additional information was obtained from: the VLBA calibrator list (Peck and Beasley 1998); the USNO geodetic catalog and the International Celestial Reference Frame (ICRF) information (http://maia.usno.navy.mil/rorf/rrfid.html); the 15 GHz VLBA survey (Kellermann et al. 1998); two trans-continental surveys at 2.6 and 22 GHz (Preston et al. 1985, Moellenbrock et al. 1996); and from SHEVE observations (Tingay et al. 2000)

Using the above ground observations 115 of the 404 sources in the VSOP all-sky sample were found to be sufficiently resolved on ground baselines and would probably not be detected with HALCA observations. The remaining 289 sources formed the VSOP Survey Observing Sample and these sources formed the basic source list for the HALCA observations during the mission. These sources are also listed in the ISAS website. Although observations are being made only for this subsample, all 404 sources in the complete sample should included in any statistical studies of these AGN.

After six months of observing it was apparent that not even this reduced sample of 289 source could be observed within the expected mission lifetime. Thus, for those GOT observations which looked at sources also found in the VSOP observing list, permission was requested from the relevant PI's to extract part of their observations for the use in the Survey Program, but only for statistical purposes. The PI's were unanimous in giving permission for such GOT/Survey extractions.

4 The VSOP Survey Ground Resources

The HALCA on-board hardware, telemetry and tracking station systems, and the data correlation are described elsewhere (Hirabayashi et al. 1998). Both the GOT and the VSOP Survey observations require a large effort and cooperation of numerous ground resources and these will be acknowledged and described in this paper, with emphasis on the VSOP survey.

4.1 The Ground Telescopes

A typical GOT array consists of HALCA with six to nineteen ground telescopes, observing for a duration of about 10 hours, or about two orbits of the spacecraft. These data generally produce images of high quality. The ground telescope time for these observations were arranged before the mission by the Global VLBI Working Group (GVWG). The VSOP Survey, on the other hand, was designed to observe using three telescopes with observation length of about one orbit. These more minimal resources made it possible for the survey to negotiate for sufficient additional ground resources *after* telescope allocations were made for the GOT experiments.

The telescopes (with supporting institution, country and total survey observing time in days in 1998–1999) are as follows: Arecibo (NAIC, Puerto Rico, 1.7d); Ceduna and Hobart (University of Tasmania, Australia, 1.2d, 10.8d); Green Bank 140-ft (NRAO, USA, 3.7d); Hartebeesthoek (HartRAO, South Africa, 12.5d); Kalyazin (Lebedev Institute, Russia, 1.4d); Kashima (CRL, Japan, 4.0d); Mopra (ATNF, Australia, 10.5d); Noto (CNR, Italy, 5.0d); Sheshan (Shanghai Univ., China, 9.7d); Torun (Copernicus University, Poland; 3.7d); Usuda (ISAS, Japan, 3.8d). Telescopes participating only in GOT observations, indirectly contributing to the survey program via data extractions, are: ATCA (ATNF, Australia, 1.5d); Effelsberg (MPIfR, Germany, 2.7d); Jodrell MKII (MERLIN/VLBI NF, UK, 0.5d); VLBA (NRAO, USA, 7.0d using three of ten telescopes).

4.2 The Tracking Stations

The ISAS Space Center facility near Kagoshima, Japan is the command and control center of HALCA. For telemetry between the ground and HALCA, five tracking stations are used: one tracking station is operated by ISAS at Usuda, Japan; three stations by the NASA Deep Space

Network (DSN) at Goldstone, CA, USA, Robledo, Spain, and Tidbinbilla, Australia; and one station in Green Bank, WV, USA, operated by NRAO and supported by NASA.

The main responsibilities of each tracking station are: (1) To transmit a high-purity carrier signal to the spacecraft in order to convert the radio signals to a lower frequency; (2) to receive the HALCA data on a 15 GHz down-link; (3) to determine the time of flight of the round-trip signal to HALCA; and (4) to record the data on video tape which is subsequently sent to one of the data correlation centers. The length of time when HALCA is visible for each tracking pass varies from a few minutes to four hours.

Three data recording formats are used for the VSOP mission: VSOP-format, developed in Japan; S2-format, developed in Canada; and VLBA-format, developed in the USA. The MKIV recording format, developed in the USA and used mostly for European telescopes, is compatible with the VLBA-format. When necessary, data among the three formats are translated with copying facilities in Mitaka and Usuda, Japan.

4.3 The Correlators

The HALCA data, which is recorded at each of the tracking stations, is shipped to one of the three correlation centers where it is correlated with ground-telescope data, approximately one month after the observations. An updated HALCA orbit, determined by JPL and by ISAS, is also supplied. The three correlators are: The VSOP correlator in Mitaka, Japan (Shibata et al. 1998); the S2 correlator in Penticton, BC, Canada (Carlson et al. 1999); and the VLBA correlator in Socorro, NM, USA (Napier et al. 1994).

Because the VSOP Survey Program was designed to use telescopes with S2- or VSOP-recording systems, most survey observations were correlated in Penticton or in Mitaka. However, the VLBA correlator is also used for data extracted from GOT experiments.

5 The VSOP Survey Observations

Sources in the VSOP survey observing list are observed in the following way. The GOT observations are first scheduled and then survey observations are placed to make the HALCA relatively efficient. About one in three HALCA observations (including GOT extractions) is a survey observation, and these account for about 25% of the total on-source ob-

serving time. A typical survey observation consists of five hours of data, about one HALCA orbit, with three well-separated ground telescopes. More than 100 of the 289 sources are also in GOT proposals, and a typical amount of survey data (three ground telescopes over five hours) are extracted at the correlator from these observations. The priority in the scheduling of the survey observations is from the strongest sources to the weakest sources. However, constraints of when a source can be observed with HALCA somewhat randomizes the selection process.

The survey ground array that is scheduled depends on source declination. Sources south of -30° use telescopes in Australia (Mopra, Hobart, Ceduna) and Hartebeesthoek in South Africa. For more Northern declinations telescopes in Eastern Asia (Shanghai, Usuda, Kashima) or telescopes in the Europe-Atlantic region (Hartebeesthoek, Noto, Torun, Green Bank 140-ft, Arecibo) are also included. Generally four ground telescopes are scheduled for each experiment, although only three (and sometimes two) telescopes are available for the observations.

After correlation of a survey observation the data are edited, fringed and calibrated. Images of the radio sources and model-fits to the visibility data are used to determine flux densities, angular sizes and brightness temperatures of the radio components. A description of the reduction and imaging techniques (Moellenbrock et al. 2000) and initial results (Lovell et al. 2000) are given elsewhere in these proceedings.

As of March 2000, 194 of the 289 sources (67%) were observed. For about 40 of the observations only two ground telescopes were available; nonetheless, most of these have produced satisfactory images and models. About 10% of the observations appear faulty (no signal was detected from HALCA although there were strong fringes from ground baselines) and these will be rescheduled if possible.

The results from the VSOP Survey Program will be enhanced by comparison with other ground observational results, across the entire EM spectrum. Some of these ground observations have been proposed specifically for support of the VSOP survey. Additional information are: (1) radio source variability; (2) the arcsec radio structure of the sources; (3) VLBA 15 GHz observations nearly contemporaneous with the VSOP survey observations; (4) compilation of relevant radio/optical/X-ray data associated with each source in a convenient data base.

6 Summary

The informal agreements made by ISAS with global observatories, with tracking stations, with correlator centers, and with a host of other supporting personnel and organizations have formed the basis for the successful VSOP Survey Program. Over two-thirds of the 289 sources in the observing sample have been observed through March 2000 and the reduction and imaging are complete for more than half of these sources.

Preliminary results are given elsewhere (Lovell et al. 2000). Many interesting sources (e.g. those with extremely compact or with peculiar radio structure) have been found, and a surprisingly large number of radio sources have significant emission unresolved at the longest HALCA baselines, corresponding to an angular size < 0.15 mas with a brightness temperature in excess of 10^{12}K. The VSOP survey program has demonstrated that hundreds of sources can be studied in future space missions at even higher resolution.

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References

Carlson, B.R., Dewdney, P.E., Burgess, T.A., et al. 1999, *PASP*, **111** 1025

Fomalont, E. B., Edwards, P. G., Hirabayashi, H., Frey, S., Paragi, Z., Gurvits, L. I. & Scott, W. K., 2000, *AJ*, submitted

Gregory, P. C., Scott, W. K., Douglas, K. & Condon, J. J., 1996, *ApJS*, **103**, 427

Griffith, M. R. & Wright, A. E., 1993, *AJ*, **105**, 1066

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

Hirabayashi, H., Fomalont, E., et al., 2000, in preparation

Kellermann, K. I., Vermeulen, R. C., Zensus, J. A & Cohen, M. H., 1998, *AJ*, **115**, 1295.

Kühr, H., Witzel, A., Pauliny-Toth, I. I. K. & Nauber, U., 1981, *A&A*, **45**, 367.

Lawrence, C.R., Bennett, J.N., Hewitt, J.N., et al. *ApJS*, **61**, 105

Lovell, J. E. J., et al., 2000, *these Proceedings*

Moellenbrock, G. A., Fujisawa, K., Preston, R. A., et al., 1996, *AJ*, **111**, 2174

Moellenbrock, G. A., et al., 2000, *these Proceedings*

Napier, P.J., Bagri, D.S, Clark, B.G. et al. 1994, *IEEE Proc.*, **82**, 658

Peck, A.B & Beasley, A.J. 1998, in *ASP Conf. Ser.* **144***: IAU Coll. 164: Radio Emission from Galactic and Extragalactic Compact*

Sources, eds. J.A. Zensus, G.B. Taylor & J.M. Wrobel (San Francisco: Astron. Soc. Pac.), 155

Preston, R.A., Morabito, D.D., Williams, G. et al. 1985, *AJ*, **90**, 1599

Shibata, K. M., Kameno, S., Inoue, M., Kobayashi, H., 1988 in *ASP Conf. Ser.* **144***: IAU Coll. 164: Radio Emission from Galactic and Extragalactic Compact Sources*, eds. J.A. Zensus, G.B. Taylor & J.M. Wrobel (San Francisco: Astron. Soc. Pac.), 413

Tingay. S., Jauncey, D., King, E, et al. 2000, in preparation.

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Corrections to VSOP Symposium Proceedings
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* In the contents, the author list for the paper starting on page 79
  is incomplete and should read
  "Ignas Snellen, Wolfgang Tschager, Richard Schilizzi et al."

* In the preface, "Orian-KL" should be "Orion-KL"!!!

* The caption to Color Figure 3 refers to the source 1928+734,
  which should be 1928+738.

* In the summary section on page 49 (Murphy et al.), the sentence
  "In that time, we have observed a variety of
   structural changes in the inner jet region near the region."
  should read
  "In that time, we have observed a variety of
   structural changes in the inner jet region near the core."

* In the references on page 175 (Fomalont et al.) and page 182
  (Moellenbrock et al.) "Fomalont et al. 2000" should be updated to
  "Fomalont, E.B., Frey, S., Paragi, Z., Gurvits, L.I., Scott, W.K.,
  Edwards, P.G., Hirabayashi, H., 2000, ApJS, 131, 95"

* On page 217 (Lovell et al), the fourth line of the final paragrpah of
  section 1 should say "(see figure on page xviii)"

* In the references on page 233 (Sambruna) an extraneous "439"
  was introduced during the editing process into the reference
  for Catanese 1999.

* In the First Author List on page 327 (in the Index), the following
  line is missing
  Junor, W.   13