FP7-RADIONET
ADVANCED LONG BASELINE INTEROPERABLE USER SOFTWARE (ALBIUS)
6.2.6 REPORT ON ASTROMETRIC CALIBRATION

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Abstract.

Very Long Baseline Interferometry (VLBI) has been unique in producing a grid of extragalactic radio source positions over the entire sky with astrometric accuracies at the level of a few tens of microarcseconds. In addition, the VLBI technique allows one to derive relative source positions over a few-degree separation with even higher accuracies. The purpose of the work carried out within the ALBiUS Joint Research Activity of FP7-RadioNet has been to study the feasibility of combining the two approaches – wide-angle and narrow-angle VLBI astrometry – in a unified way. The work has focused on developing appropriate software to simulate mixed VLBI sessions that comprise the two types of measurements and to analyze jointly and consistently those mixed data sets. We illustrate the outcome of these developments with the case of a simple such mixed VLBI session to demonstrate that this scheme has been successfully implemented.

1 Context of the work

Very Long Baseline Interferometry (VLBI) is unique among astronomical observing techniques in its capability to achieve extremely high angular resolution on distant celestial targets. Such a capability allows one to probe the structure of the observed targets (active galactic nuclei, stars, supernovae,...) in their finest details. In this respect, VLBI has important implications in various fields of astrophysics where angular resolution is essential : investigation of jet kinematics in the inner regions of active galactic nuclei (e.g. Lister et al. 2009), monitoring of the evolution of photospheres and circumstellar envelopes in evolved stars (e.g. Diamond & Kemball 2003), studies of the growth of supernovae in nearby galaxies (e.g. Marcaide et al. 2009).

VLBI also allows one to measure positions of celestial targets with unprecedented accuracy (a few tens of microarcseconds) through astrometric-type observations. Such observations led to the introduction of the International Celestial Reference Frame (ICRF), the first-ever celestial reference frame based on distant extragalactic sources (Ma et al. 1998). The current version of the ICRF – the ICRF2 – comprises 3414 radio sources (corresponding to an average of one source every 3° on the sky) with position accuracies reaching 60 microarcseconds (Ma et al. 2009). The ICRF2 relies on nearly 30 years of accumulated VLBI data acquired in standard geodetic and astrometric mode (i.e. based on sessions observing sources that are widely separated on the sky).

VLBI astrometry has also drawn the attention of the galactic community in recent years for its ability to determine the distance of star forming regions (e.g. Loinard et al. 2007) and to constrain fundamental dynamical parameters of the Milky Way and its formation and evolution history (e.g. Reid et al. 2009). Unlike ICRF-type observations, the technique used for such determinations relies on differential astrometric VLBI measurements between the targets of interest and nearby calibrators. This scheme requires a grid of calibrators shortly spaced on the sky with absolute positions accurately known beforehand. As demonstrated by Fomalont et al. (2002), relative position accuracies at the level of 10 microarcseconds may be reached with such measurements.

While the ICRF2 with a grid sampling of 3° is the basis for the identification of calibrators at present, a denser catalog would be desirable, e.g. with a grid sampling of 1° or less, since systematic errors in differential VLBI astrometry scale according to the calibrator-target angular separation (Pradel et al. 2006). The purpose of the work carried out within the ALBiUS Joint Research Activity of FP7-RadioNet was to study the feasibility of such a massive densification by combining wide- and narrow-angle VLBI astrometric measurements in a unified analysis. As described below, the work has focused on developing appropriate software to simulate and process VLBI sessions that comprise both types of measurements To our knowledge, only another such attempt has been made so far though using a different approach than ours (Martí-Vidal et al. 2008a, 2008b).

Section 2 defines the observables used in wide- and narrow-angle VLBI astrometry and provides basic information about the two observing modes. Section 3 describes the tools that we have developed to simulate mixed VLBI sessions comprising both narrow- and wide-angle VLBI astrometric measurements along with the software package used to analyze such datasets. Section 4 illustrates the outcome of our work with the case of a VLBI session that was generated with these tools and the results of analysis of the corresponding data. Further software developments which could be accomplished to extend the present work are discussed in Section 5.

2 Absolute vs differential VLBI astrometry

The three observables used in VLBI astrometry are the phase delay $\tau_{pd} = \phi/\omega$, the group delay $\tau_{gd} = \partial\phi/\partial\omega$ and the phase delay rate $\dot{\tau}_{pd} = (1/\omega)\ \partial\phi/\partial t$, where $\phi(\omega, t)$ is the fringe phase, which depends on the frequency $\omega = 2\pi\nu$ and time t. The group delay is estimated from a linear fit of the fringe phases observed at several frequencies spread over a few hundred MHz, while the phase delay rate is derived from fitting the phases over time. Group delays and phase delay rates are used in wide-angle (or absolute) VLBI astrometry (with τ_{gd} as the basic observable) whereas phase delays are used in narrow-angle (or differential) VLBI astrometry.

Standard VLBI astrometric observing sessions (i.e wide-angle observations) are typically 24-hour long as this period of time is required to separate parameters for nutation and polar motion. Observations are conducted simultaneously at two frequencies (8.4 and 2.3 GHz) so that the ionospheric contribution to the group delays and phase delay rates may be removed from a combination of the observables at the two frequencies. A total of 50 to 100 sources well spread over the celestial sphere is usually observed in each session. Full coverage of the sky is achieved by using various VLBI networks both in the northern and southern hemispheres. Sources that are common to several sessions are used to link the positions of all sources observed in these sessions, which is the basis for building celestial reference frames such as the ICRF or its successor, the ICRF2 (shown in Fig. 1), from accumulated data. In addition to source positions, other parameters of interest (station locations, Earth's orientation parameters,...) may be estimated as well as nuisance parameters (clock and troposphere variations).

Unlike global VLBI astrometry, phase-referenced (or narrow-angle) VLBI astrometry is focused on observing a small region of the sky. It consists in switching observations between the target of interest and a nearby angularly-close calibrator as shown in Fig 1. The position of the target is then derived relative to that of the calibrator using a specific treatment. See Lestrade et al. (1990) or Beasley & Conway (1995) for a full description of the procedure. In practice, the phase delay of the calibrator at the time the target was observed is interpolated from the immediately preceding and immediately following observations of the calibrator. The interpolated calibrator phase delay is then subtracted from the measured phase delay of the target, providing a differential phase delay which depends directly on the angular separation between the target and calibrator. This technique is of specific interest for observing faint targets since observations may be integrated over several hours, which is not possible with the standard (wide-angle) VLBI astrometric technique, limited to only a few-minute integration. Phase-referencing has the ability to reach even higher accuracies than the standard VLBI astrometric technique (theoretically less than 10 microarcseconds in relative separations) but is hampered by atmospheric systematic errors (Pradel et al. 2006). Since these errors scale with the target-calibrator angular separation, this provides further motivation to work towards obtaining a denser grid of calibrators.

3 Simulations and analysis of mixed VLBI sessions

As noted above, the goal of the work was to simulate mixed VLBI sessions that comprise both narrow- and wide-angle VLBI astrometric measurements and to analyze such data in a consistent way. Dealing with simulated observations rather than with real data is beneficial for studying this combination because one can identify session parameters or systematic effects that affect significantly the results and hence that are of importance for the observing strategy. These include e.g. the number of calibrators available, their angular distance to the target(s), the noise level in the simulated data, systematic atmospheric effects, etc... While not all these are discussed in the illustrating example of Section 4, the software that we developed has the ability to study the impact of all such parameters and systematic effects.

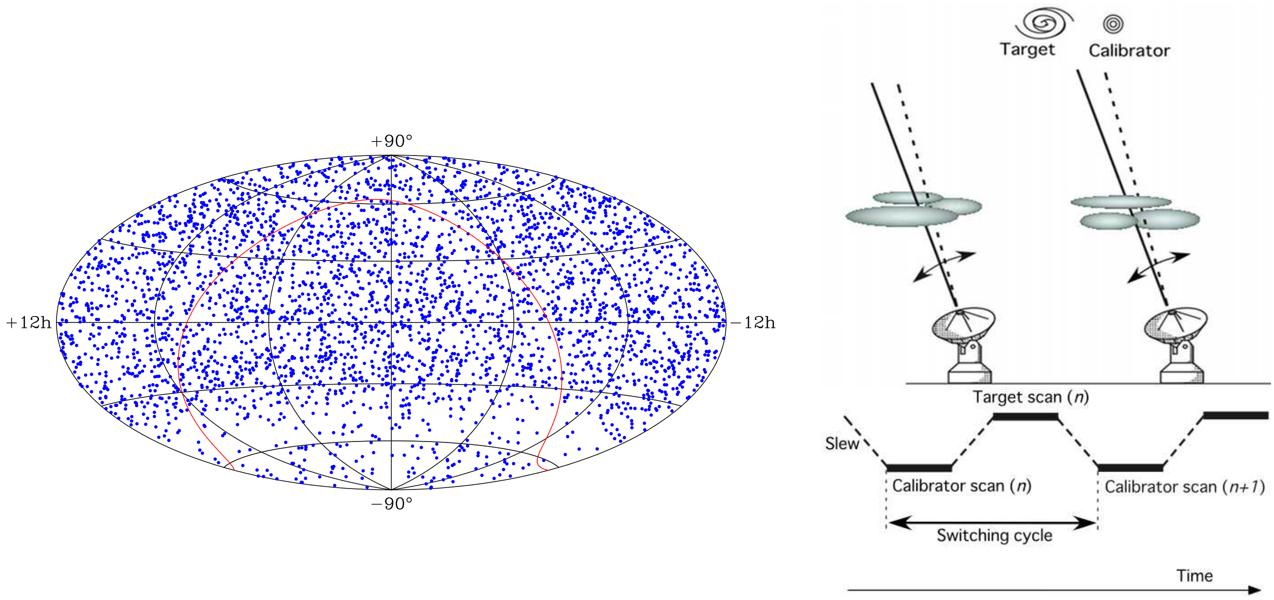

Figure 1. Left : Distribution of the 3414 extragalactic radio sources of the International Celestial Reference Frame (ICRF2) on the celestial sphere (Ma et al. 2009). The position of these sources were determined from standard VLBI astrometric observations. **Right :** Sketch showing the principle of a phase-referencing VLBI observation (adapted from Asaki et al. 2007).

3.1 Simulation software

The first part of the work has consisted in developing appropriate software to simulate VLBI sessions that include both wide-angle observations (i.e. group delays τ_{gd}) and narrow-angle observations (i.e. phase delays τ_{pd}). Simulating successfully both of these observables within the same dataset and analyzing them in a consistent way is a major achievement that open new areas for the densification of the celestial frame or for improving its astrometric accuracy based on combination of global VLBI astrometry and phase-referencing.

The software that we developed is a series of programs written in the Interface Data Language (**IDL**). This language is often used in astrophysics because it can easily handle multi-dimensional arrays such as those created to store and manipulate the many values of simulated phase delays and group delays. For completeness, the phase delay rates $\dot{\tau}_{pd}$ have been considered as well in addition to the two other astrometric observables.

A simulated VLBI session is defined as a temporal sequence of VLBI observables τ_{pd} and τ_{gd} (and possibly $\dot{\tau}_{pd}$) for celestial sources observed by a network of three or more antennas. The sequence alternates between observations on target-calibrator pairs in order to generate the usual phase referencing scheme and observations on more distant calibrators e.g. to determine corrections for wet tropospheric delays or more generally to densify the frame. The three steps to be accomplished in order to get a simulated dataset are as follows :

- *Generation of a VLBI session*
  This step is accomplished by a program that first creates an observing configuration. The input parameters needed by the program are : (i) the names and geographical locations of at least three VLBI stations (to be selected from those belonging to the European VLBI Network, Very Long Baseline Array and International VLBI Service for geodesy and astrometry) ; (ii) a list of a priori coordinates for the celestial sources to be observed (targets, nearby and distant calibrators) ; (iii) the numbers of nearby and distant calibrators (n_N and n_D, respectively) to select within the previous list of sources ; (iv) a scheme for the switching cycle between the targets and the associated nearby and distant calibrators ; (v) the date and the duration of the session (in hours) ; (vi) the frequency bands (with X band and S band as default) and the corresponding bandwidths (in MHz) ; (vii) the signal to noise ratio of the measurements ; (viii) the scan length for each target and for the nearby and distant calibrators (in seconds) ; (ix) the slewing times between the target and the nearby calibrators and to the distant calibrators (in seconds).

Based on these inputs, the program automatically selects the n_N most nearby calibrators to the target of interest. Such calibrators are selected among the current ICRF2 list of sources. Nearby calibrators are typically separated by 1 to 5° from the target. The program also identifies all calibrators that are at larger angular separations from the target (e.g. > 10°) and with elevation angles in the range 10–85° at all VLBI stations within a given period of time (e.g. 3 hours). n_D distant calibrators are then randomly selected among those with a range of declination as large as possible. The assumptions on the elevation angles and the declinations of the distant calibrators allows one to correctly sample the sky coverage above each station for a proper estimation of zenith tropospheric delays at the analysis stage.

- *Calculation of theoretical values for the VLBI observables*
  The next step consists in calculating theoretical values for the group delays, phase delays and phase delay rates based on the observing configuration and sequence of observations defined at the previous stage. Since the development of a software package to generate such values was beyond the scope of the project, we used an existing software package, **MODEST**, as the basis to accomplish this task (see below for a brief description of this software package). For this calculation, any geometrical, geophysical or atmospherical model (e.g. relativity, nutation and Earth's rotation theories, tides, plate tectonic motions, tropospheric mapping functions,...) available in **MODEST** may thus be used (see Sovers et al. 1998 for details). Phase delays are calculated for nearby calibrators and targets while group delays and phase delay rates are derived for all calibrators either nearby or distant. In this scheme, the observing times for the phase delays and group delays on the nearby calibrators may be identical or different.

- *Addition of noise to the theoretical values*
  The last step to be accomplished in order to obtain simulated VLBI observations consists in adding appropriate noise to the theoretical values previously calculated for the three VLBI observables (group delay, phase delay, phase delay rate). Noise is generated following a normally-distributed (Gaussian) law, whose dispersion is provided by the user as an input to the program. In practice, the default is to account for random noise in the VLBI quantities but systematic effects may also be considered as an additional source of noise. For example, an option is available where systematic noise depending on the elevation of the source to be observed is added to the random noise. This case is typical of systematic errors introduced by the atmosphere when sources are observed at low elevations. Note that the procedure assumes that the phase delays have been corrected for ambiguities beforehand (see e.g. Conway & Beasley 1995).

3.2 Analysis software

The second part of the work has consisted in developing the appropriate tools and schemes to analyze mixed VLBI sessions with simulated data generated as described in the previous section. By comparing the results of this analysis (post-fit residuals for the three VLBI observables, values of the estimated parameters, uncertainties of these parameters) with the original data and parameters used as input to the simulations, one can then assess the quality of the observing configuration and the impact of systematic errors.

As noted above, the development of a complete software package that accomplishes this analysis was beyond the scope of the present work. Instead, we decided to use the **MODEST** software package – an already-existing software package developed at the Jet Propulsion Laboratory (JPL) – for this purpose since it has the capability to analyze all three types of VLBI astrometric observables (group delays, phase delays, phase delay rates). We refer to Sovers et al. (1998) for a full description of the underlying modeling in **MODEST**.

MODEST stands for MODel and ESTimate and comprises two modules. The first module,"OMC" ("Observed Minus Calculated"), calculates a priori values for every VLBI observation in the session based on the geometrical and physical models implemented in **MODEST** and differences those a priori values with the observed quantities. The "OMC" results are then used by the second module "EST" which estimates the parameters of interest, e.g. the celestial coordinates (right ascension and declination) of the targets and calibrators.

The two critical points that we had deal with in this part of the work were : (i) to generate data in a binary format that can be read by **MODEST**, and (ii) to organize the writing order of the group delays and phase delays in a certain way, within that binary format, so that **MODEST** can use them *simultaneously*. The example discussed in the next section demonstrates that we have successfully resolved both of these and hence that group delays and phase delays can be processed jointly and supplement each other in mixed VLBI sessions.

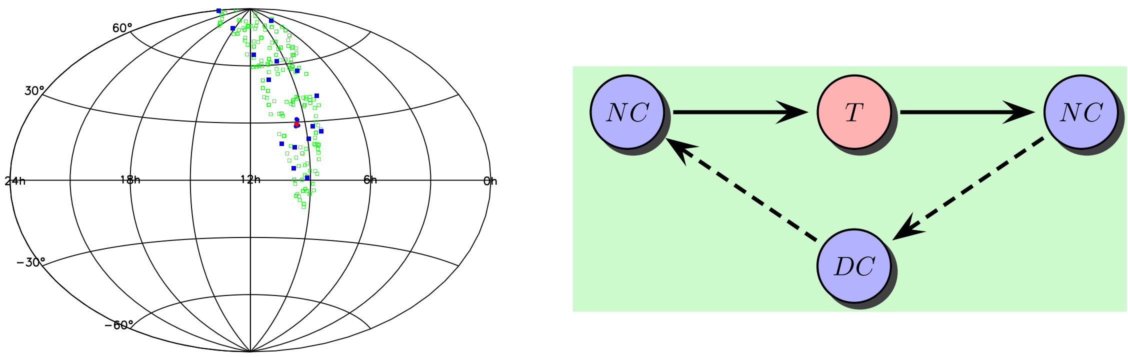

FIGURE 2. Left : Sky distribution of the target and calibrators for the simulated VLBI session presented in Tables 1 & 2. The target and four nearby calibrators are shown as red and blue dots, respectively. Suitable distant calibrators are shown as green open squares and blue filled squares with the latter indicating the 15 ones eventually used in the session after a random selection. **Right :** Sketch of the switching cycle ; T is for Target, NC for Nearby Calibrator, and DC for Distant Calibrator. Nearby calibrators are used for phase referencing while distant ones are used to estimate tropospheric delays. The cycle is repeated over the duration of the session with calibrators changing at every occurrence.

4 Illustration of the software capabilities

In this section, we use a simple mixed VLBI session to illustrate the capabilities of our simulation software and the results that we obtain after analysis of those simulated data with MODEST. The session that we consider here comprises 3 stations (SC-VLBA, BR-VLBA, Kokee) which observed 1 target, 4 nearby calibrators and 15 distant calibrators for a total of 3 hours. The nearby calibrators are those that are the closest to the target while the distant ones were selected randomly from a pool of 251 calibrators which meet the following criteria : (i) angular distance from the target $> 10°$ and (ii) elevation at each station above 10° and below 85° for the duration of the session (Fig. 2). The selection process also ensures that the range of declination covered by the 15 distant calibrators is as large as possible. Additional parameters that define the session are given in Table 1.

In addition to the source distribution, Figure 2 shows a sketch depicting the adopted observing scheme. Phase referencing is accomplished by switching observations between a nearby calibrator NC and the target T. A distant calibrator DC is then observed and the telescopes go back to observing a nearby calibrator afterwards. These steps are repeated many times over the duration of the observations, cycling over n_N and n_D calibrators. Table 2 indicates that the switching cycle of Fig. 2 has been performed 114 times and that 1026 VLBI observations have been generated for this configuration, including group delays, phase delays and delay rates.

The simulated values of the phase delays, group delays and phase delay rates generated in this way are shown in Fig. 3 for the baseline Kokee/SC-VLBA, which is the longest baseline of the network. In this example, the phase delays for the target (in the left-hand side panel) have not been phase-referenced to those of the nearby calibrators to illustrate their variations with time. The phase delays for the target and the four calibrators are comparable at the scale of the plot because these sources are all angularly close on the sky. The middle and right-hand side panels in Fig. 3 show the corresponding results for the group delays and phase delay rates (measured on the calibrators). Obvious patterns are seen, as caused by repeated observations of the four nearby calibrators. The larger scatter of the data in these panels is due to the observing of the 15 distant calibrators.

As explained above, such simulated data may then be analyzed with MODEST in order to estimate parameters of interest. Based on test solutions estimating different parameters in turn (or jointly) and by examining the corresponding parameter uncertainties, we confirm that the three VLBI observables are correctly treated by MODEST in the estimation process. We also confirm that zenith tropospheric delays may be accurately determined with the observing configuration in Fig. 2 and hence that distant calibrators are effective in their role of tropospheric calibrators. In addition to these tests, we carried out an analysis where no such parameter estimation was accomplished so that we can assess the quality of the simulated data. Figure 4 shows the post-fit residuals obtained in this case for the three observables on the Kokee/SC-VLBA baseline. The root-mean-squared residuals are 0.409 ps, 9.23 ps and 0.0102 ps/s for the phase delay, group delay and phase delay rate, respectively. These values are very close to the noise level originally implemented for these observables

Table 1. Setup parameters for the simulated VLBI session discussed in Section 4.

Date of observations	UT start time	Duration of observations	Target *a priori* coordinates
2009-11-10	12h 00m 0.0s	3 hr	$\alpha = $ 09h 28m 0.0s $\delta = +29^\circ\ 00'\ 0.0''$
Scan length for target	**Scan length for nearby calibrators**	**Scan length for distant calibrators**	**Number of nearby calibrators (n_N)**
120 s	60 s	30 s	4
Number of distant calibrators (n_D)	**Slewing time [1] NC-Target**	**Slewing time [1] NC-DC**	**Minimum separation [1] DC-Target**
15	5 s	20 s	10°
Station names	**Noise level for phase delays**	**Noise level for group delays**	**Noise level for delay rates**
SC-VLBA BR-VLBA Kokee	0.4 ps	10 ps	10 fs/s

[1]NC means Nearby Calibrator while DC means Distant Calibrator.

Table 2. Number of simulated VLBI observations available on the target and each of the calibrators for the observing configuration given in Table 1.

Source name	Source type [1]	Number of group delays	Number of phase delay rates	Number of phase delays
0615+820	DC	6	6	0
0749+426	DC	6	6	0
0810+247	DC	9	9	0
0820+560	DC	6	6	0
0833+276	DC	9	9	0
0854+213	DC	9	9	0
0906+015	DC	9	9	0
0920+313	NC	54	54	54
0920+284	NC	60	60	60
0922+316	NC	54	54	54
0928+290	T	0	0	114
0928+280	NC	60	60	60
0939+620	DC	6	6	0
0940+172	DC	9	9	0
0947+064	DC	9	9	0
1020+191	DC	9	9	0
1038+528	DC	6	6	0
1137+660	DC	6	6	0
1522+791	DC	6	6	0
2342+821	DC	9	9	0

[1]Source type : T = Target, NC = Nearby Calibrator, DC = Distant Calibrator.

in the simulation process (0.4 ps for the phase delay, 10 ps for the group delay, and 0.01 ps/s for the phase delay rate). This demonstrates that the scheme which combines phase delays and group delays in mixed VLBI sessions and the subsequent analysis of those data with **MODEST** has been successful.

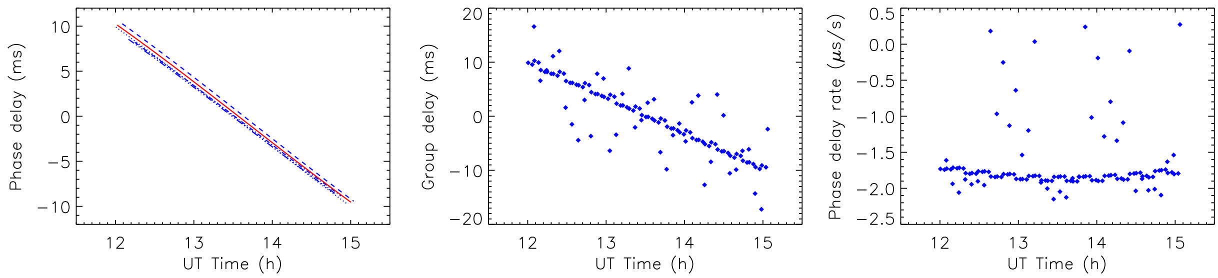

FIGURE 3. Left : Simulated phase delays for the target source and four nearby calibrators comprised in the VLBI session presented in Tables 1 & 2. Only the values of the phase delays on the baseline Kokee/SC-VLBA are plotted. The red line is for the target source while the blue ones are for the nearby calibrators. **Middle :** Same as in left-hand panel but for group delays. **Right :** Same as in left-hand panel but for phase delay rates. The data in the middle and right-hand panels are for all nearby and distant calibrators listed in Table 2.

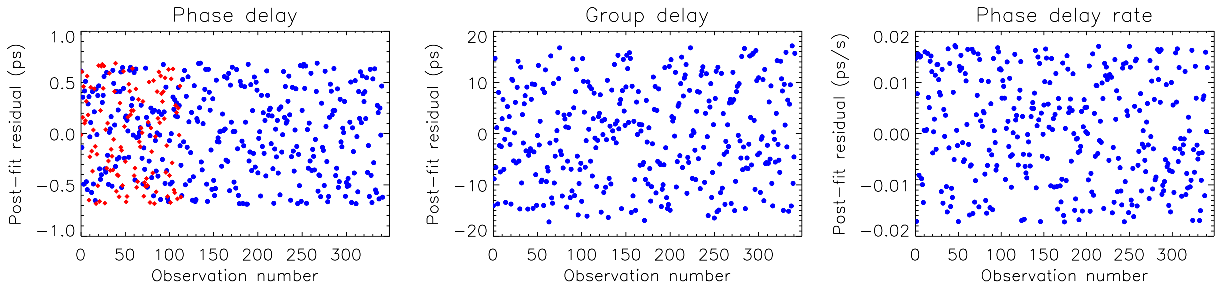

FIGURE 4. Left : Post-fit residuals of simulated phase delays after analysis with MODEST. The data are from the VLBI session presented in Tables 1 & 2. The red dots are for the target source while the blue ones are for the nearby calibrators. **Middle :** Same as in left-hand panel but for group delays. **Right :** Same as in left-hand panel but for phase delay rates. The data in the middle and right-hand panels are for all nearby and distant calibrators listed in Table 2.

5 Prospects for further software developments

The major outcome of this work is the development of a series of software tools that simulate VLBI sessions coupling phase delay and group delay measurements. The simulated VLBI data have then been successfully fitted based on the astrometric software package MODEST. The tools that we have developed are an important step towards massive simulations that mimick the densification of the celestial frame. Such simulations should help characterize new observing strategies taking advantage of both absolute and phase-referenced VLBI astrometry for improving the celestial frame either with present VLBI arrays (EVN, VLBA) or future ones such as the next generation VLBI network of the IVS or in the long term the Square Kilometre Array (SKA).

There are several areas where the software may be extended. One of them is to generalize the phase-referencing scheme to include several targets within a given region of the sky (i.e targets that could be observed with the same nearby calibrators). While this possibility has not been implemented, it is not a major issue and should be feasible with a simple extension of the programs we have developed. Another one is to extend the simulations to several such regions of the sky with the goal of ultimately covering the entire sky. This extension may be accomplished by repeating several (or many) times the previous scheme. However, a special algorithm will be necessary to deal with sources (either targets or calibrators) that are at the borders between regions.

Additionally, the statistical treatment of the simulated VLBI observables may be extended. At present, only random noise and elevation-dependent systematic errors are available to introduce in the simulated data after calculation of the theoretical values. Further options to be considered include station-dependent systematic errors (to account for the inhomogeneous quality of the telescopes) and source-dependent systematic errors (to account for the often non point-like and varying morphology of the observed extragalactic radio sources). The joint analysis of the phase delays with the group delays also offers the possibility to solve for cycle ambiguities in the phase delays. This is an option that should also be explored in terms of future software development.

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