On the way to global phase-delay astrometry

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The use of the phase-delay improves substantially the accuracy obtained in VLBI astrometry with respect to the group-delay observable. Recently, Ros et al. (1999) have extended the related phase-connection technique to a triangle of radio sources with relative separations up to 6.8° (the S5 sources BL 1803+784/QSO 1928+738/BL 2007+777). This technique has also been extended for separations up to 15° in the studies of the pair of S5 radio sources QSO 1150+812/BL 1803+784 (Pérez-Torres et al. 2000). We are carrying out a long-term astrometric programme at 8.4, 15, and 43 GHz to determine the absolute kinematics of radio source components in the 13 members of the complete S5 polar cap sample. For each epoch, all the radio sources are observed at the same frequency for 24 hours in total. Bootstrapping techniques are used to phase-connect the data jointly for the 13 objects throughout the observations. An accurate registration of the maps of the radio sources at different frequencies will allow a study of jet components with unprecedented precision and provide spectral information. This observing scheme could be extended in the future to other regions of the sky and eventually lead to global phase-delay astrometry.

1 Introduction

The improvement by four orders of magnitude in wide-angle astrometric measurements in the last 30 years, provided mainly by Very Long Baseline Interferometry (VLBI), have resulted in a better definition of the fundamental astronomical reference frame (Johnston & de Vegt 1999), the International Celestial Reference Frame (ICRF), based on the radio positions of 212 compact extragalactic radio sources. Up to the present, the group delay VLBI observable has been regularly used for such a task. The use of the more precise phase delay observable should provide an immediate improvement in accuracy. A phase-connection process is needed (Shapiro et al. 1979) to overcome the inherent \(2\pi\) ambiguity of the phases. When used with radio source pairs, the phase delay becomes the most accurate observable in astrometry. The phase-delay astrometric technique has been applied to different pairs of radio sources with separations from minutes to some degrees in the sky (among others, 3C 345/NRAO512, Shapiro et al. (1979), Bartel et al. (1986); 1038+528 A/B, Marcaide et al. (1983, 1995) and Ríoja et al. (1997); 4C 39.25/0920+390, Guirado et al. (1995b); QSO 1928+738/BL 2007+777, Guirado et al. (1995a, 1998); 3C 395/3C 382, Lara et al. (1996)).

A significant technical problem in the astrometric data reduction is the modelling and removal of the ionospheric effect. Since the latter is a frequency-dependent effect, the removal was done in the past by observing at two frequencies. The Global Positioning System (GPS) allows now to obtain ionospheric data of unprecedented accuracy. Ros et al. (2000a) and Pérez-Torres et al. (2000) used GPS data to successfully remove the ionospheric effect. Such
an approach can be applied to any VLBI astrometric observations, without the need for dual-frequency observations.

Many compact radio sources show variable structures on scales larger than the accuracy of their position estimates. If the source structure is ignored, the group-delay astrometric results may incorrectly be interpreted as a proper motion of the radio sources. Because the radio sources, with typical redshifts of 1.0, are very distant, proper motions should not be detectable. It is true that most of the emission is generally produced in the core (brightest feature) of the source, but for low frequencies, due to opacity effects, this core may not be close to the central engine of the source (mass center of the system, which should be stationary). Until the efforts of Fey et al. (1996) and Fey & Charlot (1997, 2000) the effect of source structure had been ignored in the group-delay based reference system maintenance. These authors have initiated a programme to image the radio reference frame sources and define a source “structure index” to provide a quantitative estimate of the possible astrometric quality of them. In contrast, the phase-delay analysis from the early studies of Shapiro et al. (1979) takes into account the effect of the structure and to date, the phase-delay astrometry is the only rigorous way to register radio maps with precisions of 100 µas or better. As mentioned above, this is the technique that we use in our astrometric data analysis.

2 Phase-delay astrometry of S5 polar cap sample sources

Eckart et al. (1986,1987) selected 13 radio sources from the MPIfR-NRAO 5 GHz survey (abbreviated as S5, Kühr et al. 1981) with declinations over 70°, flat spectral indices and flux densities over 1 Jy at λ6 cm. These sources, given in Table 1 (IERS coordinates, optical magnitude and redshift) constitute the S5 polar cap sample. The sky distribution of the members of the sample, with their angular separations indicated, is given in Fig. 1.

Table 1: S5 polar cap sample.

| Name      | R.A.      | Dec        | V    | z    |
|-----------|-----------|------------|------|------|
| QSO 0016+731 | 0¹19''45.78645 | 73°27'30''0175 | 18.0 | 1.781 |
| QSO 0153+744 | 1¹57''34.96500 | 74°42'43''2305 | 16.0 | 2.338 |
| QSO 0212+735 | 2¹17''30.81337 | 73°49'32''6218 | 19.0 | 2.387 |
| BL 0454+844 | 5¹8''42.36340 | 84°32'4''5438 | 16.5 | 0.112 |
| QSO 0615+820 | 6¹26''3.00612 | 82°2'25''5680 | 17.5 | 0.710 |
| BL 0716+714 | 7¹21''53.44848 | 71°20'36''3634 | 14.2 |       |
| QSO 0836+710 | 8¹41''24.36529 | 70°53'42''1735 | 16.5 | 2.172 |
| QSO 1039+811 | 10¹44''23.06255 | 80°54'39''4430 | 16.5 | 1.254 |
| QSO 1150+812 | 1¹53''12.49923 | 80°58'29''1546 | 18.5 | 1.250 |
| BL 1749+701 | 17¹48''32.84022 | 70°5'50''7687 | 16.5 | 0.770 |
| BL 1803+784 | 18¹0''45.68393 | 78°28'4''5184 | 16.4 | 0.684 |
| QSO 1928+738 | 19¹27''48.79521 | 73°58'1''5699 | 15.5 | 0.302 |
| BL 2007+777 | 20¹5''30''99855 | 77°52'43''2478 | 16.5 | 0.342 |

Guirado et al. (1995a, 1998) studied astrometrically two sources of this sample at 2.3, 5, and 8.4 GHz, QSO 1928+738 and BL 2007+777. Ros et al. (1999) added a new source
to this pair, BL 1803+784, studied the trio at 2.3 and 8.4 GHz, and determined the relative positions with $\sim 130 \mu$as precisions at 8.4 GHz. The phase connection technique was thus extended to angular separations of 6.8$^\circ$. Later, Pérez-Torres et al. (2000) phase-connected data on the pair QSO 1150+812/BL 1803+784, separated by 14.9$^\circ$. The situation now allows us to design a strategy to extend the phase-delay astrometric technique to larger sets of radio sources. The S5 polar cap sample, given the high flux densities of the radio sources and their situation on the sky, is optimal for carrying out phase-delay astrometry simultaneously for the complete sample.

All sources have neighbours at angular distances such that the use of the phase-connection technique is possible throughout a 24 hr VLBA observing run. Using the phase-delay data from the 13 radio sources we should obtain their relative positions with accuracies better than 0.1 milliarcseconds (mas).

We have observed all the 13 members of the sample at 8.4 GHz at epochs 1997.93 and 1999.41, and at 15 GHz in 1997.57 and 2000.46 using a phase-reference scheme. In each of the 24-hour observations at each wavelength, each source was observed on average for 5 hours, enough to produce high-quality hybrid maps. In Fig. 2 we show the 8.4 GHz hybrid maps from those sources of the S5 polar cap sample that were studied astrometrically in the past — Guirado et al. (1995a, 1998, 2000), Ros et al. (1999), Pérez-Torres et al. (2000).

It is possible to observe some morphological changes just from the present mapping results at 8.4 GHz, as is the case for the sources QSO 0016+731 and QSO 1928+738 (Ros et al. 2000b). As an example, we present in Fig. 3 the changes in the inner jet features of QSO 0836+710 after convolving the CLEAN-components of the map with a 0.6 mas circular beam to better compare the images. The evolution within 3 mas of the core (P.A. $-140^\circ$) is evident during the 1.5 years elapsed between the observations.

The astrometric data reduction of the S5 polar cap sample data is in progress. We can report very interesting preliminary astrometric results from the observations of epoch 1997.93. The joint phase-delay analysis for all the 13 radio sources did not present particular difficulties. The quality of our analysis is demonstrated by the low root-mean-square (30 ps)
Figure 2: VLBA images of QSO 1150+812, BL 1803+784, QSO 1928+738, and BL 2007+777 from observations on 6 December 1997 (1997.93) and 28 May 1999 (1999.41). Axes are relative $\alpha$ and $\delta$ in mas. Minimum contour levels are of 1.0 mJy/beam for QSO 1150+812 and BL 1803+784, 1.4 mJy/beam for QSO 1928+738, and 0.9 mJy/beam for BL 2007+777. Note that the convolution beam of a given source in a given epoch substantially differs from those of other sources and epochs, due to the different coverages of the $(u,v)$ plane.
Figure 3: VLBA images of QSO 0836+710 convolved with a 0.6 mas circular beam. We observe the small structural changes in the inner part of the jet. The dashed lines draw a tentative association between features from one epoch to another.

Figure 4: Postfit residuals of the (undifferenced) phase-delays at 8.4 GHz after a weighted least-squares analysis that estimates the relative separations between the radio sources. One phase-cycle at 8.4 GHz corresponds to 120 ps of phase-delay. Notice a similar trend for all sources. These trends cancel out in the differences to yield a global residual rms of \(\sim 30\) ps.

The post-fit residuals shown in Fig. 4. The phase-connection process has also been eased by the availability of an interactive, PGLOT-based software developed in our group, which permits us to efficiently correct for phase-delay ambiguities. The expected average precision (including all systematic errors) of the relative position determination of all radio sources in the sample is of \(\sim 80\) \(\mu\)as at 8.4 GHz. If extrapolated, these results indicate that our observations at 15 GHz should yield a precision of \(\sim 50\) \(\mu\)as.

Related to this work, Guirado et al. (2000) have shown the feasibility of precision differential phase-delay astrometry at 43 GHz (\(\lambda 7\) mm) by studying the pair of S5 radio sources QSO 1928+738 and BL 2007+777, separated by \(\sim 5^\circ\). For their results, the root-mean-square of the postfit residual delays is \(\sim 2\) ps, or equivalently \(\sim 30^\circ\) of phase at this frequency. There can be little doubt that the entire S5 sample can thus be studied at 43 GHz, following studies at 8.4 and 15 GHz, and the relative positions of all the sources determined with \(\sim 20\) \(\mu\)as precision. The VLBA has allocated time to observe the S5 polar cap sample also at 43 GHz.
in late 2000. Thus, the observations at 8.4 and 15 GHz will be complemented with those at mm-wavelength.

3 Conclusions

Following recent progress in the phase-delay astrometric technique (extension to larger distances, larger sets of radio sources, and higher frequencies) we have initiated a program to study the 13 radio sources of the S5 polar cap sample. We observed the sources twice at 8.4 GHz and twice at 15 GHz, and new observations are planned at these frequencies and at 43 GHz. The astrometric data reduction includes the modelling of the atmospheric, ionospheric and source-structure effects. Our first results show the feasibility of phase-connecting the 13 radio sources at 8.4 GHz, and obtain precisions in the relative separation determinations better than 0.1 mas. The absolute kinematics of the radio sources will thus be determined unambiguously. Furthermore, using the astrometric information available at 8.4, 15 and 43 GHz, it will be possible for the first time to make rigorous spectral-index maps, together with a multiwavelength study of the absolute kinematics of the S5 polar cap sources. This observing scheme could be extended in the future to further regions of the sky, on-route towards global phase-delay astrometry.

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