Astronomy and Astrophysics in the Gaia sky
Proceedings IAU Symposium No. 330, 2017
A. Recio-Blanco, P. de Laverny, A.G.A. Brown & T. Prusti, eds.
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doi:10.1017/S1743921317006731

Gaia DR1 compared to VLBI positions

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Abstract. Comparison of the Gaia DR1 auxiliary quasar solution to recent ground based VLBI solutions for ICRF2 sources.

Keywords. astrometry, reference systems, surveys, quasars

1. Introduction

In addition to observing above a billion galactic stars, Gaia catches in its net around one million distant QSOs that materialises a non-rotating reference frame directly accessible in the visible domain. The lack of global rotation rests on the assumption that distant quasars are globally at rest with respect to the CMB and can then be used to materialise a triad of inertial directions as prescribed in the ICRS principles. Regarding the orientation of this triad there is no compelling physical principle which will favour a particular choice, and the best solution is to ensure the metrological continuity by selecting the pole and the origin of right-ascension as close as possible to the current ICRF2. This alignment is achievable without loss of accuracy provided that the sources selected with radio position have an accuracy compatible with Gaia and that the radio-optical offset is smaller and random in direction. Therefore it is of utmost importance to carefully investigate the random and systematic differences between the best optical and radio astrometric catalogues of QSOs. While such a comparison has been done between the Gaia quasar solution and the ICRF2 in Mignard *et al.* 2016, we present here further analyses carried out on more recent radio solutions produced within the ongoing preparation of the ICRF3. Validating Gaia on a small subset of QSOs common to VLBI program brings confidence on the general Gaia astrometric solution for the larger set of several 10^5 found in the DR1, which materialises the optical frame.

2. Data used in these comparisons

2.1. *Gaia*

The sources are taken from 2191 ICRF2 sources published within the Gaia DR1 and available in the Gaia archive. The Gaia DR1 formal accuracy for this solution is given in Mignard *et al.* (2016). Unlike ICRF2 there is no difference of quality between the ICRF2 subsets of defining, VLBA calibrator or not. As the differences with Gaia are much smaller for the defining sources than for the calibrators, it was reasonable to conclude that the scatter seen in $(\Delta\alpha, \Delta\delta)$ reflected primarily the limited accuracy of the non-defining source in ICRF2 rather than Gaia itself.

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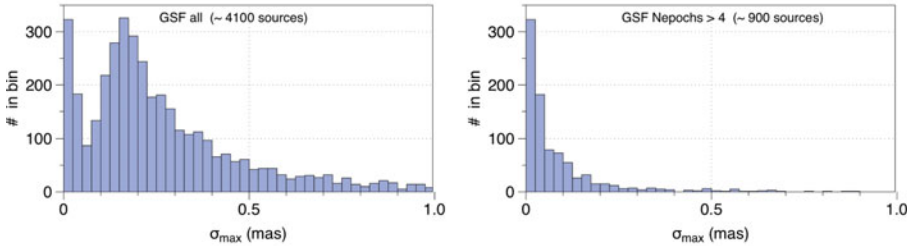

Figure 1. Formal positional accuracy of the GSFC VLBI solution. All sources with $\sigma < 1$mas (left), subset of sources observed over at least 5 epochs (right).

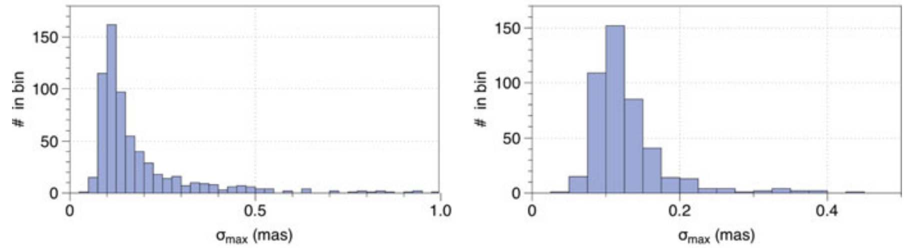

Figure 2. Formal positional accuracy of the X/Ka VLBI solution. All 673 sources (left), subset of 450 sources observed at least 25 times (right).

2.2. *GSFC*

For this new comparison we have used the most recent VLBI solution made available by the NASA/GSFC as `gsf2016a`. This catalogue includes all sources detected in X/S bands with astro/geo VLBI from 1979.7 through 2016.8 and comprises 4196 entries. Compared to ICRF2 many of the VLBA calibrators, but not all, have been observed at least at a second epoch and are of much better quality. The solution is an ICRF2-based solution, meaning the 295 ICRF2 defining sources were set to their ICRF2 positions and held to a no-net-rotation constraint. All ICRF2 sources are included and the accuracy is at the sub-mas level. The catalogue was cross-matched to Gaia observations and we found in the Gaia raw data that 3200 sources have been detected at least once by Gaia and 2700 have got a solution in the Gaia DR1 general solution. The formal error computed with the semi-major axis of the dispersion ellipse is shown in Fig. 1. The subset of well observed sources is nominally significantly better than Gaia DR1. The extended tail seen for the whole catalogue comes from the VLBA calibrators with only one epoch.

2.3. *X/Ka*

A new realisation of the Celestial Reference Frame has been produced recently in the X/Ka band (8.4/32 GHz) by Garcia-Miro *et al.* (2014) using baselines from the combined NASA and ESA Deep Space Networks for approximately 100 sessions each between July 2005 and September 2014. This results in a frame based on 654 sources (673 in the most recent update of the catalogue used in this analysis), with 525 common to ICRF2. Thanks to the addition of the ESA antenna located in Argentina in 2013, the catalogue includes 138 sources around the southern polar cap accessible for the first time. The formal positional error, computed as the semi-major axis of the error ellipse is plotted in Fig. 2 for the full catalogue (left) and the subset of the best observed sources (right). The median positional error is just above 100 μas and the tail at values larger than 500 μas is hardly visible, or even absent for the selected subset. If these uncertainties are

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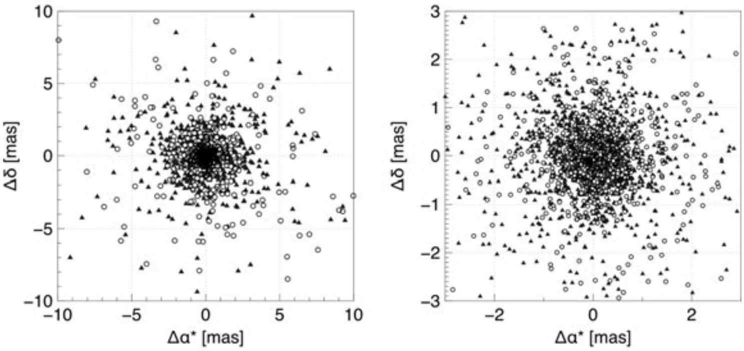

Figure 3. Positional difference between Gaia DR1 auxiliary solution and the GSF solution for the ≈ 2200 common sources within a window of ± 10 mas (left) and ± 3 mas (right). The black triangles stand for the VLBA calibrators and the open circles for the other sources, including the defining sources.

realistic, this catalogue constitutes the best reference one can use to compare with Gaia DR1 auxiliary solution and is fully independent of ICRF2 or GSF. In addition to the random errors, the authors mentioned evidence of systematic errors at the 100 μas level from tropospheric turbulence and limited calibration. The cross-match with the Gaia DR1 quasar solution ended up with 435 common sources with good Gaia solutions, most in magnitude range 18–20, but also about 80 with $G < 18$ mag.

3. Comparison to Gaia

The Gaia DR1 solution discussed here is based on the 2191 ICRF2 sources published separately in the DR1 from the Gaia auxiliary solution. Details can be found in Lindegren *et al.* (2016). In this analysis no new tie has been performed, but we checked that the remaining rotations between Gaia DR1 and the two comparison catalogues were negligible.

3.1. *GSF solution*

The main result is shown in Fig. 3, giving the scatter distribution of the positional differences between Gaia DR1 and the GSF solution within a window of 10 mas (left) and 3 mas (right). The ICRF source categories have been retained since, despite the new observations, there is still a quality difference between the defining source and the non calibration sources (open circles) and the larger set comprising the VLBA calibrators (black triangles). Generally the calibrators are more scattered throughout the diagram than the other sources. As already pointed out in Mignard *et al.* (2016), Gaia reveals here essentially the accuracy of the ICRF2 for this category of sources and this is in agreement with the quoted accuracy in ICRF2 or GSF. For Gaia there is no difference between the three classes unlike the VLBI data. Compared to the analysis done by Mignard *et al.* (2016) using the ICRF2 solution, the comparison with GSF displays a real improvement for the VLBA calibrators that have been observed at a second epoch, and no visible overall change for the other sources, since the Gaia uncertainty could be the larger source of scatter, in particular for the small set of defining sources.

3.2. *X/Ka solution*

The comparison in right ascension and declination is shown in Fig. 4 for a window of 3 mas and two selections made from Gaia formal accuracy: all common sources with Gaia

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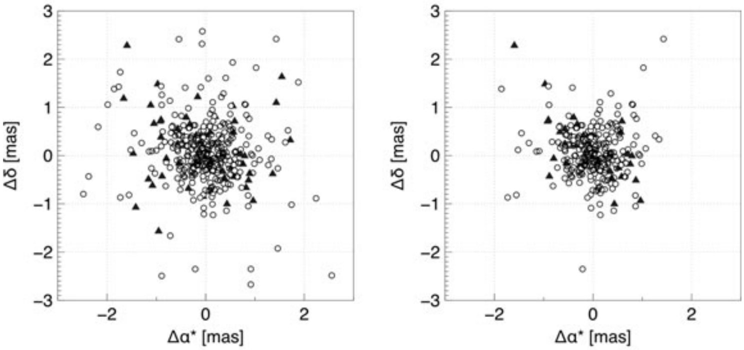

Figure 4. Positional difference between Gaia DR1 and the X/Ka solution for the common solutions within ±3mas and Gaia uncertainty < 5 mas (left , ≈ 410 sources) and < 1 mas, (right, ≈ 290 sources). The black triangles stand for the ICRF2/VLBA calibrators and the open circles for the other sources.

accuracy < 5 mas (left) and < 1 mas (right). One has 411 common solutions in the first case and 291 in the second. We have kept the distinction between the usual categories of sources inherited from the ICRF2, although this is not relevant in this case with no difference expected in accuracy in Gaia and the X/Ka VLBI solution. The reference set from the X/Ka solution is expected to be better than Gaia DR1 and the scatter is normally mostly due to Gaia uncertainty. This is clearly seen when the data are filtered with the Gaia formal accuracy at 5 mas and 1 mas. Most of the large discrepancies seen in the left diagram have been eliminated when this filter is applied. This is a strong evidence that Gaia (and X/Ka) formal errors are probably realistic with the core of the Gaia solution really in the sub-mas range. An important feature of both plots is the very regular distribution around the centre, without any visible bias in either coordinate.

4. Conclusion

We have presented new analyses of the Gaia DR1 reference frame against two independent ground based VLBI solutions. Both confirm the quality of the Gaia data and the absence of systematic offset between the radio and optical frame.

Acknowledgments

We are grateful to C.S. Jacobs for having provided us with an early access to the X/Ka solution before its completion. This research has made use of NASA Goddard Space Flight Center's VLBI source position solution gsf2016a, prepared by David Gordon and he is gratefully acknowledged for his assistance. This work has made use of data from the European Space Agency (ESA) mission *Gaia*, processed by the *Gaia* Data Processing and Analysis Consortium, (DPAC, `https://www.cosmos.esa.int/gaia`).

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