# Three Years of ICRF3 Source Positions

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**Abstract** Precise astronomical reference frames are extremely important for a wide variety of applications, including astronomical observations and navigation, to name a few. ICRF3 is the third realization of the International Celestial Reference Frame, created from the combined international efforts of nearly 40 years of VLBI radio observations of thousands of quasars. In the time since ICRF3 was adopted by the International Astronomical Union on January 1, 2019, many additional astrometric and geodetic observations have been carried out, allowing for a regular cadence of global solutions which estimate updated earth orientation parameters as well as celestial reference frame source positions. In this paper we will examine the shifts in the radio positions of ICRF3 sources over the past three years, derived from VLBI global solutions.

**Keywords** ICRF, source positions

## 1 Introduction

Very Long Baseline Interferometry (VLBI) is a powerful technique that allows us to attain extremely precise astrometric positions of celestial sources. However, this also requires precise knowledge of the positions of the antennae used for the observations. When many 'stationary' reference sources are observed from numerous locations across the globe, over long periods of time, we can solve for both in a global solution. Through meticulous efforts, long-term observation series can be combined to make quality celestial reference frames, which are important for a wide variety of applications. Radio-derived celestial reference frames have been constructed for many years using data at X and S bands, and the current international standard is ICRF3 [1], shown in Figure 1. The sources observed to construct the ICRF are quasars, which are believed to be accreting supermassive black holes in the nuclei of galaxies, commonly known as Active Galactic Nuclei (AGN).

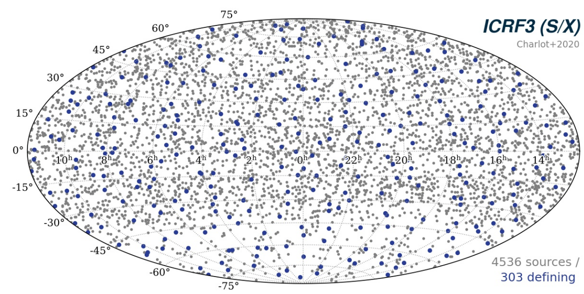


**Fig. 1** ICRF3 at S/X bands, consisting of 4536 sources, of which 303 are defining sources [1].

There are numerous aspects to consider with regards to selecting quality reference frame sources. Isotropy and widespread coverage of sources on the sky is important for ensuring proper density, and targets should appear as point-like as possible so as to avoid confusion when observing their positions. Furthermore, sources should ideally be stable in terms of both their position and brightness. However, the AGN typically observed in astrometric and geodetic style sessions are real astrophysical objects, and so by their nature will have various deficiencies in those regards. There is often extended emission to contend with, which can depend on a source's proximity and

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observing frequency, and the brightness of the various components in these physical systems can naturally vary depending on the local conditions and activity around the black hole and galaxy center. The following is a brief discussion of variations in the measured positions of reference frame sources, as compared to their ICRF3 values.

## 2 Data

In this work, we consider individual observing session measurements over time, as well as successive combined global solution position estimates made between 2018 and 2022. The positions are estimated from the USNO X/S TRF+CRF global solutions[1]. All of the data presented herein are differences in source position from the official ICRF3 values. When considering the distributions of positions, we look at both the full set of ICRF sources as well as those of just the defining sources from which the reference frame is made rigid.

Figure 2 shows an example of a time series of the R.A. and Dec. coordinates across observing sessions, for source 0107-610. The individual points show relatively large scatter paired with uncertainties on the order of 1 mas; however, with a large number of observations, the weighted root mean square (wrms) of the position differences for a source can be an order of magnitude smaller or better. Defining source positions are generally fairly stable over time, but many do still show signs of variability.

## 3 Analysis

The variability among individual observing sessions can help assess quality as a reference frame source, with an important caveat that they can also affected by local conditions at the time of the observations. It can be useful to inspect the time series of measured coordinates such as in Figure 2 for signs of variation, as dispersion of values and outliers are obvious. The wrms also gives a simple quantitative measure of variability over time.

[1] Available at https://crf.usno.navy.mil/vlbi-analysis-center

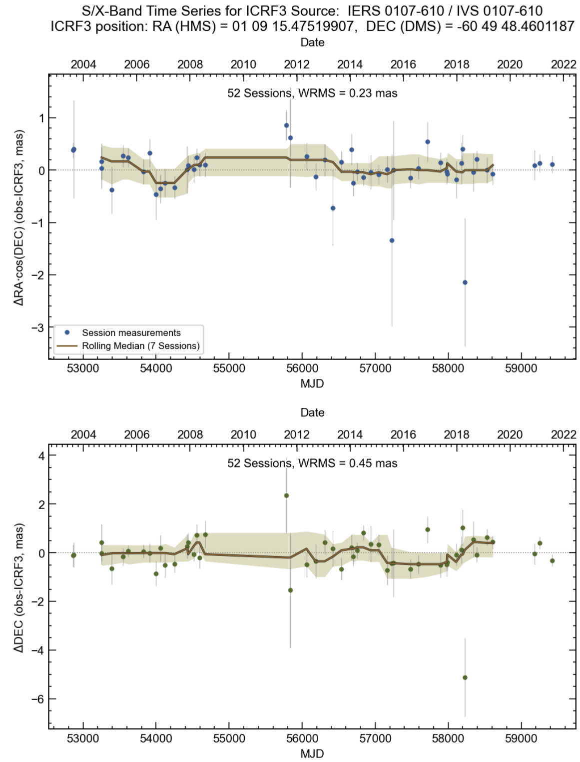


**Fig. 2** Time series of astrometric measurements of right ascension and declination: difference from ICRF3 coordinates for source 0107-610.

It is also instructive to inspect the plotted sky position (R.A. vs. Dec.) over time, for trends, changes in precision/accuracy over time, drifts, discontinuities, and other apparent motion in the sky. Variation over time can be quite striking for some sources when animated over time. Static plots from two sources with apparent motion over timescales of years are shown in Figure 3, one general ICRF3 source (left) and one defining source (right). Even some defining sources show notable trends over the total timescales of these VLBI observation series.

The uncertainties of global solution position estimates are often an order of magnitude (or better) smaller than individual session uncertainties, because they derive from the combination of numerous observations over many years. Figure 4 shows a quantitative visualization of the largest difference from the ICRF3 position in the global solution (usn2021c in this case), as the minimum threshold of $N_{sessions}$ is increased. For ICRF3 sources with at least $\sim 35$ observed sessions, the largest offsets are all $< 1$ mas. For ICRF3 defin-

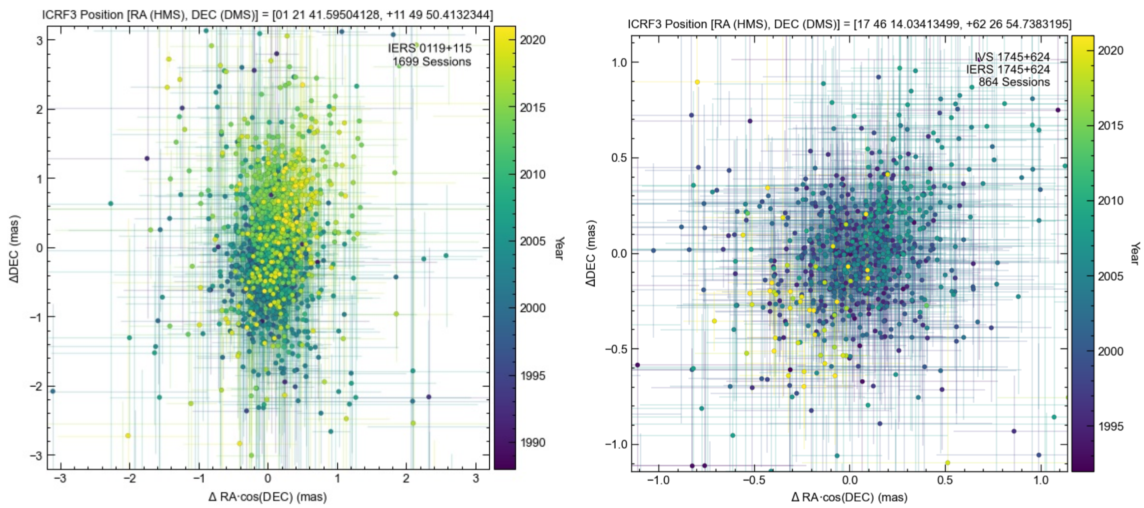


**Fig. 3** Sky plot of session observation differences from ICRF3 positions for two sources. The data are color-coded by date of the observations. While there is a fairly large amount of scatter among individual data points, the center of mass of the points clearly shifts over time. This is not only true of general ICRF sources; the source on the right is a defining source.

ing sources, the largest offset drops below 0.5 mas at a threshold of $>25$ sessions. This highlights the fact that almost all sources with large offsets have few ($\sim$ 10–20) observing sessions.

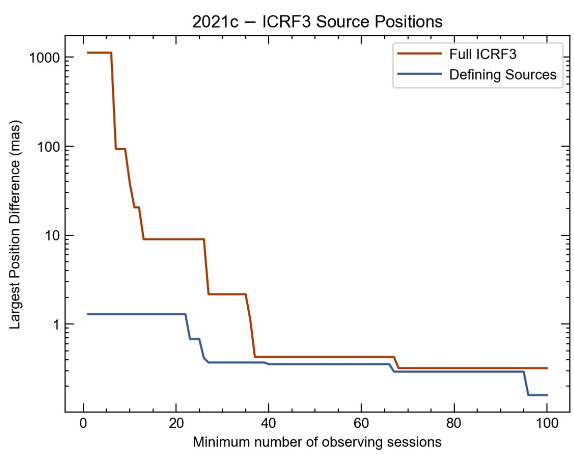


**Fig. 4** Largest difference from the ICRF3 position in solution usn2021c, as a function of the minimum threshold of observing sessions. As the threshold for observing sessions increases, the largest difference decreases. Above $\sim$ 35 observations, the largest differences from ICRF3 positions are $<1$ mas.

Animations of global solution positions over time also contain a variety of useful information. Figure 5 shows a static frame of the positions of sources on the sky, determined from the usn2021c global solution and showing only sources with $>10$ observations. The arrows denote the direction and magnitude of the offset from ICRF3. The colorscale and size of the dots denote the number of observed sessions, highlighting again the impact that the number of observations has on the differences from the reference positions.

The distributions of the position differences are also useful for characterizing the data. Figure 6 shows histograms of the differences from the ICRF3 position (separately for R.A., Dec., and total), for the usn2021c global solution. Distributions are roughly log-normal with a small number of outliers (again, primarily due to a low number of observed sessions). The distributions gradually show an improvement in differences from ICRF3 over time with successive global solutions.

Table 1 lists some extremes from the usn2021c global solution: sources with the largest differences from ICRF3, as well as sources with the smallest differences. Lists are given both for general ICRF3 sources as well as defining sources. Again, the largest offsets are generally seen for sources with few observations; for the general source list the largest differences can be tens of mas or more, but for the defining sources the largest offset is $\sim$ 1 mas. The smallest offsets are on the order of $\sim$ 1–3 microarcsec. The majority of sources in the usn2021c solution are generally well-constrained—91% of the full ICRF source list shows offsets of $<1$ mas, and 26% have offsets of

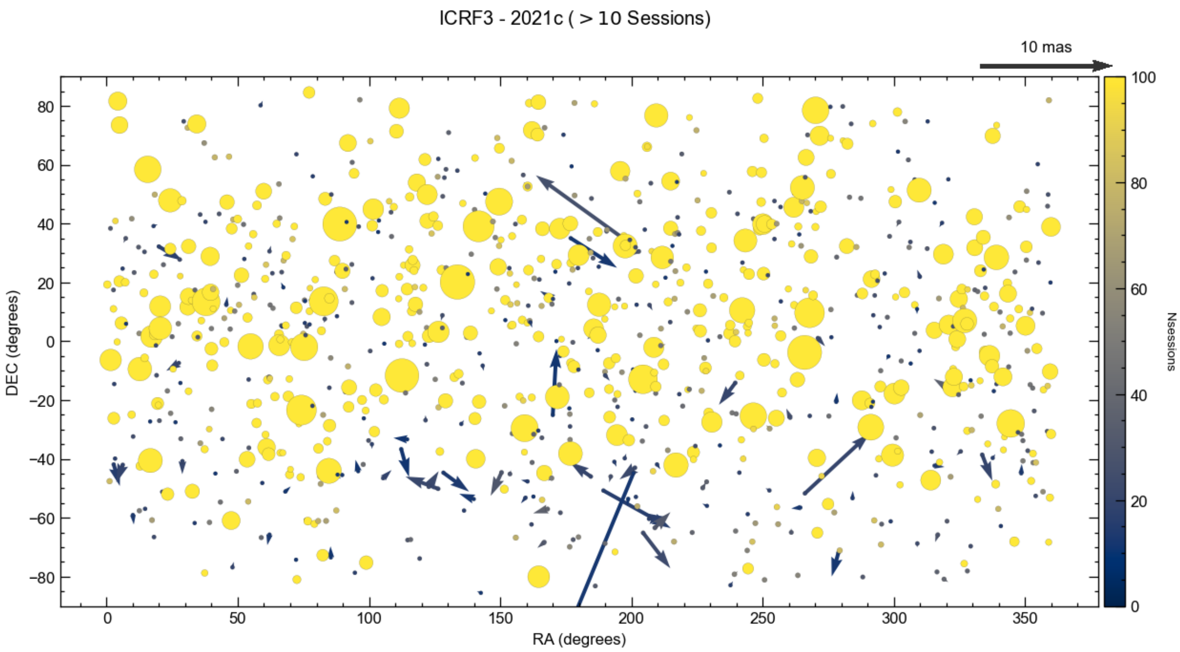


**Fig. 5** Global solution usn2021c position differences from ICRF3. The vectors denote the magnitude and direction of the differences. The circle sizes increase and the color changes with the number of observing sessions for a given source, showing that those with large position differences are those with relatively few observations.

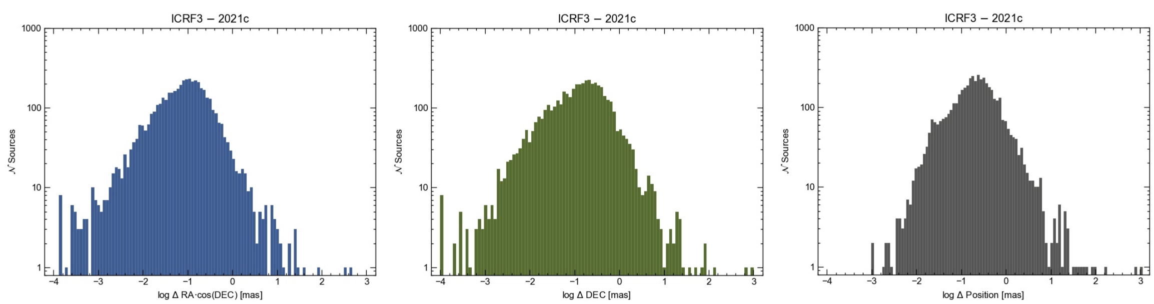


**Fig. 6** Log histograms of position differences from ICRF3, determined from the usn2021c global solution. From left to right are distributions for R.A, Dec., and total position difference.

$< 0.1$ mas, with a median value of $\sim 200$ microarcsec. The defining sources are better still—99% have differences from ICRF3 of $< 1$ mas, and 80% have differences $< 0.1$ mas, with a median of $\sim 34$ microarcsec.

## 4 Conclusions

We have a rich set of time series of ICRF3 source positions, estimated from X/S VLBI global solutions. Individual session differences allow us to investigate drifts, discontinuities, and other apparent motion on the sky with the $\sim$ mas precision afforded by VLBI and to capture the inherent measurement variability of the sources. Differences between individual global solutions enable the comparison of large distributions of source positions and large number statistics. The total number of observations—and therefore solved position estimates—is gradually improving for ICRF3 sources in general. This work will be discussed in much greater detail in a forthcoming paper (Cigan et al., *in prep.*).

There are several natural extensions to this work that we are undertaking. We will use the variability

**Table 1** Sources with the largest and smallest offsets from ICRF3.

| IVS Name | Offset (mas) | $N_{sessions}$ |
|---|---|---|
| Sources with largest 2021c-ICRF3 offsets | | |
| 2028-204 | 1122.49492 | 6 |
| 1657-298 | 770.95916 | 4 |
| 1507-246 | 160.88723 | 5 |
| 1711-251 | 93.15382 | 9 |
| 0201-440 | 81.62703 | 8 |
| Sources with smallest 2021c-ICRF3 offsets | | |
| 0537-441 | 0.00097 | 2461 |
| 0503-043 | 0.00111 | 3 |
| 1145+268 | 0.00190 | 243 |
| 2318+049 | 0.00203 | 1378 |
| 0345+460 | 0.00203 | 276 |
| Defining Sources with largest 2021c-ICRF3 offsets | | |
| 0809-493 | 1.29111 | 22 |
| 0918-534 | 1.16438 | 12 |
| 0700-465 | 0.83915 | 19 |
| 1718-259 | 0.68037 | 25 |
| 0742-562 | 0.63549 | 10 |
| Defining Sources with smallest 2021c-ICRF3 offsets | | |
| 2318+049 | 0.00203 | 1378 |
| 0307+380 | 0.00250 | 442 |
| 0552+398 | 0.00351 | 4550 |
| 0800+618 | 0.00373 | 544 |
| 0235+164 | 0.00380 | 1058 |

in the time series to investigate potential excess variance not captured by the formal solution error. Comparison with ICRF3 K-band VLBI positions will be interesting for investigating how source position varies with observed frequency—which could be due to angular resolution, inherent astrophysical properties of the objects, or other reasons. We will also utilize images (e.g., from FRIDA[2]) to investigate extended structure. We also plan to compare our radio VLBI time series of source positions to those determined in the optical by Gaia, which provide an independent set of positions in a distinct part of the spectrum but potentially arise from different parts of the astrophysical sources.

[2] https://crf.usno.navy.mil/FRIDA

## Acknowledgements

This work supports USNO's ongoing research into the celestial reference frame and geodesy. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. The authors acknowledge use of the Very Long Baseline Array under the U.S. Naval Observatory's time allocation.

## References

1. Charlot P., Jacobs C. S., Gordon D., Lambert S., de Witt A., Böhm J., Fey A. L., et al., 2020, *The third realization of the International Celestial Reference Frame by very long baseline interferometry*, A&A, 644, A159. doi:10.1051/0004-6361/202038368