Conclusions from the image analysis of the VSOP Survey

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Abstract. In February 1997, the Japanese radio astronomy satellite HALCA was launched to provide the space-borne element for the VLBI Space Observatory Programme (VSOP) mission. A significant fraction of the mission time was to be dedicated to the VSOP Survey of bright compact Active Galactic Nuclei (AGN) at 5 GHz, which was lead by ISAS. The VSOP Survey Sources are an unbiased dataset of 294 targets, of which 82% were successfully observed. These are now undergoing statistical analysis to tease out the characteristics of typical AGN sources. We present here the summary of the imaging and conclusions we have reached.

1. Introduction

The radio astronomy satellite HALCA (Highly Advanced Laboratory for Communications and Astronomy) was launched by the Institute of Space and Astronautical Science in February 1997 to participate in Very Long Baseline Interferometry (VLBI) observations with arrays of ground radio telescopes. HALCA provides the longest baselines of the VSOP, an international endeavour that has involved over 28 ground radio telescopes, five tracking stations and three correlators (Hirabayashi et al. 1998, 2000a). HALCA was placed in an orbit with an apogee height above the Earth’s surface of 21,400 km, a perigee height of 560 km, and an orbital period of 6.3 hours.

During the seven years of HALCA’s mission lifetime, most of the observing time was used for General Observing Time (GOT). The remaining observing time was devoted to a mission-led survey of active galactic nuclei at 5 GHz: the VSOP Survey Program. The major goal of the Survey was to determine the statistical properties of the sub-milliarcsecond structure of a complete sample of AGNs. (Hirabayashi et al. 2000b; Fomalont et al. 2000a). Following the end of the formal international mission period in February 2002, the
Japanese-dominated effort continued survey observations until October 2003, when HALCA lost its attitude control capability.

This paper presents the summary of the Survey imaging analysis, which has been completed, and some early conclusions from the statistical analysis. Early papers in the VSOP Survey series include Scott et al. (2004) and Dodson et al. (2008), which present the 242 images and models (P-III and P-V), and Horiuchi et al. (2004) (P-IV) which presents the statistical conclusions based on data in P-III. They analyzed the cumulative visibilities of those sources to obtain the ‘typical source structure’. We repeated this with the entire sample of sources, and discuss the the brightness temperature properties.

2. The Observations

The VSOP mission and the 5 GHz AGN Survey are fully discussed in Hirabayashi et al. (1998); Fomalont et al. (2000a,b); Hirabayashi et al. (2000a,b). Briefly, in order to be included in the VSOP Survey, a source was required to have:

- a total flux density at 5 GHz, $S_5 \geq 0.95$ Jy and
- a spectral index $\alpha \geq -0.45$ ($S \propto \nu^\alpha$) and
- a galactic latitude $|b| \geq 10^\circ$.

The finding surveys from which sources were selected were primarily the Green Bank GB6 Catalog for the northern sky (Gregory et al. 1996), and the Parkes-MIT-NRAO (PMN) Survey (Lawrence et al. 1986; Griffith & Wright 1993) for the southern sky. As this was compiled from single dish catalogues, some of the selected sources would not be detectable by HALCA due to insufficient correlated flux density on baselines longer than about 1000 km. Therefore, sources with declination $> -44^\circ$ were observed in a VLBA pre-launch survey (VLBApl, Fomalont et al. 2000b) and a cutoff criterion, a minimum flux density of 0.32 Jy at 140 MHz, was established for inclusion of a source in the VSOP Survey (Fomalont et al. 2000a). For sources south of $-44^\circ$ this cutoff could not be determined, so all sources were included. Of the 402 sources in the complete sample, 294 were selected for VSOP observations, and this sample is designated as the VSOP Source Sample (VSS) (Hirabayashi et al. 2000a; Edwards et al. 2002). Observations of the VSS were made between August 1997 and October 2003. Of the VSS sample all but 29 were observed. Fig. 1 graphically presents the outcomes; not observed, failed, no space fringes or successful.

The VSOP survey observations were made at 5 GHz, with two left-circularly polarized 16 MHz IF bandwidths, sampled with two bits (Hirabayashi et al. 2000a). GOT observations of survey sources which were made with a similar configuration, were also included (see P-III for discussion of this). Data were usually correlated at either the DRAO Penticton correlator (Carlson et al. 1999) (54%) or the NAOJ Mitaka correlator (Shibata et al. 1998) (18%), with one non-GOT experiment processed at the Socorro correlator (Napier et al. 1994) along with two dozen GOT extractions and a test experiment (a total of 28%) (see Dodson et al. 2008, for details). After correlation, the data were sent to ISAS for distribution to the Survey Reduction Team members.
3. Data Reduction

The data were imported into AIPS (Greisen 1988), amplitude calibrated (with the measured or expected system temperature and, if needed, the autocorrelation normalised) then fringe fitted. After satisfactory delay and rate calibration, the data for all spectral channels were summed to a single channel per 16 MHz sub-band (i.e. two) and exported to DIFMAP (Shepherd 1997) for self calibration and model fitting. Scripts were used as much as possible to ensure that the methods were standardized.

For the entire VSOP survey programme, 265 of the 294 sources were observed. The observations are listed in P-III Table 1 and P-V Table 2, which includes source names, experiment code, Ground Radio Telescopes, Tracking stations and Correlator used, time over which fringes were detected and the optical ID and redshift. Table 1 in P-V contains the entire summary of all the VSS targets, whether observed or not, with contemporary values of total density flux at 5 GHz (where available), the redshift, relevant references, best fit (or lower limit) observer frame brightness temperatures of the core, detected area, and flux density on the longest baselines. For some of the observed sources, fringes to the spacecraft were not detected. Many of the sources were significantly resolved on shorter ground-only baselines, so that the lack of space fringes (RMS detection is typically 0.1 Jy) is consistent with the resolving structure seen on shorter baselines. However, for others, ground observations suggested that the space baselines (typically greater than 150 Mλ) should have been detected. These were considered failures, with the reasons unknown.

4. The Results

4.1. The \((u,v)\) Coverage, Visibility Amplitudes and Images

The graphical results for most of the survey sources are given in P-III Fig. 2 and P-V Fig. 1, which shows the \((u,v)\) coverage, the visibility amplitude versus projected \((u,v)\) distance, and the image displayed in contour form. The VSOP data were able to indicate the strength and angular size of a core component, even if, in some cases, most of the most extended emission, shown with lower-resolution images, was resolved out in the VSOP data.

Lister et al. (2001) investigated the effect of the limited \((u,v)\) sampling on the imaging for HALCA and the VLBA, with simulations. In Lister, et al. (2000) the effects on fidelity of using few ground baselines with HALCA (i.e. Survey observations) was investigated by comparison of survey datasets with the complete GOT dataset from which it was drawn. The conclusions therein were that: due to poor CLEAN deconvolution stability image fidelity was about 30:1 to 100:1, that the Survey datasets would have poorer dynamic range, yet would give reasonable measures of the core brightness temperatures. Hence we expect a typical image fidelity of 20:1.

4.2. The Brightness Temperature distribution

A histogram depicting the brightness temperature distribution in the source frame for the sources with known redshifts is shown in Fig. 2. Most cores
have $T_b > 10^{11}$ K, with approximately 56% of the sources having a measured brightness temperature in excess of $10^{12}$ K in the source frame and 8% have greater than $5 \times 10^{12}$ K. The distribution presented in [Kovalev et al. (2005)] is from VLBA observations at 15 GHz. They find also a median value of $10^{12}$K, but the distribution towards $10^{13}$ and beyond is largely made up of lower limits, rather than actual measurements as we have here. We have compared the $T_b$ for the source in common with [Kovalev et al. (2005)] by selecting the data with the closest observation dates. The $T_b$ in the VSS tend to be higher, as expected since the majority of the brightness temperatures in [Kovalev et al. (2005)] are lower limits (70% of the compared sources), with a median ratio of 2.4. Detailed comparison of individual sources, in particular those with very different $T_b$, will be presented in a future paper.

4.3. The Cumulative Visibility

We have repeated the analysis of [Horiiuchi et al. (2004)] on the complete VSS dataset, but have yet to fully understand the differences we find. We formed the cumulative visibilities from the scalar average of the amplitudes, binned by $(u,v)$ radius. We include the bias correction, due to the scalar averaging. We will continue to work on this.

4.4. The Brightness Temperatures vs IDV

IDV and $T_b$ are both measures of compactness, as is the detected core area, $A$. We were given early access to the MASIV dataset (Lovell et al. 2003), which we searched for correlations between their IDV measure ($\mu$) and our measures; $A$ and $T_b$. Unfortunately the errors on these values swamps any detected correlation. We will explore the use of more robust statistical analyses to attempt to tease out the correlations.

5. VSOP Survey II

For scheduling reasons we can expect that for a considerable fraction of the mission lifetime there will be very limited ground radio telescope availability. It is important to use the satellite time as profitably as possibility, therefore we consider what might be the best use of such limited baselines. Two major problems affected the VSS experiments; limited GRT coverage and poor amplitude calibration. Furthermore a repeat of a survey of AGN cores with Space baselines at a different frequency does not have a high science return. The maximum Brightness Temperature measurable depends only on the physical baseline length, which is the same for VSOP-2 as it was for HALCA. Therefore we propose the most suitable target for a survey would be H$_2$O masers. The autocorrelation can be used for amplitude calibration and the maser structures in individual channels are usually simple, which fits the constraints for the likely Survey-II configuration. The obvious science target for such a minimal array would be to make finely sampled observations of the proper motion of the maser components.
Fig. 1) Graphical representation of the VSS, by source code, and the final status: reported in which paper, whether space fringes were detected, or whether observations failed or were not made.

Fig. 2) The distribution of $T_b$ in the source frame for the subset of 222 sources which also have a measured redshift. Measurements are shown with a filled bar, whilst lower limits are shown with an open bar.

6. Conclusions

The imaging portion of the VSOP Survey has been completed with 242 or the 294 sources modelfitted to measure the brightness temperature of the core. The distribution of these $T_b$ confirms the distributions previously found: about 50% greater than $10^{12}$, but less than 10% are greater than $5 \times 10^{12}$.

References

Carlson, B. R., et al., 1999, PASP, 111, 1025
Dodson, R., et al., 2008, ApJS, in press (Paper V)
Edwards, P. G., et al., 2002, 8th Asian-Pacific Regional Meeting, Volume II 375
Fomalont, E., et al., 2000a, in Proceedings of the VSOP Symposium, January 2000, 167
Fomalont, E. B., et al., 2000b, ApJS, 131, 95
Gregory, P. C., Scott, W. K., Douglas, K., & Condon, J. J. 1996, ApJS, 103, 427
Greisen, E. 1988, in Acquisition, Processing & Archiving of Astronomical Images, 125
Griffith, M. R., & Wright, A. E. 1993, AJ, 105, 1066
Hirabayashi, H., et al., 1998, Science, 281, 1825 (erratum 282, 1995)
Hirabayashi, H., et al., 2000a, PASJ, 52, 6, 955
Hirabayashi, H., et al., 2000b, PASJ, 52, 6, 997 (Paper I)
Horiuchi et al., 2004, ApJ, 616, 110 (Paper IV)
Kovalev, Y. Y. et al., 2005, AJ, 130, 2473
Lawrence, C. R., et al., 1986, ApJS, 61, 105
Lister, M. L., et al., 2000, in Proceedings of the VSOP Symposium, January 2000, 189
Lister, M. L., et al., 2001, ApJ, 554, 1948
Lovell J., et al., 2003, in ASP Conf. Ser. 290, 347
Napier, P. J., et al., 1994, IEEE Proc. 82, 658
Scott, W. K., et al., 2004, ApJS, 155, 33 (Paper III)
Shepherd, M. C. 1997, in ASP Conf. Ser. 125, 77
Shibata, K. M., et al., 1998, in ASP Conf. Ser. 144, 397