A Giant Step: from Milli- to Micro-arcsecond Astrometry
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Multi-wavelength VLBI phase-delay astrometry of a complete sample of radio sources

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Abstract. We report on the first global high-precision (differential phase-delay) astrometric analyses performed on a complete set of radio sources. We have observed the S5 polar cap sample, consisting of 13 quasars and BL Lac objects, with the VLBA at 8.4, 15, and 43 GHz. We have developed new algorithms to enable the use of the differential phase-delay observable in global astrometric observations. From our global analyses, we determine the relative positions between all pairs of sources with typical precisions ranging from 10 to 200 μas, depending on observing frequency and source separation. In this paper, we discuss the impact of this observable in the enhancement of the astrometric precision. Since a large fraction of the S5 polar cap sources are ICRF defining sources, this may result in a test of the ICRF stability. Our multi-epoch / multi-frequency approach will also provide both absolute kinematics and spectral information of all sources in the sample. In turn, this will provide an important check on key predictions of the standard jet interaction model.

Keywords. astrometry, techniques: interferometric, quasars: general, BL Lacertae objects: general, radio continuum: general

1. Introduction

Over the last years, we have carried out a series of VLBI observations, using the Very Long Baseline Array (VLBA) at 8.4, 15.4, and 43 GHz, aimed at studying the absolute kinematics of a complete sample of extragalactic radio sources using astrometric techniques. The target of our programme is the “S5 polar cap sample” (see Fig. 1 (a)), consisting of 13 radio sources from the S5 survey (Kühr, Witzel, & Paulini-Toth 1981, Eckart, Witzel & Biermann 1986). All sources in this sample have flux densities larger than 0.2 Jy at 8.4 and 15 GHz (0.13 Jy at 43 GHz) at the epochs of our observations and have well-defined ICRF positions. Most of the S5 polar cap sample sources have a structure that changes with time. For a reliable study of absolute kinematics of their components we need to refer the source positions and their changes with time and frequency to stable (or *fixed*) positions in the sky. The use of phase-delays allows us to refer the positions of the sources to the *phase centers* of the maps, providing a suitable reference for the source structure. In principle, the effect of source structure can be removed from the group delays, but large and rapid changes in the phase structure for this observable makes this approach complicated.

2. Observations

We observed all 13 members of the sample with the VLBA at 12 epochs (4 for each observing frequency) between years 1997 and 2004. We observed the sources in duty cycles, about 4 minutes long, using a multiple triangulation approach (see Martí-Vidal *et al.* 2008 for details). We indicate one such duty cycle in Fig. 1 (a), where the arrows mark the directions of the (antenna) slewings. The structures of the S5 polar cap sources for two epochs (years 1999.57 and 2000.46) at 15.4 GHz and two epochs (years 1997.93 and 1999.41) at 8.4 GHz, were discussed by Pérez-Torres *et al.* (2004) and Ros *et al.* (2001), respectively. At the time of writing this contribution, we have finished the astrometric analysis of the two 15 GHz epochs discussed in Pérez-Torres *et al.* (2004), and we have obtained preliminary results for the 8.4 GHz epochs on years 2001.09 and 2004.53, and for the 43 GHz epoch on year 2004.62.

3. The phase connection

Phase connection is the process by which phase-delays are converted into a non-ambiguous observable. The procedure of phase connection in our astrometric analysis is described in Martí-Vidal *et al.* (2008). It is based on previous approaches (e.g. Shapiro *et al.* 1979, Guirado *et al.* 1995), but with some substantial differences such as the use of an in-house developed automatic connection algorithm, described in Martí-Vidal *et al.* (2008), that corrects unmodelled phase-delay cycles imposing the nullity of all the closure phases. The use of this algorithm, or a similar one, is mandatory for a correct phase connection, given the large amount of data from many sources and antennas involved in our observations.

4. The University of Valencia Precision Astrometry Package (UVPAP)

For the astrometric fits and the phase-connection process we used the *University of Valencia Precision Astrometry Package*, an extensively improved version of the VLBI3 program (Robertson 1975). See Martí-Vidal *et al.* (2008), and references therein, for details of the UVPAP model. The main improvements of UVPAP include the use of the JPL ephemeris binary tables and the upgrade of relativistic effects of the Solar System bodies, computed using the Consensus Model (McCarthy & Petit 2003). The main advantage of UVPAP with respect to other software packages is the ability to perform multi-source differential phase-delay astrometric fits. The differential phase-delays are largely free from unmodelled effects of the troposphere, ionosphere, and antenna electronics (e.g. Marcaide *et al.* 1994). Thus, their use brings more precision to astrometric measurements. In Fig. 1 (b), we show the residuals of undifferential (upper plot) and differential (lower plot) phase-delays corresponding to the baseline Hancock – Kitt Peak and to ALL sources observed on the epoch 2000.46 at 15 GHz. As seen, all unmodelled contributions present in the residuals of undifferential delays cancel out when we compute the differential delays between all the source pairs (notice that the dashed lines in the lower plot mark the delays corresponding to ± 1 phase cycle at 15 GHz).

5. Differential phase-delay astrometry vs. phase-reference mapping

In essence, our global differential phase-delay astrometry is the same as the phase-reference astrometry (Beasley & Conway 1995), since in both approaches the main observable used is the differential phase (delay) between the signals coming from different sources. Nevertheless, there is an important distinction between our astrometric approach and the phase-reference technique: in the phase-reference astrometry, the coordinates of one source (the target source) are determined with respect to the coordinates of another

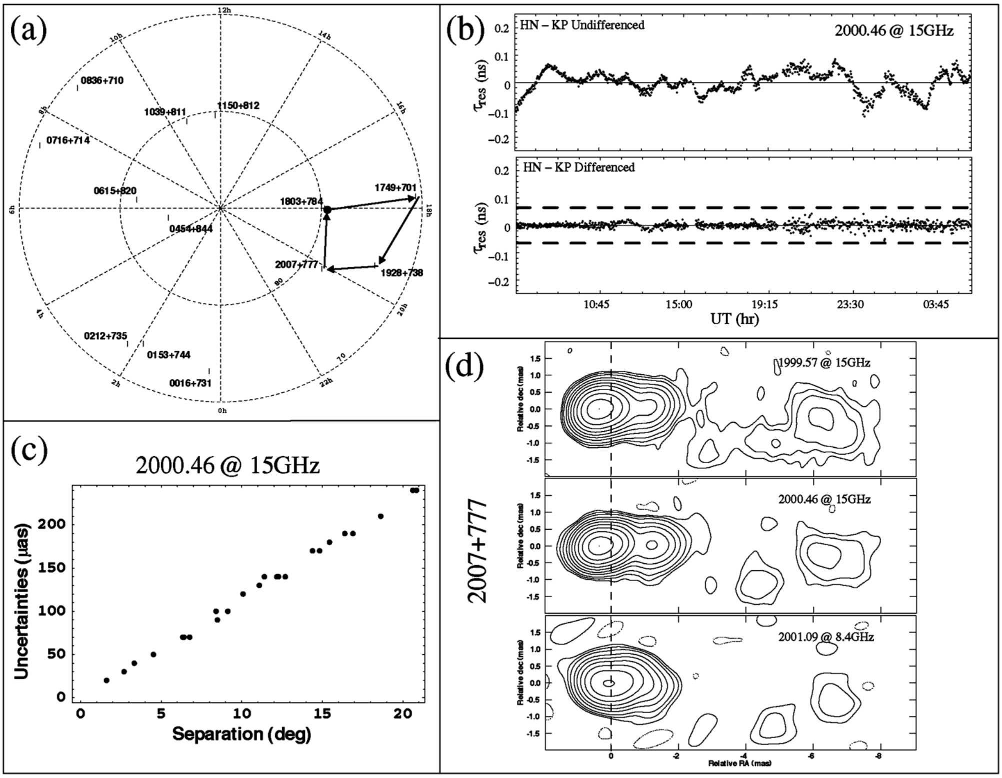

Figure 1. Several figures related to the astrometric analyses here reported (see text).

source (the reference source). *In our global analysis, we use data from all the 13 sources of the S5 polar cap simultaneously, in a single fit, thus putting more constrains on the solution and increasing the astrometric precision.* Of course, the corrections corresponding to the source pairs with large separations have relatively large uncertainties, but such sources will have more precise position estimates with respect to closer reference sources, as we show in Fig. 1 (c). In this figure, we plot the uncertainties of the source angular separations as a function of separation. The dependence is roughly linear, as predicted by Shapiro *et al.* (1979), and later found in numerical simulations by Pradel, Charlot, & Lestrade (2006). Comparing our results to those reported by Pradel, Charlot, & Lestrade (2006) using the phase-referenced technique, with our global analysis we increase the precision ~10 times.

6. Absolute kinematics

The complete analysis of our multi-epoch and multi-frequency observations of the S5 polar cap sample will allow us to study absolute kinematics of the components of all observed quasars and BL Lac objects. We will be able to check some key predictions of the standard jet interaction model, the synchrotron opacity effects and stationarity of the source cores. As an example of the results that we have from our astrometric analysis, Fig. 1 (d) shows preliminary results of the position changes of source 2007+777 for the epochs 1999.57 and 2000.46 (both at 15 GHz) and 2001.09 at 8.4 GHz. The contours are at −0.1, 0.1, 0.2, 0.4, 1, 2, 4, 8, 16, 32, 64, and 99 percent of the brightness peak at

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each epoch. The dashed line marks the right ascension of 2007+777 according to the ICRF-Ext.2 positions (see Fey *et al.* 2004). As we can see in Fig. 1 (d), there is a clear indication of a shift in the peak of brightness at 8.4 GHz towards the West, with respect to the brightness peak at 15 GHz.

7. Conclusions

We have performed the first high-precision wide-field multi-source astrometric analyses using the phase-delay observable. We have developed new algorithms and updated existing software to create UVPAP, a package that allows us to solve automatically for the ambiguities of the phase-delays and perform a multi-source differential phase-delay astrometric analysis. Such analysis brings nearly an order of magnitude higher precision than the commonly used phase reference technique.

Other wide-field high-precision astrometric analyses, similar to those reported here, are currently under way and will eventually provide spectral information and absolute kinematics of all sources in the S5 polar cap sample. Ultimately, we expect to provide a definitive test on the stationarity of the radio source cores and some stability checks for this subset of ICRF sources.

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