Current Status of The Celestial Reference Frame

Subjects: Astronomy & Astrophysics

Contributor: Aletha de Witt , Patrick Charlot , David Gordon , Christopher S. Jacobs

The International Celestial Reference Frame (ICRF) is based on the currently accepted International Celestial Reference System (ICRS) and forms the basis for all positional astronomy in the radio domain. The first three generations of this frame have been built from high precision Very Long Baseline Interferometry (VLBI) astrometric measurements of positions of extragalactic radio sources (quasars and other radio-loud Active Galactic Nuclei, AGN), with each successive realization of the ICRF becoming more precise. VLBI angular position accuracy has now improved to near the 100 micro-arcsecond (μas) level. Catalogues of positions of extragalactic radio sources with the highest precision, such as the ICRF, are crucial to many applications, such as determining the Earth's orientation in space, providing calibrator sources for astronomy, studying the motion of tectonic plates, and in spacecraft navigation. The ICRF also contributes towards the realization of a Global Geodetic Reference Frame (GGRF) for sustainable development, a resolution adopted by the United Nations in 2015.

radio interferometry astrometry active galactic nuclei ICRF

1 Introduction

The formal precision in all three components of the ICRF-3 (S/X, K, X/Ka) is quite good for well-observed sources, generally below 100 μas. So, the accuracy is limited by systematic errors. The researchers quantify the systematics by inter-comparing the three independent S/X, K, and X/Ka frames. The researchers also compare against the *Gaia* optical frame [1], which is an independent technique (optical versus radio, space versus ground, and pixel centroiding versus interferometry).

While the researchers' Very Long Baseline Interferometry (VLBI) sources have no measurable parallax or proper motion, effects such as Galacto-centric acceleration create effective proper motions that over the decades integrate up into significant position changes. The ICRF-3 is the first frame to model this Galacto-centric acceleration and refinements will surely be needed to maintain the long-term stability of the frame. There are also long-standing issues from stochastic variations in clocks and tropospheres which will be difficult to eliminate entirely. On the analysis side, there are issues with modeling source structure as well as accounting for the correlated nature of stochastic errors when weighting solutions.

In addition to maintaining temporal continuity, the researchers' The International Celestial Reference Frame (ICRF) work needs more observations on North–South baselines to improve declinations. All three radio frames suffer from a deficit of long North–South baselines which can lead to declination precision being a factor of two or more worse than right ascension precision, depending on the region of the sky being observed.

Catalogs of compact extragalactic radio sources are generally weaker in the South by factors of 2 or more, in both density and precision. This is mainly because of the much smaller number of network stations in the South, compared to the

North. Historically, approximately 80% of all antennas used in VLBI have been in the Northern Hemisphere. Even though the ICRF-3 showed significant improvement over the ICRF-2, the current S/X frame still shows deficiencies by factors of 2–3 in the South. More observations on North–South baselines are needed to improve declinations, and more southern stations are needed to observe sources in the deep South.

Since the spring 2018 cutoff date for sessions to be included in the ICRF-3, observations and analysis have continued with very positive results at S/X and K-bands [2], and at X/Ka-band [3]. Imaging work, to assess and monitor the astrometric source suitability, has also continued, and images of ICRF sources from astrometric VLBI observations at S, X, and K-bands are continuously updated, e.g., as part of the Bordeaux VLBI Image Database (BVID) [4][5], the Radio Fundamental Catalog (RFC) [6] of the Astrogeo Center, the USNO Fundamental Reference Image Data Archive (FRIDA) [7][8], and as part of the K-band CRF collaboration [9]. The current status, including the accuracy and frequency specific limiting errors, for each of the S/X, K, and X/Ka frames, are detailed below.

2. The S/X-Band Frame

The S/X frame has the most sources, but the distribution of observations is very uneven. Some 80% of the sources have been observed in fewer than 10 observing sessions. In contrast, 99 sources have been observed in 1000 or more sessions, the most observed source being OJ287 in over 4800 sessions. The S/X frame also has the most source structure issues, since source structure tends to decrease with increasing frequency (e.g., as shown in **Figure 1**).

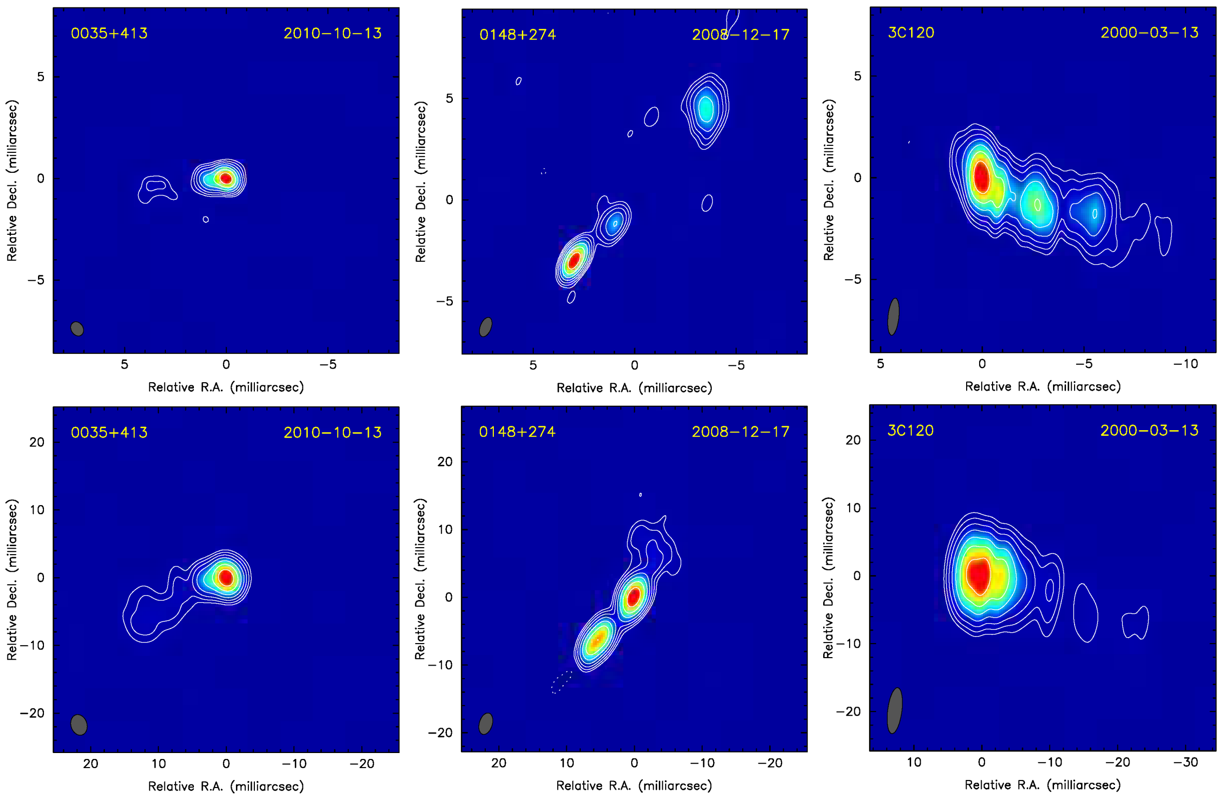

Figure 1. VLBI maps at X-band (upper sub-panels) and S-band (lower sub-panels) for three ICRF-3 non-defining sources showing single-sided jets (0035+413, 0148+274 and 0430+052). Contour levels are drawn at ±1, 2, 4, 8, 16, 32, and 64%

of the peak brightness. Note that the map scale at X-band and S-band is different. These maps are from the BVID [4]. See https://bvid.astrophy.u-bordeaux.fr/ (accessed on 13 May 2022) for full details on the map parameters.

Dedicated S/X astrometry observations received a significant boost in 2017 when the USNO began funding 50% of the VLBA's budget in exchange for up to 50% of the observing time. Twice monthly VLBA S/X astrometry sessions were made until mid-2019, and then have continued at a monthly cadence into the present, in support of the USNO mission. The sessions through spring 2018 were used to add more sources while also significantly improving the precision of existing sources for ICRF-3. Since ICRF-3, the VLBA S/X sessions have concentrated on re-observing the lesser-observed sources and on adding new sources, particularly along the ecliptic band. At present, this work has yielded an S/X catalog of ∼5460 sources. Approximately half of the additional sources added since ICRF-3 are located within 7∘ of the ecliptic, thus approximately doubling the number of ICRF sources available for navigation of interplanetary spacecraft. Precision of the 4536 original ICRF-3 S/X sources has been improved by ∼25% to ∼95 μas in right ascension and ∼160 μ as in declination. Imaging of the VLBA S/X sessions is also being made at the USNO and will serve to characterize the structure of ∼4500 sources at S/X band (e.g., [7]).

However, the VLBA can only observe down to around −45∘ declination. In order to improve the S/X frame in the deep South, starting in 2018 the sensitivity of the Southern IVS CRF observations was increased from 256 Mbps to 1 Gbps and the pool of sources was increased by a factor of two [10]. This in turn has already improved the source density and spatial coverage in the South, as well as the position accuracy of Southern sources, in both coordinates. The scheduling of these sessions was also optimized, using the most recently developed geodetic scheduling software VieSched++ [11], to allow for simultaneous astrometric and imaging observations in order to map the structure and evolution of the CRF sources in the deep South (e.g., [12]).

3. The K-Band Frame

The K-band has also benefited from the USNO's VLBA timeshare allocation. Approximately monthly K-band VLBA sessions have been made since January 2017 for astrometry and imaging. Moreover, approximately two dozen single baseline HartRAO–Hobart26 sessions have been run since ICRF-3, improving the full sky coverage at K-band. In order to improve the K-band declinations, a North–South baseline (from Spain to South Africa) has been started. First fringes were obtained in 2021 and full 24-hour observations are scheduled for mid-2022. The K-band reference frame currently has ∼1.8 million observations, a nearly four-fold increase over the ICRF-3, and has added 211 sources for a total of 1035, a 25% increase over ICRF-3. Source precision has also improved considerably at K-band to ∼45 μ as in right ascension and ∼80 μas in declination, or ∼40% better for the original 824 sources. Current K-band source precision is now nearly as precise as at S/X for 1014 sources in common to both catalogs. The biggest issue for the K-band frame is the limited number of sessions and observations from the Southern Hemisphere. In spite of this, the distribution of sources at K-band is fairly even between the North and South, even though less than 1% of the observations are made from the Southern Hemisphere. At K-band, ionosphere calibrations are less than perfect, being based on GNSS ionosphere data [13] due to the lack of dual-band observations, but do not appear to produce systematic errors above the current noise floor of ∼30 μas.

To date, a total of 5879 K-band images of 731 ICRF-3 sources, from 28 VLBA sessions spanning from 2015 to 2018, have been produced [9]. The vast majority of sources are imaged at multiple epochs. Quantitative estimates of source strength, size, compactness, and jet direction as well as the temporal stability of these quantities were derived to aid in characterizing the suitability of each as a reference source. A sample of three K-band images is shown in **Figure 2**.

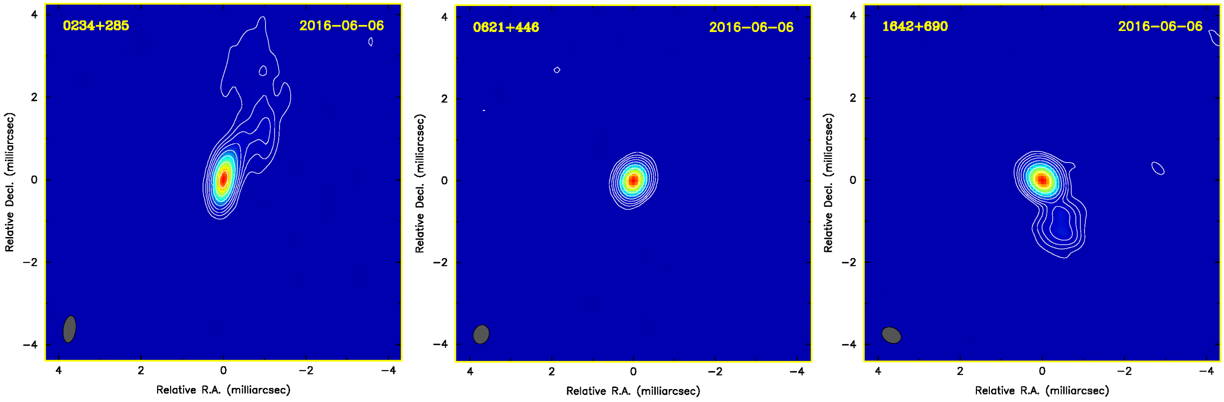

Figure 2. VLBA maps at K-band for three ICRF-3 sources (0234+285, 0621+446, and 1642+690) with compact structure or weak extended emission. The contour levels start at 3× the background rms brightness level and increase by factors of 2 thereafter. The weak extended emission, visible only in the lower contour levels, has a small impact on the astrometry. See [9] (from which these maps are reproduced) for full details on the map parameters.

4. The X/Ka-Band Frame

The X/Ka frame has the largest zonal errors due to its reliance on just two baselines for ∼85% of its data. As the X/Ka network geometry adds data from stations in Argentina and Japan, these errors are being reduced [3].

X/Ka (32 GHz) work with the combined NASA, ESA, and JAXA network has now produced 0.11 million observations. X/Ka-band sessions continue at an approximately three week cadence at 2 Gbps using a combined NASA, ESA, and JAXA network. As with the K-band program, the X/Ka program has added a long North–South baseline (Misasa, Japan, to Tidbinbilla, Australia) in order to improve declination accuracy [14]. Median source precision has improved considerably at X/Ka-band to 55, 75 μ as in right ascension and declination, respectively. Accuracy is currently limited by a quadrupole 2,0 'magnetic' distortion of 131±19 μas. The large Z-dipole distortion seen in the ICRF-3 X/Ka [15] is now statistically insignificant as long as the full α-δ parameter covariances are accounted for [3].

References

1. Mignard, F.; Klioner, S.A.; Lindegren, L.; Hernandez, J.; Bastian, U.; Bombrun, A.; Hobbs, D.; Lammers, U.; Michalik, D.; Ramos-Lerate, M.; et al. Gaia Data Release 2: The celestial reference frame (Gaia-CRF2). Astron. Astrophys. 2018, 616, A14. Available online: https://www.aanda.org/articles/aa/full_html/2018/08/aa32916-18/aa32916-18.html (accessed on 13 May 2022).
2. Gordon, D.; de Witt, A.; Jacobs, C.S. Current CRF Status at X/S and K Bands. In Proceedings of the 12th IVS General Meeting, Helsinki, Finland, 28 March–1 April 2022; Available online:

https://www.maanmittauslaitos.fi/sites/maanmittauslaitos.fi/files/attachments/2022/03/Abstarct_book_2022.pdf (accessed on 13 May 2022).

3. Jacobs, C.S.; Horiuchi, S.; Snedeker, L.G.; Firre, D.; Murata, Y.; Takeuchi, H.; Uchimura, T.; Asmar, S. The JPL 2022a X/Ka Celestial Reference Frame. In Proceedings of the 12th IVS General Meeting, Helsinki, Finland, 28 March–1 April 2022; Available online: https://www.maanmittauslaitos.fi/sites/maanmittauslaitos.fi/files/attachments/2022/03/Abstarct_book_2022.pdf (accessed on 13 May 2022).
4. Collioud, A.; Charlot, P. The Second Version of the Bordeaux VLBI Image Database (BVID). In Proceedings of the 24th European VLBI Group for Geodesy and Astrometry Working Meeting, Las Palmas de Gran Canaria, Spain, 17–19 March 2019; pp. 219–223. Available online: https://www.oan.es/evga2019/24_EVGA_2019_Las_Palmas.pdf (accessed on 13 May 2022).
5. Laboratoire d'Astrophysique de Bordeaux (LAB), Bordeaux VLBI Image Database (BVID). Available online: http://bvid.astrophy.u-bordeaux.fr (accessed on 13 May 2022).
6. Petrov, L. Radio Fundamental Catalog. Astro-geo Center. Available online: http://astrogeo.org/rfc/ (accessed on 13 May 2022).
7. Hunt, L.; Johnson, M.; Fey, A.; Gordon, D.; Spitzak, J. Imaging Over 3000 Quasars That Are a Part of the International Celestial Reference Frame. In Proceedings of the American Astronomical Society Meeting Abstracts, Honolulu, HI, USA, 4–8 January 2020; Volume 235, p. 305.30. Available online: https://assets.pubpub.org/rynkboj6/71582749259388.pdf#abs305.30 (accessed on 13 May 2022).
8. U.S. Naval Observatory Fundamental Reference Image Data Archive (FRIDA). Available online: https://crf.usno.navy.mil/data_products/FRIDA/frida.html (accessed on 13 May 2022).
9. de Witt, A.; Jacobs, C.S.; Gordon, D.; Bietenholz, M.; Nickola, M.; Bertarini, A. The Celestial Reference Frame at K-band: Imaging. I. First 28 Epochs of K-band Images. Astron. J. 2022; under review.
10. de Witt, A.; Basu, S.; Charlot, P.; Gordon, D.; Jacobs, C.S.; Johnson, M.; Krásná, H.; Le Bail, K.; Shu, F.; Titov, O.; et al. Improving the S/X Celestial Reference Frame in the South: A Status Update. In Proceedings of the 25th Working Meeting of the European VLBI Group for Geodesy and Astrometry, Virtual, 14–18 March 2021; Available online: https://www.oso.chalmers.se/evga/25_EVGA_2021_Cyberspace.pdf (accessed on 13 May 2022).
11. Schartner, M.; Böhm, J. VieSched++: A New VLBI Scheduling Software for Geodesy and Astrometry. Publ. Astron. Soc. Pac. 2019, 131, 084501. Available online: https://iopscience.iop.org/article/10.1088/1538-3873/ab1820/pdf (accessed on 13 May 2022).
12. Basu, S.; de Witt, A.; Gattano, C. Source Structure and Position Stability of Celestial Reference Frame Sources in the Deep South. In Proceedings of the 25th Working Meeting of the European VLBI Group for Geodesy and Astrometry, Virtual, 14–18 March 2021; Haas, R., Ed.; Available online: https://www.oso.chalmers.se/evga/25_EVGA_2021_Cyberspace.pdf (accessed on 13 May 2022).
13. Soja, B.; Jacobs, C.S.; Runge, T.; Naudet, C.; Gross, R.; de Witt, A.; Gordon, D.; Quick, J.; McCallum, J.; Krásná, H. Ionospheric Calibration for K-Band Celestial Reference Frames. In Proceedings of the

24th European VLBI Group for Geodesy and Astrometry Working Meeting, Las Palmas, Gran Canaria, Spain, 17–19 March 2019; Haas, R., Garcia-Espada, S., López-Fernández, J.A., Eds.; Available online: https://www.oan.es/evga2019/EVGA2019_PDF/O316_EVGA2019_Soja.pdf (accessed on 13 May 2022).

14. Jacobs, C.S.; Murata, Y.; Takeuchi, H.; Firee, D.; Asmar, S.; Uchimura, T.; Numata, K. X/Ka Network Enhanced by Misasa, Japan’s 54-meter antenna. In Proceedings of the 25th Working Meeting of the European VLBI Group for Geodesy and Astrometry, Virtual, 14–18 March 2021; Available online: https://ui.adsabs.harvard.edu/abs/2021evga.confE...3J/abstract (accessed on 13 May 2022).
15. Charlot, P.; Jacobs, C.S.; Gordon, D.; Lambert, S.; de Witt, A.; Böhm, J.; Fey, A.L.; Heinkelmann, R.; Skurikhina, E.; Titov, O.; et al. The third realization of the International Celestial Reference Frame by very long baseline interferometry. Astron. Astrophys. 2020, 644, A159. Available online: https://www.aanda.org/articles/aa/full_html/2020/12/aa38368-20/aa38368-20.html (accessed on 13 May 2022).