Time Series Analysis and Stability of ICRF2 sources

V. Raposo-Pulido, H. Krásná, T. Nilsson, R. Heinkelmann, H. Schuh

Abstract We have studied the precision and stability of the positions of the radio sources observed in 3450 VLBI sessions from 1984 to 2011 using VieVS (Vienna VLBI Software). We first estimated time-series of the radio source coordinates. Each time series was then analyzed according to stability and apparent proper motion of the source. The results were compared with the requirements for defining sources as specified by the IERS (Fey et al. 2009). Thus, with this study we aim to produce an updated list of radio sources useful for geodetic and astrometric VLBI as well as to assess the precision of them. Furthermore, we intend to provide an input to the realization of the next ICRF3.

Keywords radio sources, time series, global solution, software VieVS

1 Introduction

VLBI is the only available technique for the determination of the International Celestial Reference Frame (ICRF), which is materialized by the positions of radio sources, whose coordinates are estimated with a mean precision of 40 μas. ICRF is the practical realization of the current conventional space-fixed reference system, the International Celestial Reference System (ICRS, Arias et al. 1995). The last realization, the ICRF2, consists of 3414 sources. 295 of them were selected as defining sources (Fey et al. 2009). All of them have position errors smaller than 0.1 mas and 97 of them had been defining sources of the previous realization ICRF1 (Ma et al. 1998). 2197 out of 3414 sources were observed only in VLBA Calibrator Survey (VCS)sessions, that are astrometric survey campaigns, which are specifically designed to observe a large number of new radio sources. Our research focusses on the 1217 multi-session sources, which are regularly observed by the standard IVS (International VLBI Service for Geodesy and Astrometry) networks (Schuh and Behrend). In this study we show preliminary results of our potential contribution to ICRF3 by checking the stability of the defining sources and looking for new candidates. Where indicated, we explain the variability of the estimated coordinates and other findings determined in our VLBI solution obtained by VieVS, a geodetic VLBI analysis software (Böhm et al. 2012).

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2 Selection of Defining Sources

Following the criteria of the IERS (Fey et al. 2009), based on the VLBI data analysis of the IERS/IVS Working Group on the Second Realization of the International Celestial Reference Frame: ICRF2, a source is rejected as defining source if one of the following conditions apply:

1. Formal error > 1 mas
2. Excessive structure[1]
3. < 20 observations (group delays)[2]
4. < 2-year span of data[2]
5. > 500 μas discrepancy between catalogs[2,3]
6. Position not adjusted for each session[4]

[1] Structure index (SI) at X band, when available, is 3 or 4 the source must be rejected

[2] Assessed with global VLBI solution

[3] Offsets or coordinate differences with respect to ICRF2

[4] The source must have shown enough positional stability so as to not qualify as 'arc' source. Assessed with time series of radio sources

7. Large, significant apparent proper motions[5]

In this study we check the last five criteria with our GFZ VieVS VLBI solution using three different analysis methods. The structure index (SI) from The Bordeaux VLBI Image Database (http://vlbi.obs.u-bordeaux1.fr/) is taken into account to serve as a reference to identify significant proper motions caused by radio source structure.

3 Input Data

3450 sessions (6266771 group delays) are analyzed between the beginning of 1984 and the end of 2011 with

$$\chi^2 = \frac{v^T P^{-1} v}{n-m} < 2 \tag{1}$$

where v denotes the post-fit residuals vector, n the number of observation and constraint equations, m the number of unknown parameters and P the diagonal matrix of formal errors which are the sum of formal errors from the correlator plus an error floor of 1 cm ^{2} ($\sigma_i^2 = \sigma_{i,corr}^2 + 1\ cm^2$).

4 A priori models and parameterization

All models were chosen according to the second realization of the ICRF by VLBI: ICRF2. For every single session piecewise linear offsets were estimated for the clocks (60 min + 0.5 ps^2/s), for zenith wet delays (30 min + 0.7 ps^2/s) and for troposphere gradients (360 min + 2 mm/day + constraints 1 mm). One offset was estimated for each EOP, for station coordinates, and for radio source coordinates. For the global solution the clock parameters, zenith wet delays, troposphere gradients and EOP were reduced. The antenna positions and velocities, and the source positions were estimated as one offset each.

5 Data Analysis

The data were analyzed with the Vienna VLBI Software, VieVS. In VieVS the least squares adjustment method is used, based on a sequence of estimated constant values defined at integer hours and/or integer fractions of hour of UTC, which are linearly connected by the so-called piecewise linear offsets function. Analysis options for every session were individualized to correct the clock breaks and to remove the large outlying observations. In that way, times of clock breaks were manually specified. Particular baselines, or individual stations or sources were excluded to reach a χ^2 <2. With these options, we run VieVS twice: the first run is to get the outliers and the second run to remove them. We consider an observation as outlier, if the absolute value of the residual is larger than five times the root mean square of all residuals. The cut-off elevation angle was set to 0°, however, only a very few observations were below 5°.

5.1 Global solution

At first we processed the global VLBI solution by accumulating normal equations from the set of single sessions. The datum definition of the TRF was realized by applying no-net-translation and no-net-rotation conditions (NNT+NNR) for the most stable stations. The stations, that observed in a few sessions (velocities fixed to a priori values) were reduced, keeping the velocities of the stations with breaks due to antenna repairs, Earthquakes etc, constant and applying velocity ties between stations that are close to each other. Two different datums were applied to the source coordinates (see Tab. 1). In both cases radio sources with less than three observations were fixed and sources with less than eleven observations were reduced. Fixing a radio source means, that the coordinates are not estimated and the a priori values are used for the analysis, while reducing a radio source denotes that still estimated by equation but the parameters are not explicitly given. Special handling sources, i.e. radio sources with large structure and time dependency, were also reduced. For the datum, defining sources from ICRF2 were used but the global solution 2 only considers defining sources with more than ten observations. In our solution, characteristics of the sources and the repeatability of the observations are taken into account. However, the geometrical distribution is not considered. 16 defining sources had less than eleven observations, which were not included in the datum of the global solution 2 and they were reduced or fixed according to the number of observations (see Tab. 1). Eight additional defining sources were not found in any session: 0522-611, 1143-696, 1420-679, 1633-810, 1725-795, 1925-610, 2250+190, 2344-514, most of them with declinations smaller than -50 °. The small number of observations is due to the lack of antennas in the southern hemi-

[5] Assessed with yearly-binned global solutions. The analysis used in our study is the Allan standard deviation (Allan, 1966)

sphere. Comparing the differences between global solution 1 and 2, we find that the formal errors of the sources with less than ten sessions decrease in global solution 2 by about 120 μas. All of them have negative declinations. Sources with more than 49 sessions reach an improvement of 3 μas independently of the declination. The results although better, are far below the error floor of ICRF2.

Two different kinds of sources were analyzed separately: defining sources and candidate sources. Offsets from a priori values of defining sources were compared with the number of sessions and the declination. About 65% of both offsets (dαcosδ and dδ) are smaller than 100 μas. We notice that very few sources are frequently observed (see Tab. 2), and most of them have positive declinations. Most of these sources have good visibility, however, very few sources have high-flux density. Only for negative declinations the offsets show larger scatter. The reason is that these defining sources are selected for geometrical reasons to configure the ICRF2 datum. That is not the case for candidates sources. In Table 2, a mean value for each of the six groups is estimated. Nine sources have at least one of the offsets larger than 0.5 mas: five with less than twenty observations or/and an observing period less than two years and four with less than twenty sessions or/and SI close to 3. We did the same comparison for candidate sources (see Tab. 2). 67 sources with less than 500 sessions have offsets larger than 500 μas: 49 with less than twenty observations or/and an observing period less than two years and the rest with a high SI (larger than 3 valid for 55% of these sources). In total 182 radio sources have problems with the number of observations, year span of data or discrepancy between catalogs, about 97% of them were observed in less than twenty sessions. On the other hand, eleven ICRF2 radio sources observed in less than three sessions have offsets smaller than 100 μas with declinations bigger than 15°: 0741+214, 119+183, 1420+326, 0119+247, 0602+405, 1317+520, 1335+552, 1526+670, 1756+237, 2159+505, 2340+233. These sources have an insufficient number of observations for reliable designation as defining sources. As a consequence they have formal errors between 100 to 400 μas. However, future observations could reveal a stationary character. The radio source 1420+326 has a SI of 1 for X-band and S-band, but for most of the other sources, i.e. eight out of eleven, SI were not found.

Table 1 Configuration of the two global VLBI solutions

	global solution 1	global solution 2
Number of sessions	3450	3450
Time interval	1984-2011	1984-2011
Sources analyzed	827	811
	759 from ICRF2	743 from ICRF2
Datum sources	287	271
Fixed sources	38	42
Reduced sources	135	147

Table 2 Mean absolute values of the offsets for defining (first value) and candidate sources (second value)

Sessions	Offsets [mas]	Number of sources
< 500	0.11 / 0.22	213 / 458
500 - 999	0.03 / 0.048	25 / 9
1000 - 1499	0.02 / 0.033	16 / 4
1500 - 1999	0.017 / 0.013	9 / 1
2000 - 2499	0.032 / -	4 / -
> 2499	0.02 / -	4 / -

5.2 Time Series

For this approach 24h single session solutions were computed. A total of 822 radio sources were included. The datum definition was realized by applying NNT+NNR w.r.t. VTRF2008 (Böckmann et al. 2010) and NNR w.r.t. ICRF2 for defining sources, fixing sources with less than six observations. The time series are provided with the offset estimates in right ascension and declination for every source and every session. However, some sources have a limited number of offsets, what makes it impossible to analyze their time series. With the plots we studied the stability and repeatability of the most observed radio sources (> 1000 sessions), by checking the variation of the coordinates with time. An additional criterium was introduced to remove the outliers which were not manually discarded. Radio sources with a long time series are included in sessions which are not optimally solved for them. As a preliminary approach, sessions, where at least two radio sources with more than 1000 sessions have significant offsets, were removed (116 sessions). A total of 32 sources were observed in more than 1000 sessions: 21 defining sources, three candidate sources and eight so called special handling sources. These three kinds of sources were separately analyzed, estimating the number of sessions, where each of them have offsets smaller than 1 mas and 0.5 mas to check the stability and variations of their positions (see Tab. 3). The unexpected result is that

Table 3 Sessions with offsets smaller than 0.5 mas and 1 mas for defining, candidate, and special handling sources

Sources	Sessions with offsets < 0.5 mas	Sessions with offsets < 1 mas
Defining	~ 64%	~ 81%
Candidate	~ 55%	~ 80%
Special handling	~ 46%	~ 82%

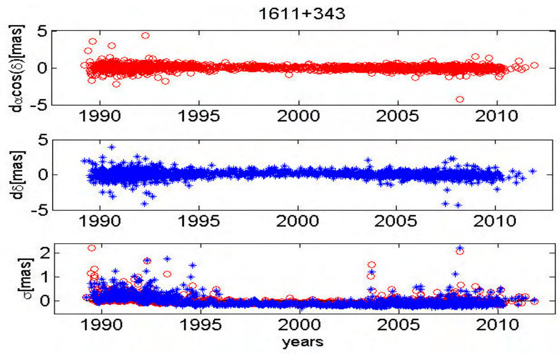

Fig. 1 Time series and difference between standard deviation estimates (with respect to the mean value) for the special handling source 1611+343

Table 4 Structure indices (SI) (first value) and total VLBI fluxes [Jy] (second value) for defining, candidate, and special handling sources. Values taken from The Bordeaux VLBI Image Database

Sources	X-band	S-band
Defining	[1,3] / ~ 2.14	[1,2] / ~ 1.54
Candidate	[2,3] / ~ 1.50	[1,3] / ~ 1.82
Special handling	[2,4] / ~ 2.66	[1,2] / ~ 2.39

special handling sources have the largest percentage of sessions with offsets smaller than 1 mas. Special handling sources exhibit significant non-linear positional variations due to the extended structure. For different epochs we can see the source either as point-like or with extended structure. At the epochs, when the source appears point-like, the offsets can be as small as those for defining sources. The source 1611+343 (Fig. 5.2) is an example, where for eight years (1996-2003) the source structure is very good. The bottom plot of Figure 1 shows the differences of the formal errors from the mean formal error (about 0.2 mas for dαcosδ and about 0.3 mas for dδ). The SI for these three kind of sources is between 1 and 4 and no bias is found (see Tab. 4). However, for all the sources the flux is in the order of several Jy. Hence, these sources were observed often because of their high-flux density and good visibility.

5.3 Yearly Global Solutions

For the yearly global solutions we divided the whole time period (1984-2011) into one year long segments. For every segment we used the same configuration as for the global solution 2 (the datum with the smallest formal errors) but including the special handling sources. We estimated the yearly global solutions, by computing the time series of the CRF. 484 sources were included in this analysis, all of them with more than one year of observation. Allan standard deviation analysis (Allan, 1966) was applied to assess the apparent proper motion of the most observed radio sources (> 1000 sessions): $\sigma_A(\tau) = \sqrt{\frac{1}{2N}\sum_{i=1}^{N-1}(x_{i+1}-x_i)^2}$ where x_i are the offsets, N is the number of yearly bins between 1 and 28 and τ is the sampling time. The criterium adapted is the partial stability criterium (Feissel-Vernier, 2003) such as the values range from 1 (AlSd $\leq$ 0.1 mas), 2 (0.1 mas $\leq$ AlSd $\leq$ 0.2 mas), 3 (0.2 mas $\leq$ AlSd $\leq$ 0.3 mas), with a rejection value of 10 for AlSd $\geq$ 0.3 mas. These partial indices clarify whether the source is stable, unstable or drifting. When we have a time series of yearly global solutions, apparent proper motions can be studied. The Allan standard deviation for sampling times is a statistical measure that takes into account the statistical scatter of coordinates. For a given length of the available time series, one could consider Allan standard deviation for sampling times longer than one year, but this estimation is expected to be more robust than for longer time spans. This is described by Feissel-Vernier (2003). In comparison to the criteria of Table 3, this analysis was made for 28 years of observations and it was applied for three different kinds of sources. The special handling sources got a partial index of 2, candidates a rejection value of 10 and defining sources between 1 and 2. 30 out of 32 radio sources were observed before 1993, when they show differences of the offsets up to 500 μas. When we consider these years in our study, the defining sources have an index of 2 or 1. It is due to the deficiency of the VLBI networks and small quantity of sources with good visibility in that years (see Tab. 5). Special handling sources show an index of 2 and candidates minimally of 3. The candidate 0119+041 (see Fig. 5.3) shows an anomalous behavior in the year 2010 (offsets ~ 4 mas) although the source was observed 91 times in this year. More observations should be scheduled in order to clarify if this source has to be considered as a special handling source for ICRF3.

Table 5 Allan standard deviations for defining, candidate, and special handling sources. The first value considers the period 1984-2011 and the second 1993-2011

Sources	AlSd [mas] ($d\alpha\cos\delta$)	AlSd [mas] ($d\delta$)	Years
Defining	0.09 / 0.07	0.11 / 0.08	> 18
Candidate	0.46 / 0.47	0.33 / 0.23	> 22
Special handling	0.11 / 0.09	0.12 / 0.11	> 22

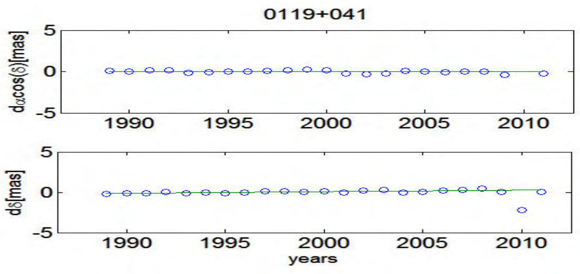

Fig. 2 Yearly global solutions for the source 0119+041

6 Conclusions

The ICRF2 defining sources are not necessarily a better configuration than a different individual datum. In our solution, where some defining sources have very few observations, we conclude that the quality of the datum is more dependent on the number of observations than the geometry. Most of the radio sources that do not satisfy the IERS criteria have a small number of observations. We could not find a clear reason for the negative results (offsets larger than 0.5 mas in global solution 2) of the defining source 1504+377. The time series show that this source was not observed during nine years (1995-2003), which worsens the results due to the lack of continuous observation. Including this source in future sessions or studying deeply the source structure would help to clarify it. In total ten non-defining sources have offsets smaller than 100 μas in less than three sessions. SI is only reported for two of them, so it would be very helpful to complete the source SI data base and to schedule more sessions including these sources in order to enable the analysis of their stabilities.

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