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Linking VLBI astrometric measurements of extragalactic radio-sources to astrophysical phenomena

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The radio-sources observed by VLBI are jetted Active Galactic Nuclei [AGN]. Most of them show a perceptible variability in their astrometric position time series (generally in the range of 0.1-1 milli-arcsecond). Such variability may be due to extrinsic effects to the source (instrumental, from the antenna network or geophysical) or may be caused by astrophysical phenomena affecting the central VLBI region of those objects, such as radio components moving from the main radio core along the jet or the influence of a supermassive binary black hole system. In order to learn more, we conducted an analysis of the direction(s) on the sky extracted from the signal in the source position time series. This analysis revealed that the astrometric variability generally happens along at least one preferred direction. However, for some sources two directions are distinguished. In parallel, *Gaia* provides optical astrometric position with an accuracy equivalent to VLBI, enabling to investigate radio-optical position offset. Comparing directions derived from radio position time series with those derived from radio-optical position offsets brings further insights into AGN astrophysical phenomena within AGN. In the future, understanding the underlying physics of AGN will be essential for the realisation of future celestial frames because of the need to identify even more stable fiducial marks on the celestial sphere.

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1. Introduction

Since nearly 40 years, more than 4000 extragalactic sources have been observed with VLBI during sessions dedicated to astro-geodesy as they permit the realisation of the most stable celestial reference frame ever made, ICRF3 being the last adopted realization [2]. These observations, their correlation and data analysis are mainly coordinated by the International VLBI Service for astrometry and geodesy (IVS) [6].

Using the observed delays and geophysical and astronomical modelling, absolute astrometric positions of the sources are adjusted simultaneously with station positions, Earth rotation parameters and other parameters linked to the Earth system or to instrumental effects. It is also possible to adjust source positions, session by session, thus allowing to detect variability on time-scales from a few weeks to a few decades. Such position time series may be derived for hundreds of sources that are observed on a regular basis. A recent study revealed that about 95% of the well-observed sources present systematics in their time series, generally at the level of 0.1-1 milli-arcsecond [3].

This astrometric variability might be due to (i) extrinsic causes, e.g. from the observing system such as the effect of the inhomogeneity of the observing network or (ii) intrinsic causes, i.e. related to the physics of the sources. The observed sources are jetted AGN and in the radio we observe their jet, and more precisely a portion of which the location depends on the frequency [4]. Physical phenomena modifying the apparent radio flux density structure may also affect absolute astrometric measurements. Correlation between photometric and astrometric variability is sometimes found, providing arguments in favour of such intrinsic effects [8].

In this study, we search for additional arguments by investigating if there is a specific direction in which the astrometric variability preferentially occurs. In parallel, the *Gaia* space mission has observed some of these sources, enabling to derive astrometric offsets between the position measured in the radio and optical bands. Since different parts of the AGN may harbour the dominating radio and optical emissions, the radio-optical offsets may also revealed a preferential direction linked to the physics of the source. By comparing those directions, we may learn more about AGN astrophysics.

In the first section, we present the data used to compute position time series and radio-optical offsets. The second section explains the method to extract a preferred direction from the position time series. In the third section, we present the results and discuss possible astrophysical phenomena involved.

2. Position time series and radio-optical offsets

The Data used to get the position time series consist of the VLBI S/X (2/8 GHz) sessions stored in the IVS data centre covering the period from the 3rd of August 1979 to the 3rd of August 2017 (6396 sessions). Positions time series were obtained through a set of 11 solutions[1]. Each solution included adjustment of the Earth orientation parameters and station coordinates corrected

[1] Each solution enables to compute the time series of a source subset and some of the rest constrain the celestial frame. If all time series were obtained through a unique solution, hence the difficulty to constrain correctly the celestial frame would affect the result)

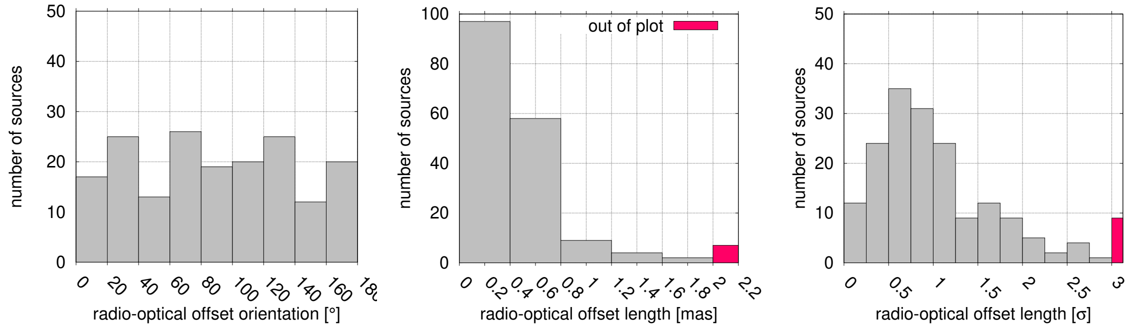


Figure 1: Radio-optical source position offset between VLBI (radio) and *Gaia* (optical). **(left)** Histogram of the directions of these offsets. **(middle)** Histogram of the offset lengths. **(right)** Histogram of the normalized offset lengths.

for tridimensional displacements due to oceanic and atmospheric loading. Antenna thermal deformations and dry tropospheric delays were fixed to a priori values. Wet zenith delays, tropospheric gradients, and clock drifts were estimated several times per session. Our data reduction model complies with the IERS Conventions 2010 [7]. More details are given in Gattano et al. [3].

We selected the position time series of 197 sources observed in at least 200 sessions for this study on which we applied the following filtering. Starting with windows of 32 years, we split them into half-length windows iteratively until the number of measurements within each window drops below 100. If that number is between 50 and 100, the mean position is then computed and retained as one point of the reduced position time series. If not, the data in the window is ignored. The reduced time series contains from two to several tens of points, from source to source. This process aims to filter the high frequency part of the signal presumed to be more sensitive to the observing system.

On the other hand, the *Gaia* collaboration published the catalogue of its 2$^{\text{nd}}$ data release which includes 2820 AGNs common to geodetic VLBI and has a position accuracy comparable to that of VLBI [5]. Among these AGNs, 177 are observed in at least 200 geodetic VLBI sessions. In Fig. 1, we present distributions of the radio-optical astrometric offsets between the VLBI mean positions (computed from the position time series) and the source positions in the Gaia DR2 catalogue. The radio-optical direction distribution (left panel) is naturally homogeneous. Offset lengths are mostly short (less than 0.5 mas, middle panel), and in general non significant with respect to the VLBI and *Gaia* uncertainties. Only 9 sources show radio-optical offsets above th 3σ level (right panel).

3. Extraction of direction from position time series

In this section, we investigate the possibility to extract a preferred direction from the reduced position time series (e.g. Fig. 2, top left panel) along which the astrometric variability occurs. For each source, we first drew the track formed by the successive position measurements in the plane of the sky (top right panel). Two successive positions make a vector that can be expressed into polar coordinates (ρ_i, θ_i) (bottom left panel). The uncertainties in the length and orientation of the vectors are derived from the formal errors in right ascension and declination for those two positions. The values θ_i are considered as measurements of the direction of position variability.

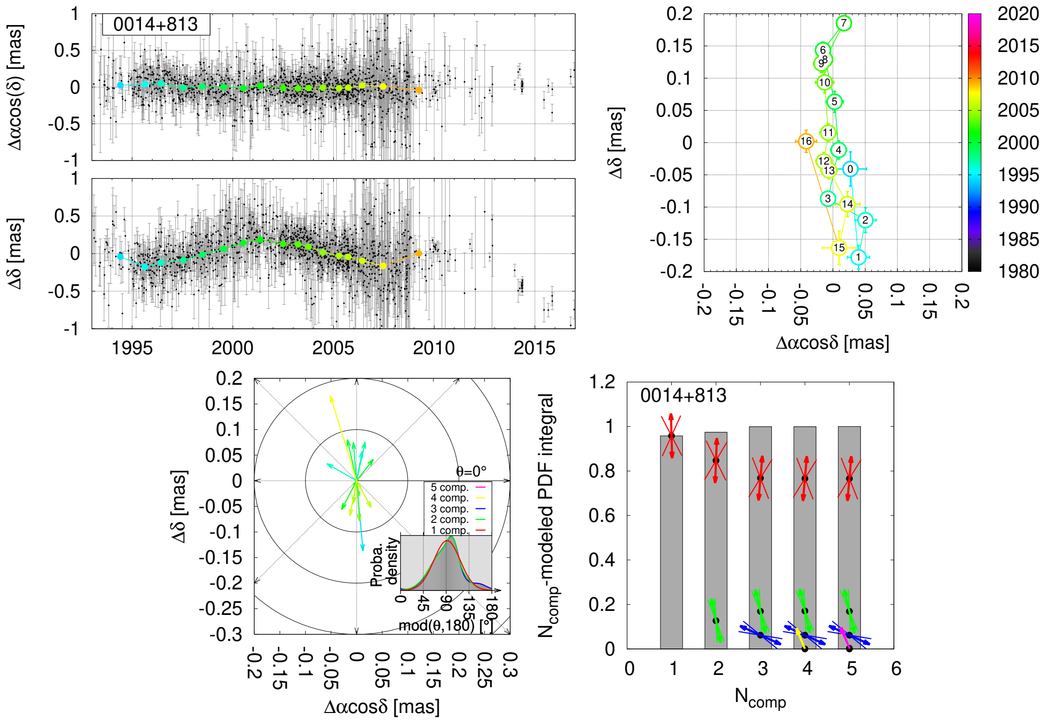
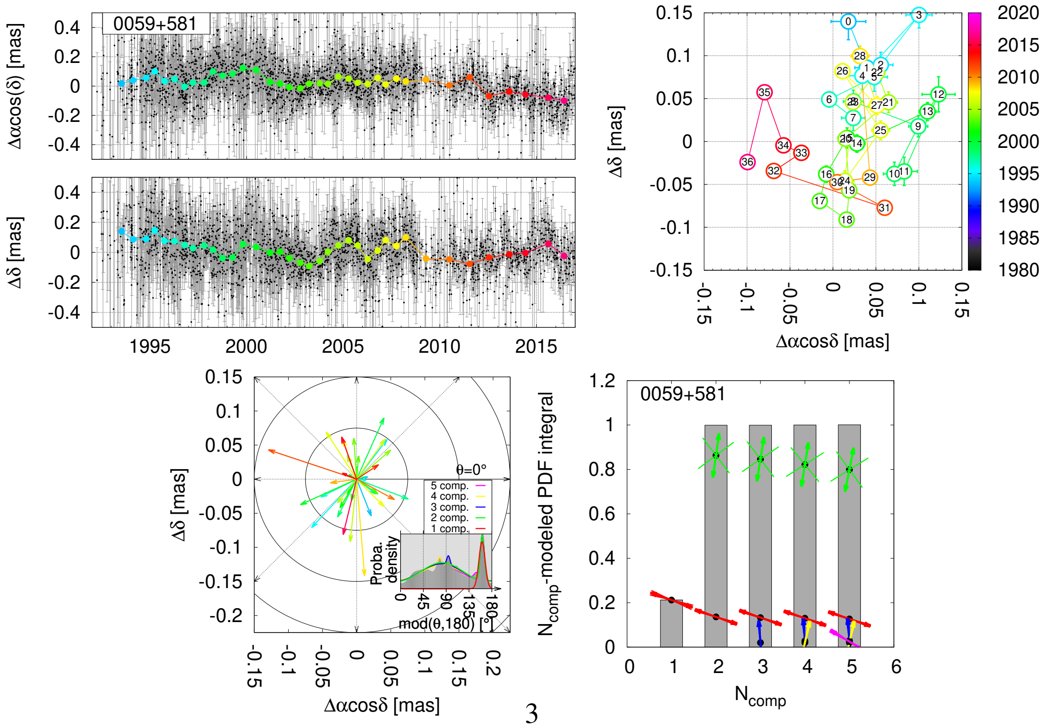


Figure 2: Extraction of preferred directions from source position time series. Case of the source 0014+813. **(top left)** Position time series expressed as offsets from the mean (black dots/gray error bars) and associated reduced time series (coloured dots). **(top right)** Reduced 2-D track on the plane of the sky. **(bottom left)** Successive position vectors and derived preferred direction PDF. The coloured lines superposed to the PDF represent the adjusted N_{dir}-model PDF (inset plot). **(bottom right)** Relevance of the N_{dir} model. Higher relevance is reflected by the gray bars being close to 1. Coloured arrows show the directions extracted along with their uncertainties, while their vertical positions give their weights in the adjustment.

Figure 3: Same as Fig. 2 for the source 0059+581.



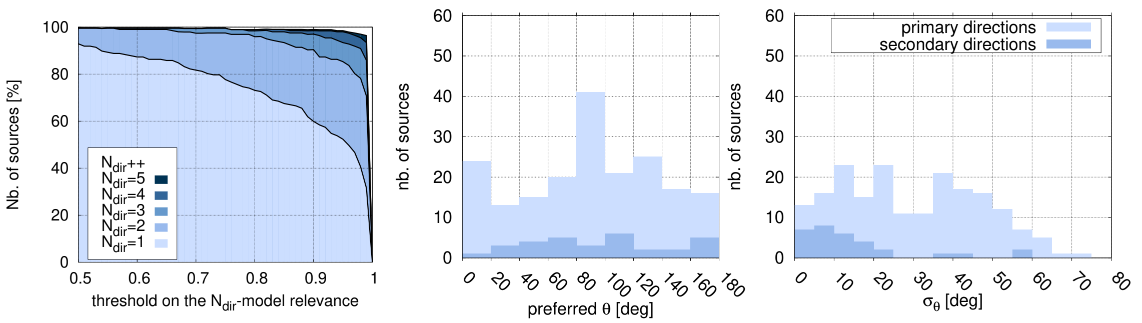


Figure 4: Statistics on the directions extracted from the source position time series. (Left) Percentage of sources with $N_{dir} = 1, 2, ...$ for a given threshold on the N_{dir} model relevance. (Middle) Histograms of the primary and secondary directions extracted when considering a threshold of 0.9 (Right) Histograms of uncertainties for the primary and secondary directions plotted in the middle panel.

Then, we built for each source a Probability Density Function [PDF] of the preferred direction by summing all such measurements. Each of the vectors contributes to the PDF by a Gaussian function centred on the direction θ_i, with half-width at half-maximum equal to σ_{θ_i} and an amplitude equal to the ratio between the length ρ_i of the vector and its error σ_{ρ_i}. The PDF built in this way is then normalized in order to make its integral equal to one, complying with the definition of a PDF (bottom left panel, gray-filled graph).

Finally, we fitted different models parametrized by $N_{dir} = 1$ to 5 Gaussian functions to the derived PDF. The adjusted Gaussian functions define the preferred directions Θ_j $(j = 1...N_{dir})$ from the position of the Gaussians and the uncertainties σ_{Θ_j} from the half-width of the Gaussians (bottom right panel, arrows and cones). The relevance of the adjusted models is given by the closeness of their integral to the unit value. Sometimes only one direction appears to be necessary, e.g. for the source 0014+813 ($\Theta_1 = 92 \pm 25°$, Fig. 2), while in other cases two directions (or more) are required, e.g. for the source 0059+581 ($\Theta_1 = 161 \pm 4°$, $\Theta_2 = 82 \pm 45°$, Fig. 3).

4. Results and discussion

Statistics on the number of directions extracted for the 197 sources in our sample are given in Fig. 4 (left panel). In this plot, we give the percentage of sources for which j directions are found given a threshold on the model relevance (priority is given to the model with the smallest number of directions). For example, if we consider a threshold of 0.9, about 60% of the sources are found to have a single preferred direction while another 30% are well fitted with two preferred directions.

The other panels show the distribution of the dominant and secondary directions and their uncertainties (middle and right panels, respectively). First, we note an excess of directions close to 90°, i.e. along the declination axis. There is no reason to expect such an excess, hence it is thought that it comes from the observing system (most probably from the inhomogeneous distribution of station positions between the northern and southern hemisphere). A similar excess is not seen for the secondary directions.

The right panel shows that the uncertainties on those directions cover a wide range of values. About half of them are well constrained ($\sigma_\Theta \lesssim 30°$) while this is not the case for the rest

($\sigma_\Theta \sim 30-70^\circ$). The absence of a well-defined direction for the astrometric variability may indicate sources for which the noise dominates the position measurements, which leads to random directions between successive positions making fitted Gaussian function larger. On the opposite, the existence of a well-defined direction may originate from a core-jet structure along that same direction with radio knots moving down the jet, hence creating the observed source position instabilities. Nevertheless, if the apparent geometry of the jet is non-linear (e.g. case of bended jets), the uncertainty on the direction extracted may take larger values.

The presence of secondary directions (most of them well-constrained, $\sigma_\Theta \lesssim 20^\circ$) is of interest as it may reflect the existence of supermassive black hole [SMBH] binary system (e.g. [1]) within AGNs. For such objects, we may indeed expect variability in the direction along the jet, as for sources with solely one SMBH, but also in the direction linking the two SMBH (assuming they both show radio activity). The difference between the two directions can nevertheless take any value.

Comparison of the primary directions (using a threshold of 0.9) with the radio-optical offset directions is illustrated by the histogram in Fig. 5. In this histogram, we see that the sources may be divided into two populations : (i) those where the two directions are aligned with respect to the uncertainties (mainly the pink bars) or (ii) those where the directions are distinct (mainly the green and blue bars). For the latter, we see that the two directions are preferentially perpendicular.

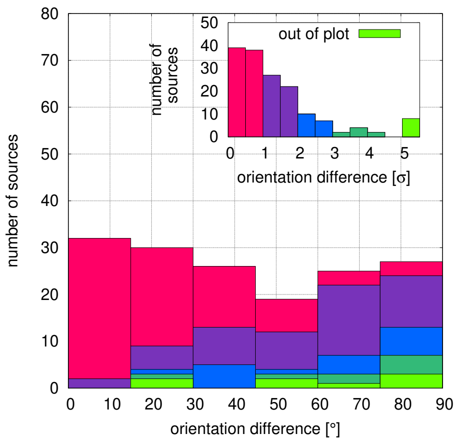


Figure 5: Histogram of differences between directions extracted from position time series and those derived from radio-optical offsets. The degree of significance is characterized by different colours : not significant at the 1σ (pink), at the 2σ level (purple), at the 3σ level (blue) ; significant at the 3, resp. 10 σ level (dark, resp. light, green).

In the case of a significant differences between the two directions, if we assume that the astrometric variability is preferentially along the jet, this implies that the radio-optical offset is directed across the jet, and hence that the accretion disk or host galaxy may harbour the dominant optical emission. On the contrary, if we assume that the VLBI-Gaia offset is directed along the jet, the astrometric variability then would occur preferentially across the jet. In this case, this may reveal the competition between the two SMBH activities in the binary system.

In the future, we plan to extract the jet direction from AGN images of the Bordeaux VLBI Image Database. This will add a new piece of information which, when compared to the presently available information (direction of astrometric variability and radio-optical offsets), may shed new lights on the astrophysical phenomena at work in the AGN central regions.

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