IS THERE AN INTEREST IN BRINGING GAIA-CRF INTO VLBI DATA REDUCTION ?

N. LIU[1], S. LAMBERT[2], Z. ZHU[1], and J.-C. LIU[1]

[1] School of Astronomy & Space Science, Nanjing University - China - zhuzi@nju.edu.cn
[2] SYRTE, Observatoire de Paris - France - sebastien.lambert@obspm.fr

ABSTRACT. The very long baseline interferometry (VLBI) and *Gaia* mission provide two main realizations of the celestial reference frame, which are the International Celestial Reference Frame (ICRF) and *Gaia*-CRF, with similar precision. One weakness in the ICRF is the large-scale systematics which is not supposed to be seen in the *Gaia*-CRF. It is, thus, possible to consider the *Gaia*-CRF as another option besides the ICRF in the VLBI data reduction. We generate several VLBI global solutions with different configurations on the celestial frame and compare VLBI products. Our preliminary results show that different a priori catalogs only introduce an orientation offset in the celestial frame together with corresponding bias in the UT1 and nutation series. If we fix the defining source position to *Gaia* DR2, the estimated celestial frame will be brought closer to the *Gaia*-CRF in terms of dipolar terms.

1. INTRODUCTION

The celestial reference frame (CRF) now has several realizations at an accuracy level of tens of micro-arc second (μas) since publishments of the *Gaia* Data Release 2 (DR2, Gaia Collaboration et al. 2016, 2018a, 2018b) and the third generation of International Celestial Reference Frame (ICRF, Charlot et al. 2019). The International Celestial Reference Frame (ICRF) is realized through positions of a set of radio sources measured by the very long baseline interferometry (VLBI) in the radio domain, while the *Gaia* celestial frame (*Gaia*-CRF) is constructed via positions and proper motions of extra-galactic objects in the optical domain.

One weakness in the ICRF is that it contains large scale systematics due to the north-south network asymmetry. A systematic position error of about 50 μas in the South (around $\delta = -30°$) in the ICRF2 was reported in, e.g., Liu et al 2018 but is now partly accounted for by modeling of the Galactic aberration. These systematics are not supposed to be present in *Gaia*-CRF because the scanning law of *Gaia* allows a more uniform sky coverage. The current precision of *Gaia* data is only comparable to that of VLBI but one should note that the *Gaia* DR2 used only less than half of data collected during the whole mission. As a result, the final *Gaia* -CRF could be potentially more precise (lower position error) and more accurate (lower systematics) than the radio frame. Under this situation, it would be interesting to consider the *Gaia*-CRF as an option for the VLBI data reduction. Besides, analyzing the VLBI observations within the *Gaia*-CRF could be a possible way for the radio-optic frame link. The remaining problem is the radio-to-optical distance but, except for a few sources, it should not produce any global systematics and affect the maintenance of the celestial frame datum.

For these reasons, we propose to test the possibility of considering the *Gaia*-CRF in the VLBI data reduction, to look at to which extent one could use the *Gaia*-CRF (i.e., an independent datum) as a priori and how such an a priori perturbed the VLBI products: celestial reference frame (CRF), Earth Orientation Parameters (EOP), and terrestrial reference frame (TRF).

2. METHOD AND MATERIALS

In the VLBI data reduction, a set of equations is added to the normal equation before solving it to fix the reference frame (both CRF and TRF) and reduce the degeneracies among CRF, TRF, and EOP. These special equations are called constraints. To fix the celestial frame, a so-called No-Net-Rotation (NNR) constraint is applied to a priori positions of a special ensemble of radio sources, that is, defining sources. This NNR constraint permits no (or as low as possible) rotation between the a priori and a posteriori catalogs (CRFs). In the state-of-art VLBI global solution, the NNR constraint is applied to the ICRF3 position of 303 defining sources to maintain the celestial reference frame. Instead, if we apply the NNR constraint to the *Gaia* position of an ensemble of well-selected sources, VLBI observations are then analyzed within the frame of *Gaia*-CRF. This is our implementation of *Gaia*-CRF in the VLBI data reduction.

For illustration purposes, we chose the 250 sources in the ICRF3-prototype subset of *Gaia* DR2 (`gaiadr2.aux_iers_gdr2_cross_id`[1]) common to the 303 ICRF3 defining sources. These sources represent the most precise positions in the current ICRF3 catalog but not in the *Gaia*-CRF2 (since the *Gaia* position error is quite uniform) and consist of the defining source list used in this work.

To check if the radio-optical position offset is significant, we calculated the angular separation ρ and normalized separation X between *Gaia* and ICRF3 S/X position for these 250 sources following the methods in Mignard et al. (2016). These two quantities are depicted in Figure 1. The angular separation is less than $\rho_0 = 0.71\,\mathrm{mas}$ (indicated by the horizontal red line) for the bulk (95%) of sources. In an ideal case, X is expected to follow a Rayleigh distribution, then the theoretical number of sources whose normalized separation X is greater than a certain value X_0 falls below one for $X_0 = 3.3$ (indicated by the vertical red line). If we take ρ_0 and X_0 as upper limits, most sources (about 90%) do not present a genius radio-optical offset.

Figure 2 demonstrates the dependency of the difference between *Gaia* DR2 and ICRF3 positions on the declination for 250 common sources, in the sense of *Gaia* DR2 minus ICRF3. We expanded these position differences onto a set of vector spherical harmonics (VSH; Mignard and Klioner, 2013) of the first degree to study the global difference. The model is given as followed.

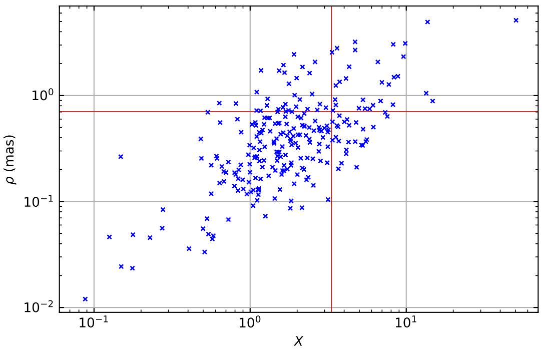
$$\begin{aligned} \Delta\alpha\cos\delta &= -R_1\cos\alpha\sin\delta - R_2\sin\alpha\sin\delta + R_3\cos\delta - G_1\sin\alpha + G_2\cos\alpha, \\ \Delta\delta &= +R_1\sin\alpha - R_2\cos\alpha - G_1\cos\alpha\sin\delta - G_2\sin\alpha\sin\delta + G_3\cos\delta. \end{aligned} \tag{1}$$

The rotation vector R characterizes the orientation between celestial frames while the glide vector G reveals the dipolar deformation or zonal errors in the celestial frame. A weighted least-squares fit of Eq.(1) gives an orientation offset of $\sim -70\,\mu\mathrm{as}$ on the X-axis (R_1) and glide terms at a level of $50\,\mu\mathrm{as}$.

We ran four global solutions using VLBI observations made at S/X-band during 1979-2019 with identical parameterizations except for the CRF. Solution A and C used the *Gaia* DR2 positions as the a priori source positions while B and D used the ICRF3 SX positions. The positions of defining sources (only 250 defining sources here) were adjusted in the solution A and B but fixed in solution C and D. The option of estimating adjustments to the position of defining sources means that the celestial frame will be adjusted in the VLBI analysis process. If not, the new celestial frame will be fixed tightly to the a priori frame. The number of global parameters is same between A and B as well as between C and D, later pair having about 500 less.

Table 1 summarizes the configuration and post-fit statistical information on these solutions. We find that the post-fit root-mean-square (RMS) and reduced-χ^2 would slightly increase if fixing the defining source positions to their a priori position; they were greater when fixing the defining source positions to the *Gaia* position. This result indicates that the ICRF3 positions suit VLBI data better than the *Gaia* DR2 positions in the case of fixing defining source positions.

[1] `http://gea.esac.esa.int/archive/`



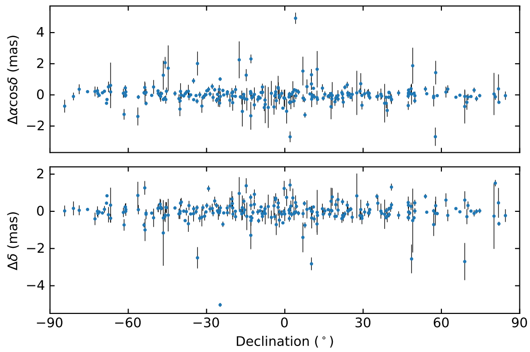


Figure 1: Angular separation and normalized separation between the *Gaia* DR2 and ICRF3 SX positions for the 250 common sources.

Figure 2: Positional difference between the *Gaia* DR2 and ICRF3 SX positions for the 250 common sources and their ICRF3 positions as a function of declination.

Table 1: Configurations of VLBI solutions.

Label	A priori catalog	Defining Source position	Post-fit RMS ps	Reduced-χ^2
A	Gaia DR2	adjusted	26.37	1.19
B	ICRF3 SX	adjusted	26.37	1.19
C	Gaia DR2	fixed	28.03	1.34
D	ICRF3 SX	fixed	26.44	1.20

3. COMPARISON OF VLBI SOLUTIONS

3.1 Celestial Reference Frame

When we only changed the a priori catalog, it is the case for solution A and B. Figure 3 depicts the positional difference between solution A and B for 4600 common radio sources as a function of the right ascension and declination. Both diagrams present a nearly perfect pattern of rotation. The fitting to the first order of VSH shows that only a dominant component of $R_1 \sim -55\,\mu$as, possibly inherited from the rotation between a priori positions, as well as $R2$ and $R3$ on the same order of $\sim +20\,\mu$as. No significant terms of glide are reported. It indicates that using different positions of the same ensemble of defining sources in the VLBI global solution would only alter the orientation of the estimated celestial frame but will not influence the zonal property.

The impact of fixing the defining source position to different a priori position on the resulted estimations of (other) source positions is presented in Figure 4. A small rotation-like pattern shows up from the noisy residuals whose weighted RMS is about 50 μas both in right ascension and declination. The rotation is estimated to be as large as $+150\,\mu$as in R_1 and $-90\,\mu$as in R_2. Meanwhile, dipole terms are found to be larger than 80 μas for all three components.

Besides the inter-comparison amongst solutions, we also compare these solutions to the *Gaia* DR2. It is intended to check if using *Gaia* DR2 as the a priori catalog would bring the celestial reference frame to the *Gaia*-CRF, the latter supposed to be free of declination-dependent errors. The rotation between each solution and *Gaia* DR2 highly agrees with the others, except the R_1 component of the solution D. The dipole parameter between solution C and *Gaia* DR2 is smaller than D in Y- and Z- component, but greater in X-component. It inspires us that the zonal-like error in the ICRF, if existing, could be minimized via the option of fixing the defining source positions to *Gaia* DR2.

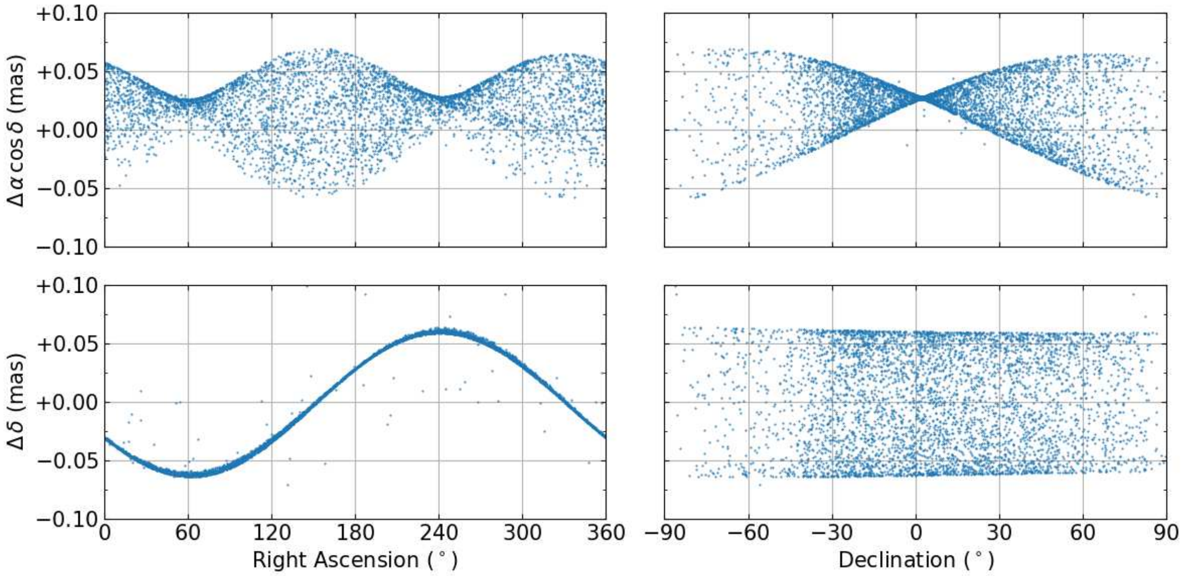


Figure 3: Positional difference for 4600 common sources between solution A and B as a function of the right ascension (left) and declination (right), in the sense of "A−B".

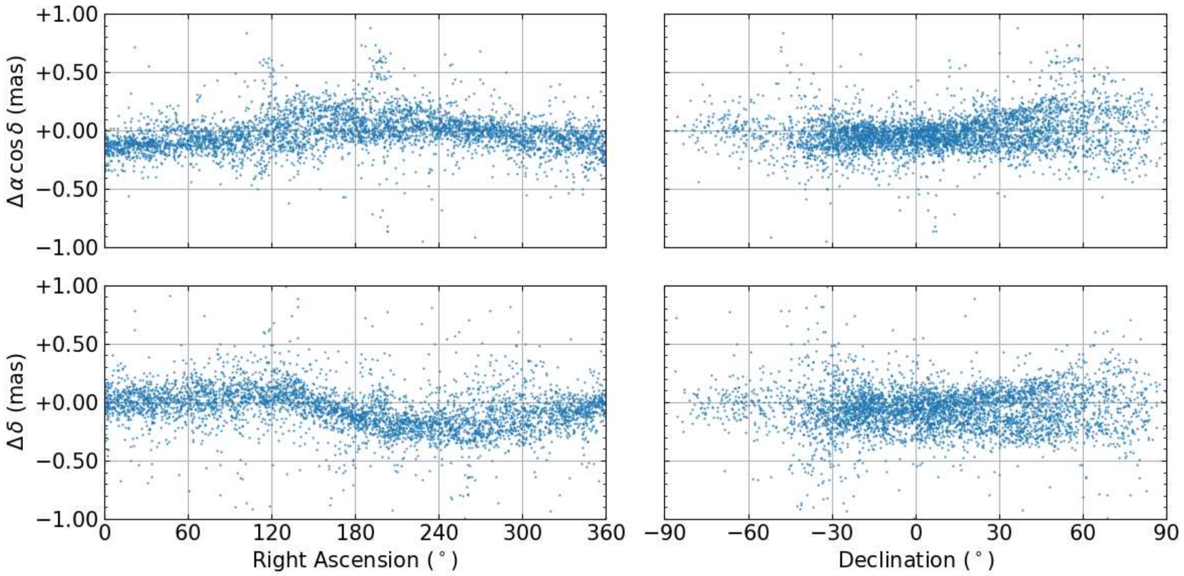


Figure 4: Positional difference for 4356 common sources between solution C and D as a function of the right ascension (left) and declination (right), in the sense of "C−D".

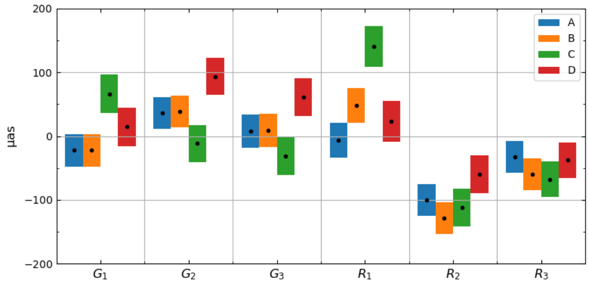


Figure 5: VSH parameters fitted to position differences between various solutions and *Gaia* DR2. The black dot sindicate the estimate while the bar shows the 1-sigma.

3.2 Earth Orientation Parameters

In this section, we studied the impact of different CRF parameterization choices on the EOP series, which are the polar motion (x_p and y_p), UT1, length-of-day (LOD), and offset of Celestial Intermediate Pole (dX and dY).

Figure 6 demonstrates constant EOP offsets between solutions A and B: nearly zero in polar motion and LOD, $\sim 2\,\mu$s in UT1, about $\sim +80\,\mu$as in dX, and $\sim +60\,\mu$as in dY, the last three terms matching the rotation component R_3, R_2, and R_1 between celestial frames.

In the case of fixing the defining source positions to their a priori, the impact of different a priori catalogs on the EOP, as shown in Figure 7, is more complicated. From the running medians (red line) one can still find a rough corresponding relation between EOP and orientation of CRFs as found between solutions A and B, but other signals are mixed, especially a period pattern in LOD before 1995. These signals require further investigation which will be carried out in the future.

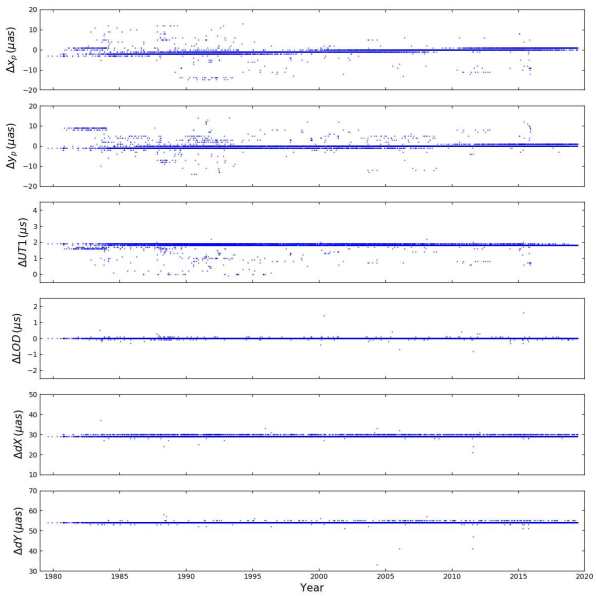


Figure 6: Difference of EOP series between solution A and B, in the sense of "A−B".

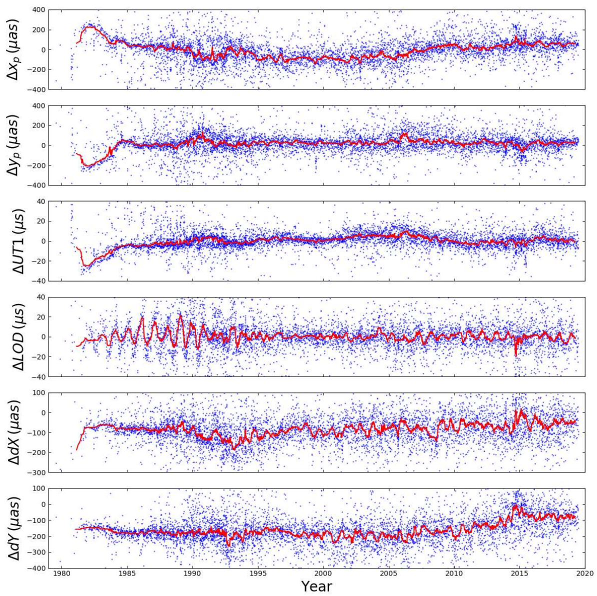


Figure 7: Difference of EOP series between solution C and D, in the sense of "C−D". The red line indicates the running median.

3.3 Terrestrial Reference Frame

We compared the station positions and velocities for these four solutions. The difference between solution A and B is less than 0.1 mm for station positions and almost zero for velocities. In the case of "C−D", the difference is larger: about 0.5 mm and 0.1 mm/yr for station positions and velocities, respectively.

4. CONCLUSION

We explore the possibility of analyzing VLBI data within the frame of the *Gaia*-CRF2. We found that the orientation of CRF axes would be influenced if we used different a priori catalogs but adjusted the position of defining sources. Meanwhile, the estimated EOP would have some bias that corresponds to the orientation between estimated CRFs. The terrestrial frame is slightly perturbed by different CRF parameterizations. If we fixed the positions of defining sources to be their positions in the *Gaia* DR2, both rotation and dipole term of estimated source positions would be influenced, the later brought closer to *Gaia*-CRF2. This analysis strategy offers us the option of reducing the declination-dependent errors in the ICRF only when the *Gaia* frame is ideally free of declination-dependent systematics. Limited by the precision of the *Gaia* DR2, we could not draw any constructive conclusions. The main question of this work should be re-tested with upcoming releases of *Gaia*.

Acknowledgement. We are funded by the National Natural Science Foundation of China (NSFC) under grant No. 11833004. This work has made use of data from the European Space Agency (ESA) mission *Gaia* (`https://www.cosmos.esa.int/gaia`), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, `https://www.cosmos.esa.int/web/gaia/dpac/consortium`). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.

4. REFERENCES

Charlot P., et al., 2020, "The third realization of the International Celestial Reference Frame by VLBI", A&A , doi: 10.1051/0004-6361/202038368.

Gaia Collaboration, Brown, et al., 2018b, Gaia Data Release 2. Summary of the contents and survey properties, A&A 616, A1.

Gaia Collaboration, Mignard, et al., 2018a, Gaia Data Release 2. The celestial reference frame (Gaia-CRF2), A&A 616, A14.

Gaia Collaboration, Prusti, et al., 2016, The Gaia mission, A&A 595, A1.

Liu, N., et al., 2018, A&A 609, A19.

Mignard, F., Klioner, S., 2012, Analysis of astrometric catalogues with vector spherical harmonics, A&A 547, A59.

Mignard, F., et al., 2016, Gaia Data Release 1. Reference frame and optical properties of ICRF sources, A&A 595, A5.