Towards a Multi-waveband Optical-radio ICRF

Patrick Charlot[1], *on behalf of the IAU Multi-waveband ICRF Working Group*

Abstract A new working group entitled "Multi-waveband ICRF (International Celestial Reference Frame)" has been established by the International Astronomical Union (IAU) in 2021. The objective of this working group is to work toward the realization of a multi-waveband celestial reference frame, incorporating positions in both radio and optical bands and ensuring their consistency over the various bands. The end goal of the working group will be to produce the next-generation VLBI frames at the S/X (2.3/8.4 GHz), K (24 GHz), and X/Ka (8.4/32 GHz) bands, or at any other radio band that may emerge in the coming years, to match these with the optical realization from the Gaia space mission, and to place all such positions on a common grid guaranteeing consistency of the source positions over the different bands. Before this can be accomplished, a number of questions relating to the construction of such a multi-waveband frame are to be addressed. These include dealing with non-uniform sky distributions, agreeing on a consistent treatment of Galactocentric acceleration, establishing common practices to align reference frames in different bands, and considerations regarding wavelength and time-dependent source positions. A proper terminology for referring to the individual (per band) components of the reference frame must also be defined. The targeted date for completion of this future multi-waveband ICRF is 2027, meaning a possible adoption by the IAU General Assembly that will take place the same year.

Keywords ICRF, Celestial Reference Frame, VLBI, Gaia, Active Galactic Nuclei, Astrometry

1. Laboratoire d'Astrophysique de Bordeaux, Univ. Bordeaux, CNRS

1 Introduction

For two decades, from the late 1990s to the late 2010s, VLBI had been the sole technique able to measure the astrometric positions of extragalactic sources with high accuracy and, hence, to realize the International Celestial Reference Frame (ICRF). In this period, three successive realizations of the ICRF have been generated. The first ICRF was released in 1998 [1], which was followed by ICRF2 in 2009 [2] and ICRF3 in 2018 [3]. The second and third realizations had improved quality (e.g., in terms of sky coverage and position accuracy) compared to their predecessors and supplanted these after adoption by the IAU. The number of sources in the successive frames grew from 608 in the first ICRF to 3,414 in ICRF2 and 4,588 in ICRF3, while at the same time the noise floor in the source coordinates decreased from 250 µas in the first ICRF to 40 µas in ICRF2 and 30 µas in ICRF3. Additionally, ICRF3 included two further frequency components, namely at K band (24 GHz) and X/Ka band (8.4/32 GHz), besides the standard S/X band (2.3/8.4 GHz) component that underlay the first two realizations, thus making ICRF3 the first multi-frequency celestial frame ever built.

The launch of the European Space Agency mission Gaia in 2013 [4] changed this monopoly situation because it gave the chance to build a highly accurate extragalactic frame in the optical band for the first time. The first of its kind, Gaia-CRF2, was released in 2018 [5], followed two years later by Gaia-CRF3 [6], which was adopted by the IAU as the optical counterpart of the ICRF3 in 2021. These frames provide optical position accuracies that match those of the ICRF3, but the density of sources is much higher—Gaia-CRF2 includes more than 0.5 million extragalactic sources (quasars), while Gaia-CRF3 has three times more (about 1.6 million). Future Gaia data releases planned for 2026 (Release 4) and beyond 2030 (Release 5) will provide even more sources and will have increased position accuracies.

The brief overview given above shows that four reference frames, three in the radio band and one in the optical band, currently co-exist, all with a similar level of accuracy. While the Gaia frame provides many more sources, it cannot help with geodesy, Earth's rotation, spacecraft navigation and other Earth-based applications, where VLBI remains mandatory. Each waveband therefore has its own unique value. On the other hand, the current situation offers the potential for building a multi-waveband (optical-radio) ICRF. Investigating this possibility is the mission of the newly created IAU Working Group on Multi-waveband ICRF, introduced in Section 2. Major subjects to be addressed prior to generating such a multi-waveband frame (sky distribution, Galactocentric acceleration, alignment of frames) are reviewed in Section 3. A proper terminology for referring to the individual components of the frame is also essential and is underlined in Section 4. The timeline for delivering this multi-waveband frame is given in Section 5.

2 The IAU Working Group on Multi-waveband ICRF

The Multi-waveband ICRF working group, established by the IAU in 2021, took over from two former IAU working groups: (i) the working group on the *Third Realization of the International Celestial Reference Frame*, terminated in 2018 with the realization and adoption of the ICRF3 by the IAU (IAU 2018 Resolution B2) [3] and (ii) the working group entitled *Multi-waveband realizations of the International Celestial Reference System (ICRS)*, terminated in 2021 after the release and adoption of the Gaia-CRF3 as the optical realization of the ICRS (IAU 2021 Resolution B3) [6].

The mandate of the working group is to work towards the realization of a multi-waveband celestial reference frame, incorporating positions in both radio and optical bands and ensuring maximum consistency of these positions between the various bands. In detail, this means producing the next generation VLBI frames at S/X, K, and X/Ka bands, and at any other radio band that may emerge in the coming years, matching these with the optical realization from Gaia, and placing all such positions on a common grid guaranteeing consistency of the source positions over the different bands.

Membership was established by assembling the expertise considered necessary to reach this objective, covering a wide range of fields, from VLBI and Gaia to reference frames and active galactic nuclei. The working group comprises 18 members coming from 14 institutions located in nine different countries (Table 1). Since 2021, the work has focused on several essential subjects which are discussed in the following section.

3 Areas of Work

Before a multi-waveband celestial frame can be generated, a number of questions relating to the construction of such a frame are to be addressed. These include dealing with non-uniform sky distributions, agreeing on a consistent treatment of Galactocentric acceleration, establishing common practices to align reference frames in different wavebands, and considerations regarding wavelength and time-dependent source positions. Further details on these topics are given below.

3.1 Sky Distribution

Having a uniform sky distribution of sources over the celestial sphere and a uniform distribution of position uncertainties is essential to limit the deformations of the individual frames produced in each waveband and to properly align these frames on a common grid.

As shown by the sky distribution plotted in Figure 1 (upper panel), uniformity is far from being reached in the case of ICRF3. The VLBI frame has a deficit of sources in the South, and the precision of the positions also becomes lower as declination decreases, leading to an asymmetry between the North and the South. This situation comes from the limited number of radio telescopes in the Southern Hemisphere and cannot be easily resolved. Despite ongoing projects (such as the construction of a 40-m Chinese/Argentinian radio telescope in Argentina), it will be difficult to catch up with the North. The non-uniformity of the VLBI frame is therefore likely a situation we will have to live with.

Table 1 Members of the IAU Multi-waveband ICRF Working Group during the triennium 2021–2024.

Name	Affiliation	Country
Sonia Anton	University of Coimbra	Portugal
Felicitas Arias	Observatoire de Paris	France
Patrick Charlot (Chair)	University of Bordeaux & CNRS	France
Alet de Witt	South African Radio Astronomy Observatory	South Africa
Bryan Dorland	US Naval Observatory	USA
David Gordon	US Naval Observatory	USA
Robert Heinkelmann	Helmholtz Centre Potsdam	Germany
Christopher S. Jacobs	Jet Propulsion Laboratory	USA
Sergei Klioner	Technical University of Dresden	Germany
Hana Krásná	Technical University of Vienna	Austria
Sébastien Lambert	Observatoire de Paris	France
Lennart Lindegren	Lund University	Sweden
Valeri Makarov	US Naval Observatory	USA
Zinovy Malkin	Pulkovo Observatory	Russia
François Mignard	Observatoire de la Côte d'Azur	France
Elena Skurikhina	Institute of Applied Astronomy	Russia
Jean Souchay	Observatoire de Paris	France
Oleg Titov	Geoscience Australia	Australia

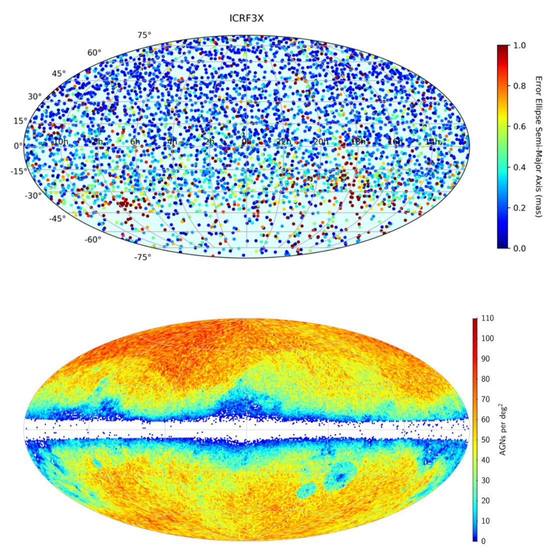

Fig. 1 Sky distribution for the ICRF3 and Gaia-CRF3 frames. The upper panel shows the position of the 4,536 sources that are comprised in the S/X component of ICRF3 (reproduced from [3]). The lower panel shows the sky density of the 1.6 million sources that are comprised in Gaia-CRF3 (reproduced from [6]).

While being much more uniform, the Gaia frame also shows some inhomogeneities. As seen from the Gaia-CRF3 sky density plotted in Figure 1 (lower panel), there are only a few sources in the Galactic plane. This paucity comes from Galactic extinction, which prevents the instrument from detecting sources in this area of the sky. As the cause is not technical but physical, the situation is not expected to improve in future data releases. A possibility for densifying the frame in these regions would be to search for known sources (such as ICRF sources) in the Gaia data because the sources are there but cannot be identified by Gaia on its own. This is an interesting area where VLBI may help Gaia to identify quasars.

3.2 Galactocentric Acceleration

Galactocentric acceleration (i.e., the centripetal acceleration of the solar system barycenter with respect to the Galactic center) is a phenomenon that manifests itself through apparent large-scale proper motions of the extragalactic sources, as pictured in Figure 2. The VLBI and Gaia observations are sensitive to the effect on the long term and allow for estimating the acceleration vector. Based on the ICRF3 and Gaia-CRF3 data sets, two independent estimates of the amplitude of the vector have been obtained: 5.8 ± 0.3 µas/yr for ICRF3 [3] and 5.05 ± 0.35 µas/yr for Gaia-CRF3 [7]. Besides the slight difference in magnitude (equivalent to 1.8 σ), the approach used to account for the effect in the realization of the frames also differs. While the effect was modeled in ICRF3 by

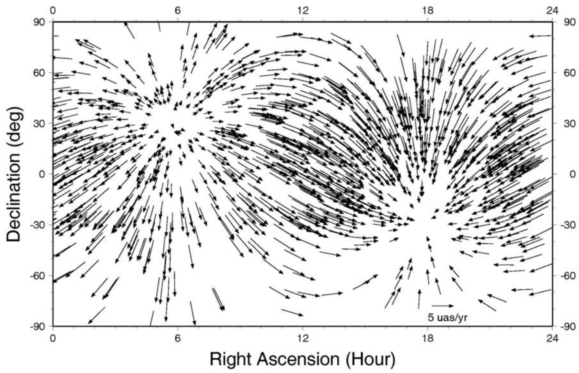

Fig. 2 Aberration proper motion field resulting from a solar system barycenter acceleration vector with amplitude 5.8 µas/yr, pointing to the Galactic center (reproduced from [3]).

using the VLBI-estimated amplitude, it was not corrected in Gaia-CRF3. Instead, the proper motions of the sources were estimated and are considered an integral part of the Gaia-CRF3 frame.

In the context of generation of a multi-waveband frame, a consistent treatment of Galactic acceleration should be sought to have the source positions at any epochs directly comparable in the different radio and optical bands. This may be achieved by adopting either one or a combination of the estimates. New improved values from Gaia are expected by 2026 for Data Release 4 (DR4) and beyond 2030 for Data Release 5 (DR5), the final Gaia data release. On the VLBI side, the estimate of the acceleration vector is expected to improve too due to the increased time base and denser observations in recent years. Updates can be done by the time of DR4 and DR5 for direct comparisons with the Gaia values. Additionally, it appeared to the working group that there is a need to redefine the vocabulary employed, because the observed phenomenon reflects the motion of the solar system barycenter relative to the background of extragalactic sources, which may not be only due to the rotation around the Galactic center.

3.3 Alignment of Individual Frames

An issue that arises when aligning individual frames is to decide which sources to consider for the alignment. In other words, should all sources in common between the frames be used in the alignment process or only a subset of them? Using all sources improves the statistical determination, but lower-quality sources (e.g., with extended structures) may have an adverse effect on the result of the alignment, as also does the asymmetry of the VLBI frame. For this reason, the ICRF3 defining sources, which served to orient the VLBI frame onto the ICRS, were chosen among the high-quality sources, while at the same time their distribution was arranged to be uniform over the celestial sphere [3]. Whether the concept of defining sources, which has been used for all three ICRF realizations, should be continued in the context of the pursued multi-waveband frame is a matter that is investigated by the working group.

The alignment process is further complicated by the fact that a notable portion of the sources shows offsets in position between the different wavebands (about 25% when comparing ICRF3 and Gaia-CRF3, see [9]), and that this portion is likely to be augmented in the future because the next Gaia data releases and next-generation VLBI frames will have increased position accuracy. Additionally, a number of ICRF sources are found to have position instabilities on scales of weeks to years [8], hence making the situation even more complex. In general, such effects appear to be related to the physics of the underlying objects—both the positional offsets between bands and time variability of the positions occur along the VLBI jet direction—which gives clues on how to treat them in the analysis [9, 10]. At present, the working group is leaning toward identifying a subset of sources with stable positions and no measurable offsets between bands to serve for the alignment.

4 Terminology

Originally, the ICRF terminology was defined without any waveband in mind. But, because VLBI has been the only technique able to build the ICRF until the advent of Gaia, the term ICRF has been implicitly linked to VLBI. In view of the anticipated multi-waveband frame, a proper vocabulary must be defined to distinguish the individual components of the frame. The terminology must also be valid beyond Gaia and be able to accommodate any new waveband or frequency that may emerge in the future. After discussion, the working group agreed on the following naming:

ICRFnW-F

where n is the identifier of the realization, W is a code to identify the waveband, and F is a specific frequency identifier within the waveband, consisting of up to two characters. The latter is used when there is more than one frequency component within a given waveband.

Applying this terminology to the next realization of the ICRF (which will be the fourth one) leads to the following denominations: ICRF4 would denote the entire multi-waveband frame; ICRF4R would denote all radio components of the frame, while ICRF4G would denote the Gaia component; ICRF4R-X, ICRFR-K, and ICRFR-Ka would denote the individual radio components at X band, K band, and Ka band. Based on current VLBI developments, one can also foresee two potential further radio components in the future: at Q band (43 GHz) and with the VLBI Global Observing System (VGOS). These components would then be referred to as ICRFnR-Q and ICRFnR-VG, respectively, if they become part of realization n of the ICRF.

We note that the agreed terminology does not allow for distinguishing between dual-band and single-band VLBI observing schemes (e.g., S/X band vs. X band, or X/Ka band vs. Ka band). But this was viewed as a technical point which was judged not necessary to convey to the users. More importantly, the ICRF users must know which radio frequency the individual components refer to, which is yielded by the F identifier.

5 Timeline for the Next ICRF

The working group considered potential dates for the realization of the next ICRF, either 2027 or 2030, to be in line with future IAU General Assemblies. Considering the accumulation of data and improvements on the VLBI side, it was felt that waiting for 2030 would be too late from a VLBI-only point of view. Additionally, the next Gaia data release (DR4) is planned for 2026, that is before 2027, while the final one (DR5) will be after 2030, meaning that Gaia DR4 will still be the release in use by 2030. There would hence be no reason to wait for 2030 also from that perspective. Based on these considerations, the decision was taken to build the next ICRF by 2027, thus aiming at a possible adoption by the IAU General Assembly in that year.

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References

1. C. Ma, E. F. Arias, T. M. Eubanks, A. L. Fey, A.-M. Gontier, C. S. Jacobs, O. J. Sovers, B. Archinal, P. Charlot (1998) The International Celestial Reference Frame as Realized by Very Long Baseline Interferometry. *The Astronomical Journal*, 116, 516.
2. A. L. Fey, D. Gordon, C. S. Jacobs, C. Ma, R. Gaume, et al. (2015) The Second Realization of the International Celestial Reference Frame by Very Long Baseline Interferometry. *The Astronomical Journal*, 150, 58.
3. P. Charlot, C. S. Jacobs, D. Gordon, S. Lambert, A. de Witt, et al. (2020) The third realization of the International Celestial Reference Frame by very long baseline interferometry. *Astronomy & Astrophysics*, 644, A159.
4. Gaia Collaboration, T. Prusti, J. H. J. de Bruijne, A. G. A. Brown, A. Vallenari, C. Babusiaux, et al. (2018) The Gaia mission. *Astronomy & Astrophysics*, 595, A1.
5. Gaia Collaboration, F. Mignard, S. A. Klioner, L. Lindegren, J. Hernández, U. Bastian, et al. (2018) Gaia Data Release 2. The celestial reference frame (Gaia-CRF2). *Astronomy & Astrophysics*, 616, A14.
6. Gaia Collaboration, S. A. Klioner, L. Lindegren, F. Mignard, J. Hernández, M. Ramos-Lerate, et al. (2022) Gaia Early Data Release 3. The celestial reference frame (Gaia-CRF3). *Astronomy & Astrophysics*, 667, A148.
7. Gaia Collaboration, S. A. Klioner, F. Mignard, L. Lindegren, U. Bastian, P. J. McMillan, et al. (2021) Gaia Early Data Release 3. Acceleration of the Solar System from Gaia astrometry. *Astronomy & Astrophysics*, 649, A9.
8. C. Gattano, P. Charlot (2021) Characterizing the astrometric instability of extragalactic radio source positions measured with geodetic VLBI. *Astronomy & Astrophysics*, 648, A125.
9. M. H. Xu, S. Lunz, J. M. Anderson, T. Savolainen, N. Zubko, H. Schuh (2021) Evidence of the Gaia–VLBI position differences being related to radio source structure. *Astronomy & Astrophysics*, 647, A189.
10. S. Lambert, N. Liu, E. F. Arias, C. Barache, J. Souchay, F. Taris, J. C. Liu, Z. Zhu (2021) Parsec-scale alignments of radio-optical offsets with jets in AGNs from multifrequency geodetic VLBI, Gaia EDR3, and the MOJAVE program. *Astronomy & Astrophysics*, 651, A64.