VLBI SURVEY OF WEAK EXTRAGALACTIC RADIO SOURCES AS A POTENTIAL LINK BETWEEN THE RADIO AND OPTICAL REFERENCE FRAMES

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ABSTRACT

The International Celestial Reference Frame (ICRF) is realised through a series of precise radio interferometric (Very Long Baseline Interferometry, VLBI) measurements of selected bright compact extragalactic sources. Using the technique of phase-referencing, VLBI has a potential to observe many (up to $\sim 10^4$) faint radio sources, inherently relating their positions to the reference objects with ICRF coordinates known accurately. Here we briefly describe the results of a pilot project for a Deep Extragalactic VLBI–Optical Survey (DEVOS). We comment on the perspective of using such a survey for tying the radio and optical reference frames.

Key words: VLBI; Extragalactic reference frames; Quasars; Surveys.

1. INTRODUCTION

Currently the International Celestial Reference Frame (ICRF) is adopted by the International Astronomical Union (IAU) as the fundamental celestial reference frame (Ma et al. 1998). The ICRF is defined by the positions of more than 200 extragalactic radio sources (active galactic nuclei, AGNs) regularly observed with Very Long Baseline Interferometry (VLBI) over a long period of time. In the optical, the Hipparcos catalogue – the most accurate available to date – is linked to the ICRF through radio interferometric observations of twelve radio stars (Kovalevsky et al. 1997). However, due to the stellar proper motions, the quality of this link is known to degrade with time.

With a sensitive next-generation space astrometry mission like Gaia, a quasi-inertial reference frame can *directly* be established in the optical (e.g., Mignard 2002), using a sample of at least $\sim 10^4$ clearly detected quasars brighter than $V = 20^{\mathrm{m}}$. In about 10–15 years time, the Gaia optical reference frame will most likely supersede the current radio realisation of the ICRF. However, the latter will retain its importance at least because the Earth rotation and orientation are uniquely measured with VLBI by linking the terrestrial reference frame defined by the radio antenna locations and the quasi-inertial celestial reference frame defined by the extragalactic radio sources (Fey et al. 2004).

The limiting visual magnitude of Gaia will enable observing the optical couterparts of practically all the ICRF defining radio-loud AGNs (Fey et al. 2001). The accurate link between the radio and optical reference frames is essential not only for astrometry, but for astrophysics as well. The high-resolution stucture of the AGNs observed at different electromagnetic wavelengths can only be registered correctly if the coordinates are expressed in consistent systems. It is commonly assumed – but in fact could not yet be tested – that the brightness peaks in radio and optical coincide in quasars.

The quality of the link is enhanced with the increasing number of common objects in both the optical and the radio. Therefore any survey that offers an extensive list of suitable link sources is valuable for improving the tie between the radio and optical reference frames, even if the individual positional accuracy of the sources is somewhat worse than that of the reference frame defining objects.

Here we briefly introduce the Deep Extragalactic VLBI–Optical Survey (DEVOS), and comment on the possibilities and limitations of using such a survey for tying the radio and optical reference frames.

2. DEVOS SAMPLE AND PILOT OBSERVATIONS

The DEVOS is ultimately aimed at imaging $\sim 10^4$ radio sources with VLBI at 5 GHz frequency. Its target sources are one or two orders of magnitude fainter in radio than those typically studied with VLBI until now. At present, the various existing VLBI surveys are in fact flux density limited at ~ 100 mJy. The milli-arcsecond (mas) resolution radio images of a large number of radio-loud AGNs, coupled by optical identifications and in many cases spectroscopic redshifts, would lead to an unprecedented data base for a multitude of astrophysical, cosmological and astrometric studies (Mosoni & Frey 2004; Mosoni et al. 2005). Optical identification for most of the sources is ensured by surveying the celestial areas covered by the

Sloan Digital Sky Survey (SDSS, e.g., Abazajian et al. 2004) or the 2dF Quasar Survey (Croom et al. 2004).

The DEVOS sample is initially selected from the US National Radio Astronomy Observatory (NRAO) Very Large Array (VLA) Faint Images of the Radio Sky at Twenty-centimeters (FIRST) survey catalogue (White et al. 1997), according to the following criteria: (1) minimum integrated flux density at 1.4 GHz frequency is 30 mJy, (2) maximum angular size is $5''$ (i.e., the sources are unresolved in FIRST), and (3) maximum separation from a bright, compact VLBI reference source is 2°.

The *reference object* selected serves as phase-reference calibrator for subsequent radio interferometric observations. It can either be an ICRF defining object or one with high-accuracy ICRF coordinates measured and available in the literature. Phase-referencing is an observing technique to extend the signal coherence time in order to increase the on-source integraton and thus the sensitivity of the interferometer array, i.e., to detect weaker sources. This can be done by regularly interleaving observations between the target and the nearby strong reference source within the atmospheric coherence time. The delay, delay rate and phase solutions obtained for the calibrator are interpolated and applied for the target source data. Most of the phase errors introduced by geometric, ionospheric, tropospheric and instrumental effects are removed this way (e.g., Lestrade et al. 1990; Beasley & Conway 1995).

In DEVOS we reverse the usual logic of choosing a target source first and then finding a nearby phase-reference calibrator. Here we pick suitable reference objects and survey *all the possible target objects* that lie in their close vicinity, within 2° angular distance. Potential VLBI reference sources are distributed in the sky in sufficient density (e.g., Beasley et al. 2002) so that phase-referenced observations can practically be conducted anywhere.

During the course of the standard VLBI data reduction (calibration and hybrid mapping) procedure (e.g., Diamond 1995), the self-calibration used for imaging the bright reference source corrects for unmodelled phase errors by fixing the *a priori* position of the reference source. Therefore the positions of the weak phase-referenced programme sources are given relative to the calibrator source position.

To make an effective use of the VLBI arrays, and to refine the poorly constrained astrometric positions of the target sources selected from FIRST, the initial sample is ‘filtered’ using 5-GHz observations with the UK Multi-Element Radio Linked Interferometer Network (MERLIN). The programme sources that appear compact and bright enough ($>$ 2 mJy/beam) at the MERLIN angular resolution of $\sim$ 50 mas qualify for subsequent VLBI observations.

The 5-GHz VLBI observations lead to $\sim$ 1 mas angular resolution images of a fraction of the programme sources down to the brightness level of $\sim$ 1 mJy/beam. Results of the pilot project described below indicate that about half of the originally selected FIRST sample sources are detected with VLBI at the highest angular resolution, and thus powered by AGN activity with corresponding brightness temperatures of at least 5×10^6 K.

In order to test the feasibility of our approach, and to estimate the resources needed for the full long-term project, we conducted pilot DEVOS observations with MERLIN on 24–28 March 2001, and with a global array of 19 radio telescopes of the European VLBI Network (EVN) and the NRAO Very Long Baseline Array (VLBA) on 28 May 2002. The technical details of the observations are given by Mosoni et al. (2005). The quasar J1257+3229 was chosen as a phase-reference calibrator, close to the North Galactic Pole. There were a total of 47 sources selected from the FIRST catalogue satisfying the criteria given above. With MERLIN, 37 sources have been detected. (The rest appeared completely resolved at $\sim$ 50 mas angular sclale and thus excluded from further high-resolution imaging.) The global VLBI experiment proved that 20 of the 37 MERLIN-detected sources could be imaged at $\sim$ 1 mas angular resolution (Mosoni et al. 2005). Detailed optical cross-identifications will be done as soon as the data for the corresponding SDSS field become available.

Optical counterparts within $5''$ to 8 out of 20 VLBI-detected AGNs are found in the catalogue of Automatic Plate Measuring (APM) identifications using the Palomar Observatory Sky Survey (POSS) first-epoch red (E) and/or blue (O) plates (McMahon et al. 2002). We present here VLBI images of two characteristic sources (Figure 1). The first one, J125858.6+325738 ($E = 19\overset{\mathrm{m}}{.}24$, $O = 19\overset{\mathrm{m}}{.}55$) is an example of an AGN with a relatively complex, double radio structure at a scale larger than its positional accuracy. On the other hand, as far as its radio structure is concerned, J130310.2+333406 ($E = 19\overset{\mathrm{m}}{.}59$, $O = 19\overset{\mathrm{m}}{.}13$) is a typical compact core-dominated source. Note that this AGN is about a factor of 100 weaker at GHz frequencies than the objects traditionally imaged with VLBI, and used for defining the reference frame, therefore we must be able to find a large number of similar AGNs in DEVOS in the future.

In the case of the pilot project, both the right ascension and declination of the phase-reference calibrator (J1257+3229) were known to the accuracy of 0.5 mas in the ICRF (Beasley et al. 2002). The relative astrometric errors for the target sources are known to correlate with the target–reference separation. In our case at 5 GHz, they should not be more than 0.5 mas even at the maximum angular separation of 2 ° (cf. Chatterjee et al. 2004). Consequently, the AGNs detected with VLBI in the pilot DEVOS experiment have sub-mas ICRF positional accuracy.

3. CONCLUSIONS

The number of link sources (n) is one of the important factors in the overall accuracy of the radio–optical reference frame tie, the latter being improved with $\sqrt{n}$. A survey like DEVOS could provide in addition a significant number of potential link sources with sub-mas ICRF positional accuracy. Moreover, the astrometric quality (i.e., the mas-scale structural complexity) of each object could be judged from the high-resolution radio images readily

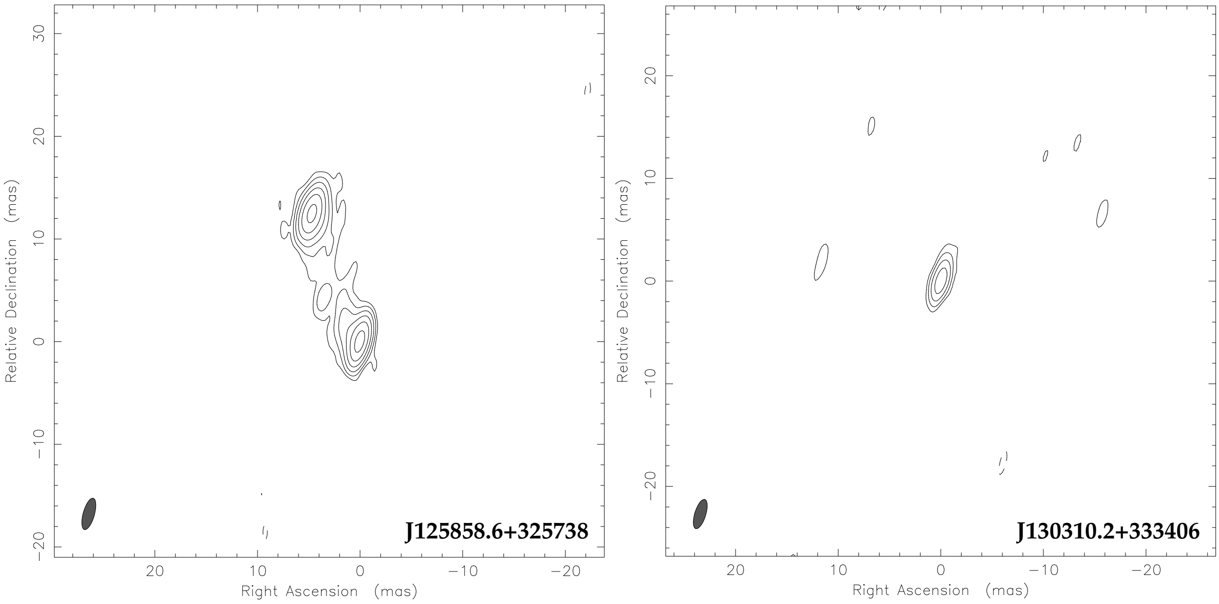

Figure 1. Examples of 5-GHz global VLBI images of two compact radio sources form the DEVOS pilot project (Mosoni et al. 2005). The lowest contours are drawn at ±0.41 mJy/beam (left) and ±0.34 mJy/beam (right). The peak brightnesses are 17.8 mJy/beam and 4.5 mJy/beam, respectively. The positive contour levels increase by a factor of 2. The coordinates are relative to the bightness peak. The Gaussian restoring beams (∼3 mas × 1 mas (FWHM) at a major axis position angle ∼17°) are indicated with ellipses in the lower-left corners.

available from this imaging survey. Studies have shown a clear correlation between the compactness and the formal positional uncertainties of ICRF sources: the more extended sources have lower astrometric quality (Fey & Charlot 2000, and references therein).

Efforts are underway to extend the ICRF (e.g., Fey et al. 2004) and to increase the sky density of the compact extragalactic radio sources with accurate ICRF coordinates in the northern sky (e.g., Charlot et al. 2004). The north–south asymmetry in the ICRF defining sources has also been realised for a long time. Among the defining sources of the ICRF, only less than 30% are in the southern hemisphere (Ma et al. 1998). The reason is primarily technical since the VLBI arrays and observations are traditionally concentrated in the northern hemisphere. The mas-scale structures of several southern-hemisphere radio sources are now studied in order to identify possible objects suitable for ICRF extension (Ojha et al. 2004).

DEVOS, a VLBI survey of many (up to $\sim10^4$) extragalactic radio sources will provide a number of AGNs that (i) are compact enough to be considered as good reference points in the radio, (ii) are bright enough in optical to be observed with Gaia, and (iii) have radio positions accurate to 1 mas or better. Therefore these sources will potentially be valuable for building up a data base for tying the radio and optical reference frames, and possibly investigating local frame deformations.

Due to practical observational reasons, the DEVOS will concentrate on the northern hemisphere, and thus will not contribute to solving the problem of the general lack of southern VLBI sources. The technical developments foreseen in the coming years at the MERLIN and the EVN – the considerable increase in the sensitivity in particular – are encouraging and would enable the DEVOS to be completed in about 10 years (Mosoni et al. 2005), just in time for Gaia applications.

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