Vienna Contribution to the ICRF3

First results

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Abstract The current realization of the ICRS, the ICRF2, was published in 2009. New stations were implemented, and the amount of data from the southern hemisphere increased dramatically. The demands on the accuracy of the celestial reference frame are higher than ever, with the GAIA mission providing a catalog in the visible spectrum with comparable accuracy. These advances in VLBI and new demands on accuracy entail the necessity of a new version of the celestial reference frame which will be called ICRF3. We will report on the progress and plans of the Vienna group to estimate such a reference frame. Differences in our solution (especially in declination) compared to other groups are discussed. Furthermore, we examine issues which arise during the estimation process such as a declination bias (a maximal offset of about 150 μas in declination).

Keywords ICRF, VLBI

1 Introduction

The latest release, the International Celestial Reference Frame 2 (ICRF2) (Fey *et al.*, 2015), is the official realization of the International Celestial Reference System (ICRS). It was created in 2009 and utilizes Very Long Baseline Interferometry (VLBI) data from 1979 to 2009. Since the creation of the ICRF2, the number of S/X-band group delays almost doubled from about 6.5 million to about 10 million. This massive increase in data points is due to advances in the VLBI technique and an ever growing network of participating stations.

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In the near future the recently launched Global Astrometric Interferometer for Astrophysics (GAIA) satellite will provide first results. GAIA will map objects in the sky in the visible part of the electromagnetic spectrum and will do that with an accuracy comparable to VLBI, see Bourda *et al.* (2012) for more information. Hence, the reference frame provided by VLBI can be compared with the frame provided by GAIA. This comparison will shed light on the inherent systematic effects of the techniques and will provide insight into astrophysical phenomena such as the core shift. Consequently, the need for a reference frame in the radio domain with the best possible accuracy is high.

Because the demands on the reference frame provided by VLBI and the large amount of new data are steadily increasing, the community decided to work on a new release which will incorporate the new data and state-of-the-art analysis techniques.

1.1 Motivation

The motivation of this work is to create a comparable Celestial Reference Frame (CRF) with data analyzed by the Vienna group using the software Vienna VLBI Software (VieVS) (Böhm *et al.*, 2012). On the one hand, it is important to compare independent (in terms of analysis strategy and software) solutions in order to find bugs in the individual solutions and, on the other hand, having more people analyze the same data leaves less room for error and should yield better results. Furthermore, it is good to have as many different solutions as possible, if the ICRF3 working group

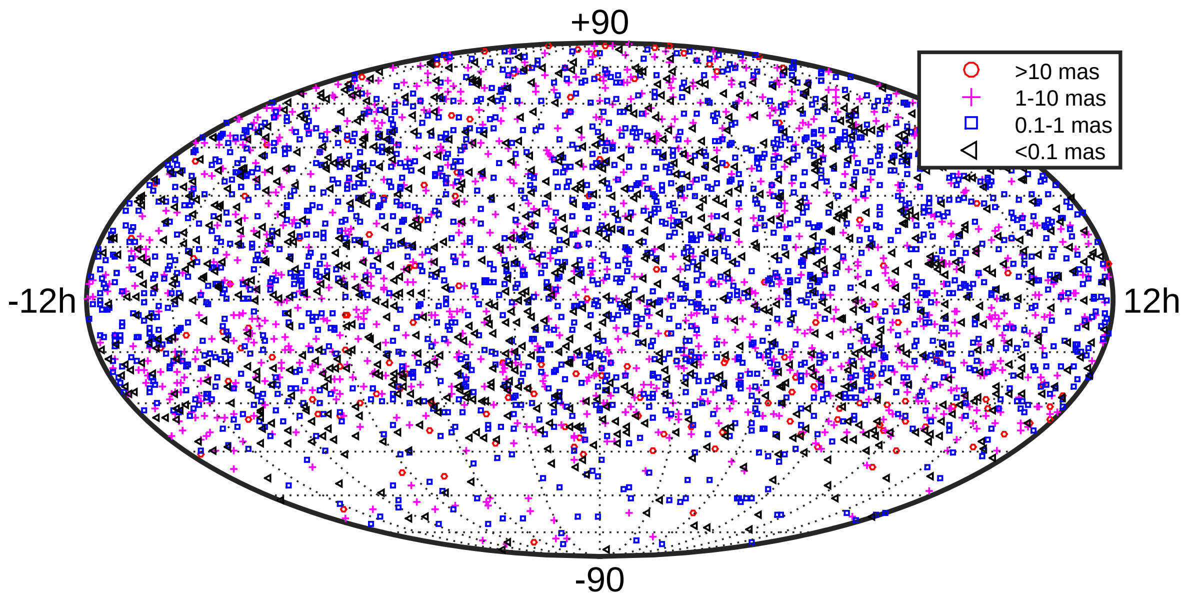

Fig. 1 Map of all source estimates of the Vienna CRF solution w. r. t. the ICRF2. The individual estimates are grouped according to their size and depicted with different markers.

of the International Astronomical Union (IAU) decides to stack more than one solution in a similar approach to the terrestrial reference frame estimation (different Analysis Centers submitting normal equation systems which are then stacked), see Bachmann *et al.* (2016) for more details.

2 Methodology

In order to estimate a CRF from VLBI data a couple of process steps have to be applied.

First, the data have to be selected. In this solution, we used data which were corrected for the ionospheric delay and for which the ambiguities were resolved. The data are provided by the International VLBI Service (IVS) in the form of NGS cards. Not all sessions are suitable for CRF estimation. Therefore, a selection of adequate sessions has to be carried out (see Section 2.2 for details on the selection of sessions). In a second step the whole history of VLBI data has to be analyzed session-wise (see Section 2.1 for details on the selected parameters). From this analysis, normal equation matrices are saved for each session. The final step is to stack all the normal equation systems into one global system and estimate a global CRF (see Section 2.1 for details on the selection of global parameters).

In order to validate the resulting CRF it has to be compared to solutions from other groups. A well-tested way to realize that is by estimating transformation parameters between different CRFs. Such a comparison can be found in Section 4.1.

2.1 Parameter Selection

A standard single session analysis with state-of-the-art geodetic parameterization incorporating the IERS 2010 conventions (Petit & Luzum, 2010) was conducted. Additionally, atmospheric loading was applied. Parameters, such as zenith wet delays (piecewise linear offsets every 20 minutes with a relative constraint of 1 cm), gradients (piecewise linear offsets every six hours with a relative constraint of 0.05 cm), clock parameters (piecewise linear offsets every one hour with a relative constraint of 1.3 cm, one rate, and one quadratic term), Earth Orientation Parameters (one offset per session) and station and source coordinates (one offset per session) were estimated, and normal equation matrices were created.

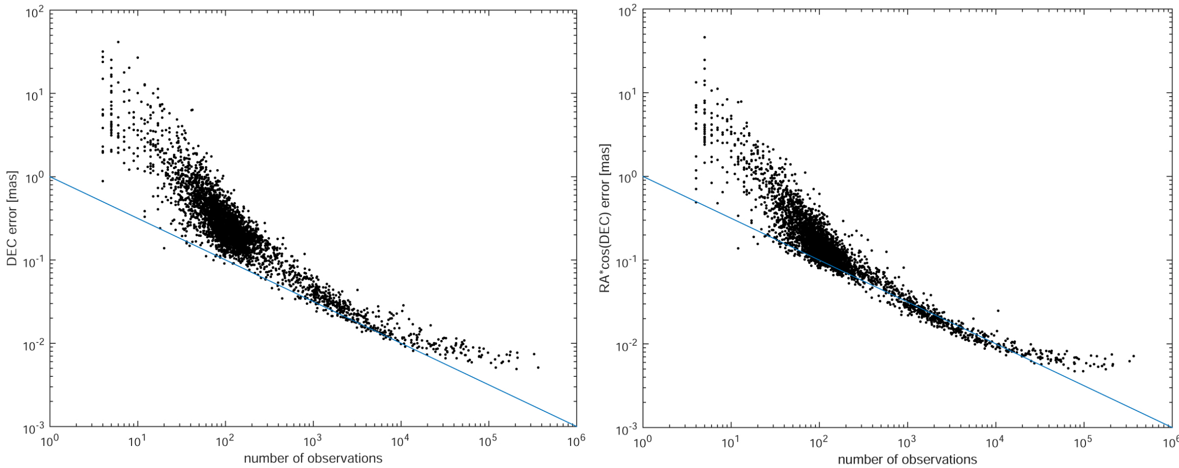

Fig. 2 Formal errors (DEC on the left and RA on the right) of the sources from the Vienna CRF solution plotted over their number of observations.

Following the single session analysis the normal equation matrices must be rearranged and stacked. Certain parameters must be reduced, which means that they are estimated session wise. In our solution those parameters are EOP, special handling sources (unstable sources), stations which only observe in a few sessions, and auxiliary parameters (clock and troposphere). In order to get an invertible equation system sources with fewer than three observations have to be fixed to their a priori values. Global parameters, such as station positions, velocities, and source positions are then estimated with a No-Net-Rotation (NNR)/No-Net-Translation (NNT) (on datum stations) and NNR (on defining sources) approach, respectively.

2.2 Session Selection

Not all VLBI sessions are created equal. Therefore, it makes sense to only select sessions which are suitable for the task. We decided to base our session selection on a few criteria. First, we only wanted sessions where the chi-square is above 3 (no reweighting was applied), which means that the measurements fit well to our models and a priori values. Secondly, we discarded sessions which have a low (in our case 200) number of observations. Lastly, we removed some sessions by hand. After this process we ended up with 4,776 VLBI sessions. Additionally, the 24 VCS-I and the eight VCS-II sessions were added.

3 Results

In this section we will present the results of our current Vienna solution.

Figure 1 depicts the estimates of the Vienna solution w.r.t. the ICRF2. Most (46.2%) of the estimates are between 0.1 and 1 mas, 26.4% are between 1 and 10 mas, 23.5% are smaller than 0.1 mas, and 3.9% are larger than 10 mas.

In Figure 2, the formal errors of RA and DEC over the number of observations are illustrated. One can see that in principle the formal errors get better with a larger number of observations (the ideal case would be the $1/\sqrt(N)$ rule, where N is the number of observations, which is depicted as a line though the plot). The exceptions from the rule are sources which are observed the most. After approximately 10^4 observations, the formal error does not seem to get smaller with more observations.

4 Discussion

4.1 Comparison with Other Catalogs

In order to validate the Vienna solution with other state-of-the-art CRF solutions, a comparison was conducted. The methodology is similar to the catalog comparison found in Lambert, S. (2014). In general the

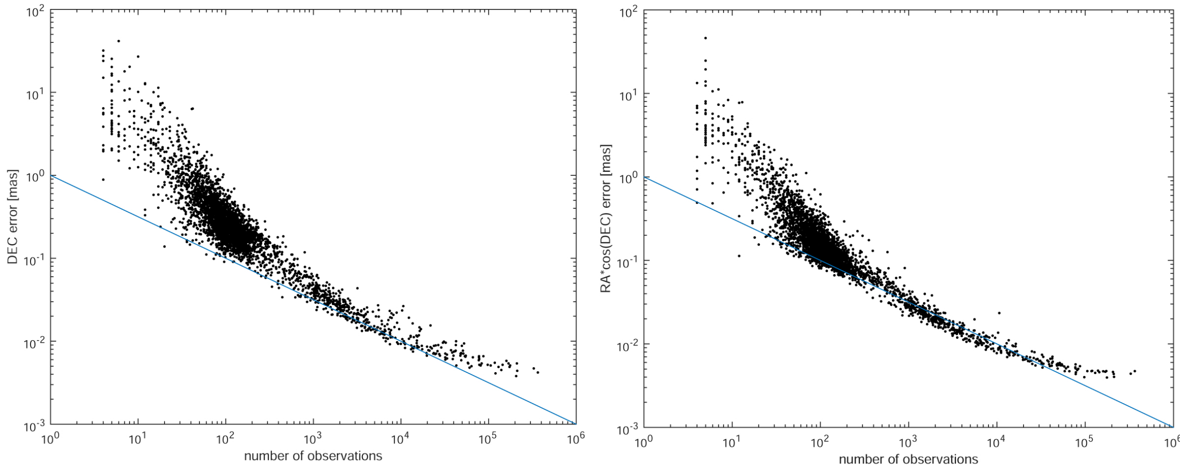

Fig. 3 Formal errors (DEC on the left and RA on the right) of the sources from the Vienna CRF solution with fixed EOP for regional sessions plotted over their number of observations.

295 defining sources were used to calculate rotations in three directions (A_1, A_2, and A_3), slopes in right ascension (RA) and declination (DEC) over DEC (D_α and D_δ), and a bias in DEC (B_δ) between the Vienna solution and a recent solution provided by USNO (Fey, personal communication) and GSFC[1]. The resulting parameters are listed in Table 1.

Table 1 Catalog comparison between the Vienna solution and recent solutions from GSFC and USNO.

	A_1 [µas]	A_2 [µas]	A_3 [µas]	D_α [µas/rad]	D_δ [µas/rad]	B_δ [µas]
VIE vs GSFC	-4 ± 5	-36 ± 4	21 ± 6	-6 ± 8	**-45 ± 8**	**41 ± 6**
VIE vs USNO	-6 ± 5	-10 ± 4	13 ± 6	-18 ± 8	**-40 ± 8**	**46 ± 6**

The Vienna CRF does differ from solutions provided by other groups. In particular, the Vienna solution has a rather large slope in DEC over DEC and a large bias in DEC compared with the other solutions (see Table 1 for details). We are still not sure where this difference originates from. One explanation would be the session selection. In our solution a larger number of sessions was excluded which in turn resulted in a significant reduction in observations for some of the rarely observed defining sources. We did not weight the defining sources before doing the comparison, which means that uncertainties in these rarely observed source coordinates propagate directly into the transformation. We will fix this in the near future and do the comparison again.

1 http://gemini.gsfc.nasa.gov/solutions/2015a_astro/2015b_astro.html

4.2 Formal Errors of Vienna Solution

Another effect which is present in the Vienna CRF is that our formal errors are too large compared to other solutions. In principle, this deviation could be due to the fact that our individual solutions are not reweighted in the single session analysis, but further investigation is necessary.

Malkin (2009) showed that EOP quality is dependent on the size of the network. We decided to create a solution where we fix the EOP for regional (such as the AUSTRALS) sessions and found that it has a significant impact on the formal errors of sources, see Figure 3. One can see that, compared to Figure 2, the formal errors of frequently observed sources (right side of the plot) are significantly reduced. More investigation concerning this effect will be done in the future.

4.3 Declination Bias

Figure 4 depicts the difference in DEC of the Vienna solution w. r. t. the ICRF2 over DEC. This bias, from here forth called declination bias, was so far only found to be present in current CRF solutions based on the software Calc/Solve. Because the declination bias can also be seen in the Vienna solution, which uses VieVS, we can conclude that the effect is real and most likely not software dependent. We did several tests in order to find the origin of the declination bias and arrived at very similar conclusions (the bias is due to the new Australian telescopes etc.) to what was presented (Ma, personal communication) by the GSFC group.

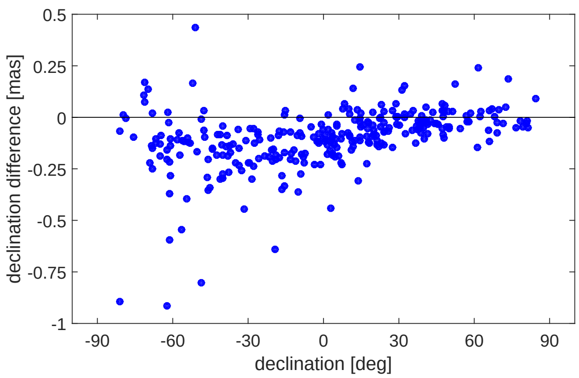

Fig. 4 Declination bias as seen between the Vienna solution and ICRF2.

4.4 Outlook

In the future we will focus our research on the declination bias. Furthermore, we will test the influence of new troposphere analysis strategies, such as a more refined gradient model and ray-traced delays, on the CRF.

Acknowledgements

This work was supported by the Austrian Science Fund (FWF, project I2204).

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