VLBI Surveys of Active Galactic Nuclei

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Abstract. A review is given on the current status and selected results from large VLBI surveys of compact extragalactic radio sources made between 13 cm and 3 mm wavelengths and covering the entire sky. More than 4200 objects are observed and imaged with dynamic ranges from a hundred to several thousand at (sub)parsec scales. Implications to the VSOP-2 project are discussed.

1. Introduction

During the last several decades, a number of large Very Long Baseline Interferometry (VLBI) surveys were conducted covering the frequency range between 2 and 100 GHz including the first space VLBI survey with the space radio telescope HALCA (e.g., Lovell et al. 2004, Dodson et al. 2008). VLBI surveys which have observed and produced images for more than 100 objects are summarized in Table 1. We discuss below selected results from these surveys as well as their implications to the planned next generation science driven space VLBI mission VSOP-2 (Hirabayashi et al. 2004).

2. Selected results from large VLBI surveys of extragalactic jets

Only a few of the sources have an overall radio structure which is almost unresolved even at the longest spacings. However, most of the observations do not have enough resolution to resolve structure across the jet (e.g., Kovalev et al. 2005, Helmboldt et al. 2007). The distribution of the measured brightness temperatures of the jet cores, calculated in the source frame, peaks around $10^{12}$ K and extends up to about $10^{14}$ K (Horiuchi et al. 2004, Kovalev et al. 2005, Dodson et al. 2008). This is close to the limit set by the dimensions of individual VLBI arrays. However, for many sources only a lower limit is determined. The observed values can be explained as the result of Doppler boosting.

It is important to note that the highest measurable value of the brightness temperature does not depend on the observing frequency (see equation (5) in Kovalev et al. 2005). It depends on the physical length of the interferometric baselines as well as on the signal-to-noise ratio (S.N.R.) of VLBI measurements. This is demonstrated in Figure 1 as a dependence of the resolution limit versus S.N.R. calculated according to a criteria proposed by Kovalev et al. (2005), equations (1,2). See for more discussion also Lobanov (2005).
Table 1. Large VLBI surveys of extragalactic radio sources.

| Name                    | λ (cm) | No. of sources | Recent reference | Comments        |
|-------------------------|--------|---------------|------------------|-----------------|
| CJF survey              | 18 & 6 | 293           | Pollack et al. (2003) | complete       |
| ICRF/RDV                | 13 & 3.6 | 500         | Ojha et al. (2004)  | open            |
| VLBA Calibrator survey  | 13 & 3.6 | > 3400       | Kovalev et al. (2007) | open, complete |
| VSOP VLBApls            | 6      | 374           | Fomalont et al. (2000) |                |
| VSOP survey             | 6      | ≈ 300         | Dodson et al. (2008)  |                |
| VIPS                    | 6      | 1127          | Helmboldt et al. (2007) | open, complete |
| 2 cm Survey / MOJAVE    | 2      | 250           | Kovalev et al. (2005)  | open, complete |
| VERA FSS / VLBA GaPS    | 1.35   | > 500         | Petrov et al. (2007)  | open            |
| ICRFext 22 & 43 GHz     | 1.35 & 0.7 | > 100     | Lanyi et al. (2005)   |                |
| GMVA 3mm                | 0.3    | 121           | Lee et al. (2008)     |                |

Note. — Comments in the last column mean the following. ‘Complete’: the sample or its sub-sample is complete, flux-density-limited; ‘open’: all or some of the data are publicly available in a form of uv and/or image FITS files.

Figure 1. Dependence of the resolution limit versus signal-to-noise ratio. Results of theoretical estimation for a circular Gaussian beam with the full width at half maximum equal to 1 mas for a naturally weighted image.

Fractional linear polarization of the opaque quasar cores is generally low (< 5%). Extended jet features often show strong linear polarization (up to ~ 50 per cent) indicating synchrotron radiation of optically thin regions with highly ordered magnetic field (e.g., Lister & Homan 2005, Helmboldt et al. 2007). Circular polarization, if any, is detected, in general, on the level less than 0.5% mostly in the cores (Homan & Lister 2006).
3. Implications, prospects, and challenges of the VSOP-2 project

A VSOP-2 experiment to measure brightness temperature of jet cores in a complete sample of AGNs could be valuable for statistical studies of the properties of extragalactic jets, for a population analysis of the jet orientation and other basic parameters like the Doppler factor (see, e.g., Lobanov et al. 2000, Homan et al. 2006). It should be taken into account, while planning such a survey, that the highest measurable brightness temperature does not depend on the wavelength of observations. It depends in turn on the interferometer baseline length and the S.N.R. (see § 2). An obvious conclusion is that 8 GHz observations involving VSOP-2 space telescope and big ground-based dishes (e.g., EVN) will provide the highest sensitivity of the ground-space correlated-flux-density measurement being the most efficient configuration for such a survey.

It is planned to implement a fast switching capability for the VSOP-2 space radio telescope to allow phase referencing technique to be used for successful VLBI observations of weak targets. This is especially important at high radio frequencies which have a very limited coherence time of less than several minutes. We present here accumulated results of the search for compact extragalactic sources which are suitable as phase reference calibrators in VLBI experiments at or below 8 GHz (Ma et al. 1998, Fey et al. 2004, Beasley et al. 2002, Fomalont et al. 2003, Ojha et al. 2004, Petrov et al. 2005, 2006, Kovalev et al. 2007, Petrov et al. 2008). Figure 2 shows the sky coverage for more than 3000 calibrators while Table 2 provides a probability to find a calibrator within a given search radius. These results incorporate additional objects found in VLBA surveys recently which were not included in the Asaki et al. (2007) analysis. It can be immediately seen that a probability to find a phase calibrator required for

Figure 2. Extragalactic radio sources detected in the ICRF/VCS surveys at 2 and/or 8 GHz (Ma et al. 1998, Fey et al. 2004, Beasley et al. 2002, Fomalont et al. 2003, Ojha et al. 2004, Petrov et al. 2005, 2006, Kovalev et al. 2007, Petrov et al. 2008).
Table 2. Probability to find a calibrator within a given search radius for two declination (δ) zones following results from 2 and 8 GHz VLBI surveys, see references in the caption to Figure 2. Sources were assigned the calibrator classification according to criteria described in Kovalev et al. (2007).

| Search radius (deg) | Probability (%) δ > −40° | δ < −45° |
|--------------------|----------------------------|-----------|
| 0.5                | 6.7                        | 1.5       |
| 1.0                | 24.4                       | 5.7       |
| 1.5                | 46.7                       | 12.3      |
| 2.0                | 67.5                       | 20.6      |
| 2.5                | 82.9                       | 30.0      |
| 3.0                | 92.1                       | 40.0      |
| 3.5                | 96.7                       | 49.9      |
| 4.0                | 98.7                       | 59.2      |
| 4.5                | 99.4                       | 67.8      |
| 5.0                | 99.7                       | 75.4      |

VSOP-2 observations at X-band (8 GHz) within several degrees of the search radius is quite high for declination δ > −40°.

It is important to note that the full list of calibrators includes a complete sub-sample of sources with integrated VLBA flux density greater than 200 mJy at 8 GHz and declination δ > −30° (see for details Kovalev et al. 2007). This means that there are almost no bright compact sources “left” in that region of the sky. In order to increase the calibrator source coverage in the declination range −50° < δ < −30° a dedicated VLBA survey is proposed. The calibrator coverage south of declination −50° will be increased by the Australian LBA survey started in February 2008, this campaign will observe ∼ 500 candidate sources (P.I.: L. Petrov).

The situation at 22 and 43 GHz is not so well advanced currently. Only several hundred extragalactic objects were observed and imaged in the framework of the astrometric/geodetic program by Lanyi et al. (2005). In addition to that, results of dedicated 22 GHz VLBA survey of extragalactic sources with low galactic latitude will become available soon. However, 22 and 43 GHz observations of the complete sample of compact objects (Kovalev et al. 2007) are needed in order to find more sources to be used as VLBI phase calibrators at these high radio frequencies.

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