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IAU Working Group on Multi-waveband ICRF
Terms of Reference

Context

The International Celestial Reference Frame (ICRF) is materialized by highly-accurate positions of extragalactic objects. Those positions have been derived based on observations by Very Long Baseline Interferometry (VLBI), the only astronomical technique able to achieve the desired accuracy (at the sub-milliarcsecond level) until the recent advent of Gaia.

The first ICRF (Ma et al 1998), adopted by the IAU in 1997, was aligned onto the International Celestial Reference System (ICRS), which was defined by the International Earth Rotation Service (IERS) in the 1990s, in accordance with the orientation of the FK5 optical catalog, to maintain continuity in orientation (Arias et al. 1995). The next two decades showed two further realizations, ICRF2, adopted in 2009 by the IAU (Fey et al. 2015), and ICRF3, adopted by the IAU in 2018 (Charlot et al. 2020). Each of these realizations brought increased position accuracy and source density thanks to ongoing VLBI observing by several networks, among which that of the International VLBI Service for Geodesy and Astrometry (IVS), the Very Long Baseline Array (VLBA) and the Deep Space Network (DSN).

With ICRF3, two new features were also introduced in the realization of the frame: (i) the modeling of Galactic acceleration, and (ii) the determination of source positions in three radio bands (8 GHz, 24 GHz and 32 GHz). The former implies that ICRF source positions are now not anymore fixed with time, while the latter by creating the first multi-band celestial reference frame ever generated may be regarded as an initial stage toward including further bands in the future.

At the same time, the Gaia space mission, launched in 2013, has made possible the measurements of the positions of a larger sample of extragalactic objects in the optical band with the same level of accuracy and fully independently from the VLBI positions. Notably, the Gaia-CRF2 celestial frame (Gaia collaboration 2018) is the first ever realization of an extragalactic frame in the optical band. Future Gaia data releases will lead to further improved quality with ever increased source density.

The current situation thus sees four frames with similar accuracies coexisting, three in the radio band and one in the optical band. We thus believe that the time is now ripe to move to a fully unified multi-waveband celestial reference frame.

Objectives

The objectives of the working group are to work toward the realization of a fully consistent and integrated multi-waveband celestial reference frame, incorporating positions in both radio and optical bands. This includes producing the next generation VLBI frames at the S/X, K, and X/Ka bands, or at any other radio band that may emerge in the coming years, matching these with the optical realization from the Gaia space mission, and placing all such positions on a common grid guaranteeing consistency of the source positions over the various bands. All issues relating to the construction and designation of such a multi-waveband frame are to be studied, with specific attention to the following ones:

- **Sky distribution**
  Having a uniform distribution of sources over the celestial sphere and a uniform distribution of coordinate uncertainties is essential to limit deformations of the individual frames produced in each waveband and to properly align these on a common grid. While such properties are largely verified for the Gaia optical frame, that is not the case in the radio band with ICRF3 showing a deficiency of sources in the south and asymmetries in the coordinate uncertainties (precision in

declination is lower by a factor of two). Correcting this non-uniformity goes through increasing VLBI observing in the southern hemisphere, which may be accomplished through IVS or other organizations responsible for astrometric VLBI, as per [IAU (2018) Resolution B2](). The working group may also initiate supplemental VLBI observing programs on its own if necessary.

- **Galactic acceleration**
  The acceleration of the solar system in its motion around the Galactic center, with an amplitude of about 5 μas/yr, is now seen from the VLBI and Gaia measurements and has been integrated into the realization of ICRF3 and Gaia-CRF3. As data accumulates, present estimates of this amplitude will further improve and the data will also determine whether the acceleration vector is purely directed toward the Galactic center or shows some significant offset. By the end of the Gaia mission, a final value should be fixed, considering both the Gaia and VLBI estimates, and adopted to replace the 35-year old and obsolete present IAU value. This value should be used to produce the proposed multi-waveband celestial reference frame.

- **Alignment of frames**
  There is not a single way to align reference frames produced independently at different bands or with different techniques. Whether only rotations or both rotations and deformations should be considered in the alignment process, whether individual source positions should be given equal weights or weighted separately, whether all sources or only a subset of them (e.g. the so-called defining sources in the successive ICRF realizations) should be considered, is a matter of debate. In this respect, the working group should establish a common practice, to be applied for generating the proposed multi-waveband realization and any other future realizations.

- **Wavelength and time-dependent source positions**
  Besides the above common practice to be established, the process to align reference frames at different bands may be further affected by wavelength-dependent source positions. Comparing ICRF3 and Gaia-CRF2 shows that source positions in the radio and optical bands do not coincide for a significant portion of the sources. Even within the three radio bands, positions are found to differ for a fraction of the sources. Additionally, positions may show instabilities with time, as revealed by VLBI time series, and this may also be the case on the optical side when position time series are released by Gaia. In this context, the working group should propose a scheme to work with, possibly considering source physics if deemed to be relevant.

- **Terminology**
  In addition to these tasks, dealing with the construction of the frame, the working group should also work toward defining a proper terminology for referring to the individual (per wavelength) components of the reference frame. Due to historical reasons, the ICRF terminology, though not attached specifically to the radio band, has been associated with the VLBI realizations, simply because there was no other technique with similar capabilities until the advent of Gaia. Whether keeping this terminology, incorporating the Gaia optical realizations, or whether a new one should be defined, will also be one the outcome of the working group.

The proposed timeline for the work is that the activities described here be carried out during the first triennium, i.e in the period 2021-2024, while the anticipated multi-waveband celestial reference frame would be produced during the following triennium (2024-2027), which would also be in line with the final Gaia Data Release, meaning a possible adoption by the IAU at the 2027 General Assembly. The period till then should also be utilized to strengthen the VLBI frame in the south, as noted above.

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