Maintenance of the International Celestial Reference Frame

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1. Construction of the ICRF3

Part of the activities of the ICRS Centre team at Paris Observatory have been related to the construction of the third realization of the International Celestial Reference Frame (ICRF3). These activities are a contribution to the Working Group on ICRF3 created at the XXVIII IAU General Assembly in 2012. The mission of the WG-ICRF3 is to propose to the XXX IAU General Assembly in 2018 a catalogue of radio source positions to realize the ICRS, which would include a larger interval of observation than that of ICRF2 for the computation of precise coordinates, assuring the representation of the axes of ICRS through a set of position-stable radio sources, namely defining sources. Objects in the new frame should allow the orientation of the Gaia catalogue onto ICRS.

The contribution to this task focused on (a) the comparison and analysis of different VLBI prototype solutions for a study of systematic effects and deformations, (b) the analysis of positional stability and statistics for improving the set of defining sources of the frame, (c) the implementation of a strategy for selecting stable sources respecting a homogeneous special distribution.

An important improvement with respect to ICRF2 has been the possibility of providing a multi-frequency catalogue. With this aim, prototype solutions on S/X, K, and X/Ka bands were included in the analysis. The ICRF2 (Fey et al. 2015) and the Gaia catalogue issued for the Data Release 2 (GDR2; Prusti et al. 2016; Brown et al. 2016, 2018; Mignard et al. 2018) were used as references for catalogue comparisons. The model used for the catalogue comparisons is that adopted since 2016 at Paris Observatory, which includes the three classical rotation angles, three deformation (glide) parameters and ten quadrupole parameters (see Section 3 of this report for the formulae and a discussion). Eight analysis centres produced prototype solutions for testing various effects, included the Galactic aberration correction. Complete independence between solutions had not been possible due to the use of common software for some. In all cases the no-net-rotation condition was imposed to the ICRF2 defining sources. Results of these comparisons will be available in Charlot et al. (2018). The three final ICRF3 catalogs at S/X, K, and X/Ka bands are publicly available at the ICRS Centre web site at http://iers.obspm.fr/icrs-pc/newwww/icrf.

2. Monitoring of the ICRS

One mission of the IERS ICRS Centre is the monitoring of the ICRS, which includes verifications of the stability of the axes of the system materialized though the frame, the possible deformations of the frame and the astrometric evolution of its defining sources. The comparisons realized as a contribution to the WG on the ICRF3 gave indication of the existence of deformations in the ICRF2 depending on the declination, mostly visible for sources at high South declination. This could be confirmed by the comparison with the Gaia DR2 catalogue, under the hypothesis that the Gaia frame is not subject to any significant deformation.

The IERS ICRS Centre at Paris Observatory developed the tools for analyzing the astrometric quality of radio source positions (Lambert 2014). These analyses focused on the monitoring of the defining sources in ICRF2, and on the detection of possible candidates for defining sources in ICRF3. Coordinate time series for a number of sources have been analyzed, ranking them according to their statistical behavior. We used as indicators the weighted root-mean-square of the time series in the direction of the maximum variance (computed from the major axis of the error ellipses), and the chi-square computed along this direction. Also, a visual inspection of the time series was made to detect special features (noise level, slopes, etc.). Structure indices had also been considered, but a formal inspection by the Bordeaux team completed the evaluation. These analyses were also performed on the so called "special handling sources" of the ICRF2. These are 39 sources which had been detected unstable at the elaboration of the ICRF2, and consequently treated as arc parameters in the VLBI solutions. The ensemble of analyses gave the following results:

- A number of ICRF2 defining sources presents positional instability and should be excluded from this category;
- There is no clear evidence of significant instability in the position time series of the special handling sources, suggesting that they could be resolved as global parameters in the VLBI solutions.

Based on these results, it is clear that a major revision is necessary on the set of defining sources of the new frame. The criteria adopted in the elaboration of the previous versions of the celestial reference frame focused on the position stability without considering the spatial distribution of objects. This could be one of the reasons for the deformations present in the ICRF2. The sources observed by the VLBI programs has increased in number, but a big progress happened with the observation of objects South from the equator. With this improved distribution it is possible to design a method privileging a homogeneous spatial distribution. The method retained consisted on dividing the celestial sphere into 324 equal sectors, and in each one to select the best source, considering positional stability shown in the time series and radio structure. This resulted on only two empty sectors. The classification of sources in the sectors permitted to retain a list of 303 sources qualified to be defining sources in ICRF3; 54% of them are defining sources of ICRF2, 83% are in Gaia DR2.

3. Analysis of recent VLBI catalogs

3.1. Data

We analyzed three catalogs submitted to the International VLBI Service (IVS) in 2017. One catalog was submitted by the Italian Space Agency (ASI; solution asi2017a); one catalog was submitted by Geoscience Australia (aus2017b); one catalog was submitted by BKG (bkg2017a). The aus2017b catalog was obtained with the OCCAM geodetic VLBI analysis software package (Titov et al. 2004), whereas the other two catalogs were obtained with Calc/Solve (Ma et al. 1986). As reference catalogs, we considered the current reference recommended by the International Astronomical Union (IAU), i.e., the second realization of the International Celestial Reference Frame (ICRF2; Fey et al. 2015) and the second data release of Gaia (DR2; Prusti et al. 2016; Brown et al. 2016, 2018; Mignard et al. 2018). These two reference catalogs, that were obtained by independent techniques and analyses, are of comparable accuracy but, though the former provides positions measured at the standard VLBI S/X frequency, the latter gives the positions of the same objects in the optical domain.

3.2. Overview of the catalogs

The distribution on the sky of the radio sources in each catalog is plotted in Fig. 1 together with the distribution of the standard errors. In the sky maps, the color indicates the overall error computed as the major axis of the error ellipse, calculated using the correlation information between the coordinates as provided in the catalogs. The number of sources in each catalog, the mean epoch of the observations, and the median positional errors are reported in Table 1.

The ASI solution contains a smaller number of sources than the other two catalogs. However, these are sources that have the best positional errors, so that the median error is neatly lower than for other catalogs. The comparison, restrained to 920 sources that are common to all three catalogs and to the two references, shows that ASI and BKG have similar accuracy while standard errors of AUS are larger by a factor of two. Over this common sample, the median error of the ICRF2 is a bit larger than that of AUS while the median error of Gaia DR2 is larger than that of the ICRF2 by a factor of 1.3.

An overall comparison of the error distribution with that of the reference catalogs as well as the dependence of the error on the declination are displayed in Fig. 2, for which we took the running median error within windows of 15 degrees. Note that the ICRF2 standard errors were inflated and a noise floor of 0.04 mas was imposed *a posteriori*, whereas the initial values of the standard errors could be much lower that this threshold, as they are for the three analyzed catalogs of this report.

The declination-dependent error in Fig. 2 reflects the results of Table 1 with an additional aspect: both AUS and ASI solutions show larger errors at mid-latitudes in the southern hemisphere, likely in association with the network asymmetry and the lower number of observations in the south. This feature does not show up clearly for BKG. The Gaia DR2 solution does not show such systematic effects (the Gaia scanning law allows to cover both hemispheres symmetrically).

	N	Mean Epoch	Median Error RA*	Median Error Dec	Median Error EEMA
ICRF2	3414	2001.41	396.7	739.0	756.9
Gaia DR2	2820	2015.50	233.1	211.0	263.7
asi2017a	1406	2007.53	53.2	88.3	92.5
aus2017b	4166	2009.41	313.7	551.0	579.1
bkg2017a	3606	2005.17	238.1	428.3	450.9
920 common sources					
ICRF2	920	2001.06	119.7	147.5	185.3
Gaia DR2	920	2015.50	207.5	189.0	232.9
asi2017a	920	2007.42	42.7	66.1	67.2
aus2017b	920	2008.53	114.0	147.5	154.0
bkg2017a	920	2006.48	48.2	68.5	71.2

Table 1. Statistics of the catalogs, including the two references (ICRF2 and Gaia DR2) used in this report. N is the number of sources. The mean epoch corresponds to the average of the mean observational epochs of each source. Unit is µas.

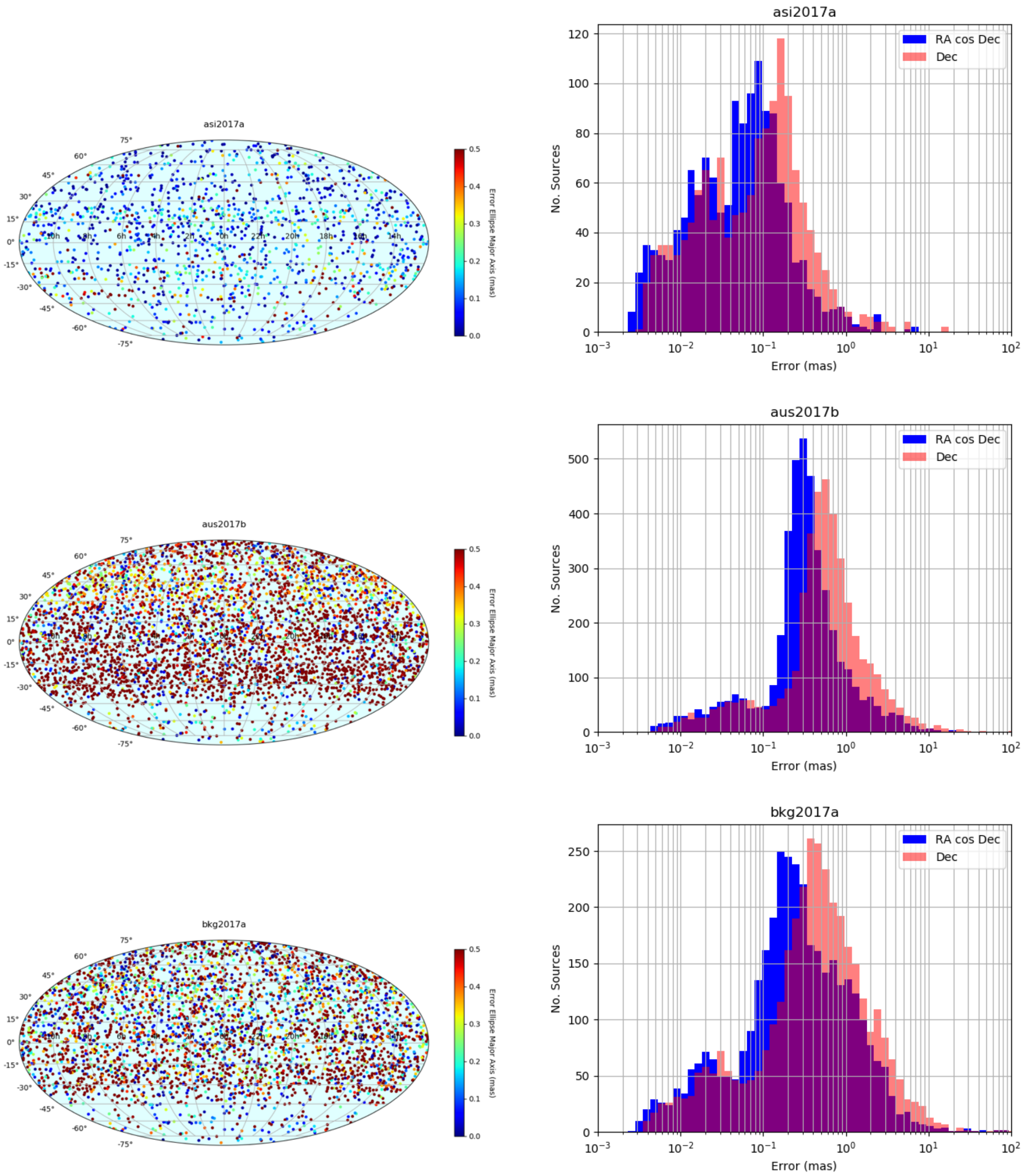

Figure 2. Left: sky distribution of the catalogs highlighting the overall positional error computed as the major axis of the error ellipse. Right: distribution of the standard errors on source position.

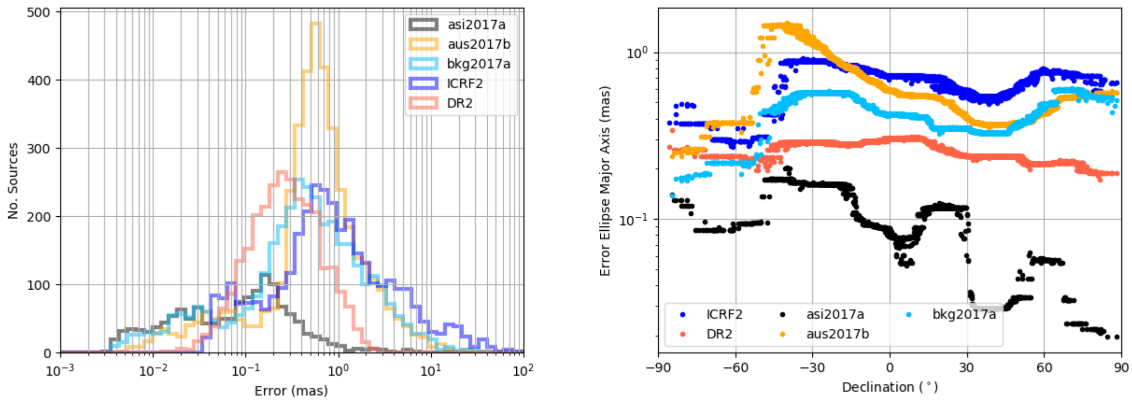

Figure 3. Left: overall comparison of the standard error distribution. Right: standard errors in source positions as a function of the declination smoothed by taking the running median within bins of 15 degrees.

3.3. Comparison with ICRF2 and Gaia DR2

Figure 4 displays the differences in declination between the catalogs and the references averaged within bins of 15 degrees. All three catalogs share the common feature of large (0.1-mas level) zonal differences with the ICRF2. A similar comparison with Gaia DR2 reveals that the zonal deformation is much smaller, concluding that recent VLBI catalogs are closer to Gaia than to the ICRF2. Since Gaia DR2 is not expected to present zonal deformations, Fig. 4 suggests that recent VLBI catalogs are less deformed than ICRF2.

Before further comparison, we removed sources that have (i) less than three observations in one catalog, or (ii) an error ellipse major axis larger than 5 mas in one catalog, or (iii) a normalized separation between catalogs larger than 5.

To model large-scale systematics, we used a 16-parameter transformation accounting for rotations around the three axes, a glide, and degree-2 electric- and magnetic-type deformations (see, e.g., Mignard and Klioner 2012). With respect to earlier works, we added therefore ten parameters mainly because the examination of the coordinate differences as a function of the declination revealed a sin 2δ pattern that was not accountable by the glide alone. The coordinate differences $\Delta\alpha$ and $\Delta\delta$ between a catalog and a reference catalog read

$$
\begin{aligned}
\Delta\alpha\cos\delta &= R_1\cos\alpha\sin\delta + R_2\sin\alpha\sin\delta - R_3\cos\delta - D_1\sin\alpha + D_2\cos\alpha + M_{20}\sin 2\delta \\
&+ \left(E_{21}^{\mathrm{Re}}\sin\alpha + E_{21}^{\mathrm{Im}}\cos\alpha\right)\sin\delta - \left(M_{21}^{\mathrm{Re}}\cos\alpha - M_{21}^{\mathrm{Im}}\sin\alpha\right)\cos 2\delta \\
&- 2\left(E_{22}^{\mathrm{Re}}\sin 2\alpha + E_{22}^{\mathrm{Im}}\cos 2\alpha\right)\cos\delta - \left(M_{22}^{\mathrm{Re}}\cos 2\alpha - M_{22}^{\mathrm{Im}}\sin 2\alpha\right)\sin 2\delta, \\
\Delta\delta &= -R_1\sin\alpha + R_2\cos\alpha - D_1\cos\alpha\sin\delta - D_2\sin\alpha\sin\delta + D_3\cos\delta + E_{20}\sin 2\delta \\
&- \left(E_{21}^{\mathrm{Re}}\cos\alpha - E_{21}^{\mathrm{Im}}\sin\alpha\right)\cos 2\delta - \left(M_{21}^{\mathrm{Re}}\sin\alpha + M_{21}^{\mathrm{Im}}\cos\alpha\right)\sin\delta \\
&- \left(E_{22}^{\mathrm{Re}}\cos 2\alpha - E_{22}^{\mathrm{Im}}\sin 2\alpha\right)\sin 2\delta + 2\left(M_{22}^{\mathrm{Re}}\sin 2\alpha + M_{22}^{\mathrm{Im}}\cos 2\alpha\right)\cos\delta,
\end{aligned}
$$

where α and δ are the coordinates of the object in the reference catalog. We used weighted least-squares to solve the system, with weights computed using the available covariance information (i.e., the standard errors on individual source coordinates and their correlation). The values of transformation parameters adjusted to the catalogs compared to the ICRF2 and

Gaia DR2 and their standard errors are reported in Fig. 5. The resulting statistics corresponding to that of Table 2 after removal of systematics are reported in Table 3. Figure 5 clearly reveals that the only really significant deformations between the catalogs and the ICRF2 lie in the D_3 and E_{20} parameters, that are associated to the purely zonal deformations in cos δ and sin 2δ, respectively, along the polar axis of the celestial frame. Such deformations show up in all three catalogs at comparable levels of about 100 µas. No significant deformations are seen with respect to Gaia DR2. A part of the detected zonal differences between ICRF2 and the three analyzed catalogs is imputable to the uncorrected Galactic aberration that moves sources towards the Galactic centre following a glide of amplitude close to 5 µas/yr (e.g., Kovalevsky 2003; Titov et al. 2011). Nevertheless, given the median epochs of the catalogs, this effect is expected to be of 20 to 40 µas in D_2 and D_3 so that it cannot explain all the present results. Another part of the zonal differences is likely an evidence that the VLBI network has improved since the construction of the ICRF2 (and, especially, it was enforced in the southern hemisphere).

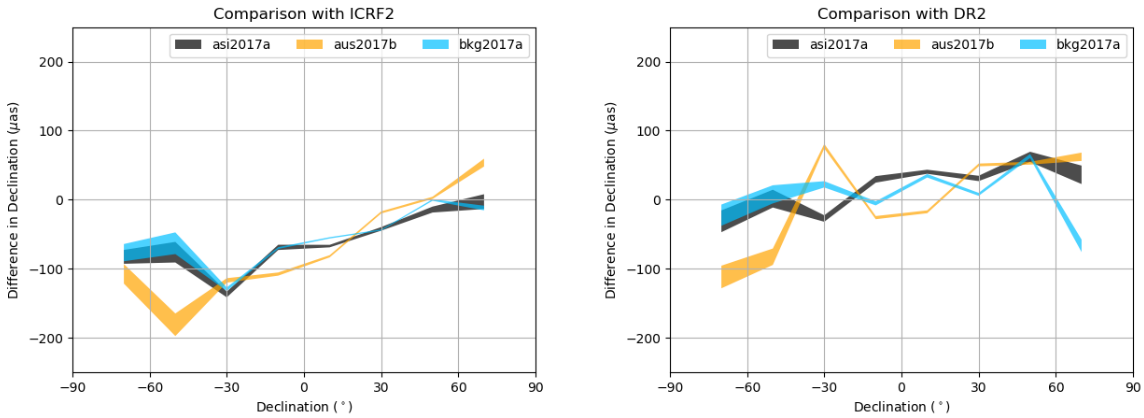

Figure 4. Differences in declination between the catalogs and the references (ICRF2: left; Gaia DR2: right) averaged in bins of declination of width 15°.

	Before				After					
		Wrms		χ^2			Wrms		χ^2	
	N	RA*	Dec	RA*	Dec	N	RA*	Dec	RA*	Dec
With respect to ICRF2										
asi2017a	1367	82.4	101.8	0.8	0.9	1264	79.3	93.4	0.8	0.8
aus2017b	3282	121.1	153.5	0.6	0.7	2780	120.2	142.2	0.6	0.6
bkg2017a	3133	86.0	109.3	0.4	0.5	2782	83.7	100.9	0.4	0.4
With respect to Gaia DR2										
asi2017a	1048	231.4	244.5	2.4	2.6	856	229.0	240.8	2.4	2.6
aus2017b	2696	320.8	336.1	1.8	1.6	2375	318.3	334.0	1.8	1.5
bkg2017a	2454	317.3	337.4	2.1	2.1	2089	315.9	335.1	2.1	2.0

Table 2. Statistics of the differences of the catalogs to ICRF2 (top) and Gaia DR2 (bottom) before and after removal of large-scale systematics. N represents the number of sources used in the comparison. Unit is µas.

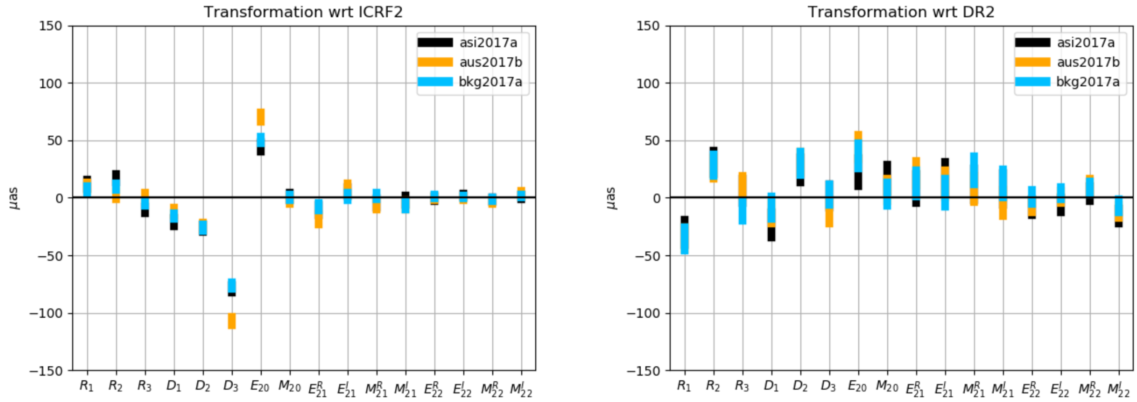

Figure 5. Transformation parameters between the catalogs and the references (ICRF2: left; Gaia DR2: right).

3.4. Conclusions and recommendations

Three catalogs were submitted in 2017. They are all consistent with ICRF2 at the level of 30 μas except for zonal deformations in cos δ and sin 2δ for which the amplitude of the difference reaches about 100 μas (likely a combination of effects including the Galactic aberration and a network improvement). All three catalogs are consistent with Gaia DR2 within 50 μas.

For a better evaluation of the consistency of the VLBI products and a better maintenance of the reference frame, especially in the frame of the next realization (ICRF3, Charlot et al. 2018) that will replace the ICRF2 as of 1 January 2019, we encourage analysis centres to submit catalogs. These catalogs should be as complete as possible, i.e., processing as much VLBI sessions as possible since 1979. Analysis strategies should be rigorously documented and motivated (e.g., why estimating some source coordinates as session parameters instead of global parameters?). The main points that will be scrutinized in the next reports will be the 100-μas level zonal systematics, their relation with the Galactic aberration, and the agreement with the current (DR2) and future releases of Gaia.

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