Future Realizations of the ICRF: Radio and Optical

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Abstract. At the XXIII General Assembly of the International Astronomical Union (IAU), held August 1997 in Kyoto, Japan, the International Celestial Reference Frame (ICRF) (Ma et al., 1998) was adopted as the fundamental astronomical celestial reference frame. As a consequence, the definitions of the axes of the celestial reference system are no longer related to the equator or the ecliptic but have been superseded by the defining coordinates of the ICRF. The ICRF is currently defined by the radio positions of 212 extragalactic objects obtained using the technique of Very Long Baseline Interferometry (VLBI) at frequencies of 2.3 and 8.4 GHz over the past 20+ years. A number of astrometric space programs have been proposed over the last few years. Since the astrometric accuracy of these missions is expected to exceed that of the current radio-based ICRF, the success of these space missions may motivate a future redefinition of the ICRF at optical wavelengths. We review the potential for future realizations of the current radio wavelength ICRF, and review the status of various space astrometric missions having the capability to produce high accuracy optical wavelength reference frames.

1 The Future of the ICRF: Radio

1.1 The ICRF-Ext.1

The primary objectives of ICRF-Ext.1 (Gambis, 1998, Fey et al., 2004), the first extension of the ICRF, were to provide positions for extragalactic radio sources observed since the definition of the ICRF (July 1995) and to refine the positions of candidate and other sources using additional observations. A secondary objective was to monitor sources to ascertain whether they continue to be suitable for use in the ICRF. The data added to the ICRF in this extension spanned December 1994 through April 1999 and was obtained from both geodetic and astrometric observing programs. Approximately 0.6 million new observations from 461 sessions were added. There were 59 new sources. The positions and errors for the defining sources were unchanged from the ICRF. Improved positions and errors for the candidate and other sources were estimated and reflect the changes in the data set and the analysis. The 59 new sources were added with ICRF coordinates. As in the original ICRF, the formal errors were inflated applying an additive variance and a scaling factor to provide more realistic errors.

1.2 The ICRF-Ext.2

The primary objective of ICRF-Ext.2 (Fey et al., 2004), the second extension of the ICRF, was to provide positions for extragalactic radio sources observed since the definition of the ICRF (July 1995) and its first extension (April 1999) and to refine the positions of candidate and other sources using additional observations. The data added to the ICRF in this extension spanned May 1999 through May 2002 and was obtained from both geodetic and astrometric observing programs. Approximately 1.2 million new observations from approximately 400 sessions were added. There were 50 new sources. The positions and errors for the defining sources were unchanged from the ICRF. Improved positions and errors for the candidate and other sources were estimated and reflect the changes in the data set and the analysis. The 50 new sources were added with ICRF coordinates. As in the original ICRF, the formal errors were inflated applying an additive variance and a scaling factor to provide more realistic errors.

1.3 The VLBA Calibrator Surveys

The VLBA Calibrator Survey (VCS1) (Beasley et al., 2002) is the largest high-resolution radio survey ever undertaken and triples the number of sources available to the radio astronomy community for VLBI applications. The VCS1 resulted in a catalog containing milliarcsecond-accurate positions of 1332 extragalactic radio sources distributed over the northern sky. The positions were derived from astrometric analysis of dual-frequency 2.3 and 8.4 GHz VLBA snapshot observations. The VCS1 observations were carried out in 10 24 hr sessions (epochs) spanning the period 1994 August to 1997 August. In total, 1811 radio sources were observed in the VCS1 campaign. The final VCS1 catalog contains positions of 1289 sources from dual-frequency solutions, and 43 source positions derived from an 8.4 GHz only solution. To align the VCS1 positions with the reference frame defined by ICRF-Ext.1, the positions of 315 ICRF-Ext.1 reference sources observed were fixed at their catalog values during the astrometric processing. The formal errors were inflated applying an additive variance and a scaling factor to provide more realistic errors.

The VCS2 (Fomalont et al., 2003) resulted in a catalog containing milliarcsecond-accurate positions of an additional 276 extragalactic radio sources. This survey fills in regions of the sky that were not completely covered by the previous surveys including sources near the Galactic plane, $-45° < \delta < -30°$, and VLA calibrators.

The VCS3 (Petrov et al., 2005) resulted in a catalog containing milliarcsecond-accurate positions of an additional 360 extragalactic radio sources. This survey fills in regions of the sky that were not completely covered by the previous surveys including sources with $\delta > -45°$ where the calibrator density is less than one source within a 4° radius.

1.4 Extending the ICRF to Higher Radio Frequencies

Because the positions in the ICRF now form the underlying basis for all astrometry, subsequent IAU resolutions have encouraged the astrometric community to extend the ICRF to other wavelengths. In 2001, a program was initiated to observe the ICRF at higher radio frequencies using the Very Long Baseline Array (VLBA) telescope of the National Radio Astronomy Observatory (NRAO). A multi-institutional team consisting of scientists from the National Aeronautics and Space Administration (NASA), the U.S. Naval Observatory (USNO), NRAO and Bordeaux Observatory was assembled and VLBA observations at 24 and 43 GHz were started in May 2002 (Jacobs et al., 2002). The long term goals of the program are to 1) develop higher frequency reference frames for improved deep space navigation, 2) extend the VLBA calibrator catalog at 24 and 43 GHz, 3) provide the benefit of the ICRF catalog to new applications at these higher frequencies, and 4) study source structure variation at 24 and 43 GHz in order to improve the astrometric accuracy. Preliminary results of the astrometry have been presented by Jacobs et al. (2002b). Preliminary results of the imaging have been presented by Fey et al. (2002) and Fey et al. (2004b).

1.5 Densification of the ICRF in the Southern Hemisphere

The goals for ICRF observing include: 1) obtaining additional data on astrometric sources for more precise positions, 2) obtaining source position stability information from time series at useful time resolution, 3) densification of defining sources, especially in the southern hemisphere and 4) source structure monitoring. To accomplish these goals, various observing programs are underway. The International VLBI Service (IVS) schedules regular Celestial Reference Frame (CRF) experiments for the specific purpose of maintenance of the ICRF. In recent years, these CRF experiments have concentrated primarily on observing sources in the southern hemisphere. The U.S. Naval Observatory currently has a joint program with the Australia Telescope National Facility (ATNF) for astrometry and imaging of southern hemisphere ICRF sources (Fey et al., 2000). The goals of this USNO/ATNF joint 5-year program are to image all southern hemisphere ICRF sources at least twice for structure monitoring and to search for new astrometric sources for densification. This program has yielded, to date, milli-arcsecond accurate positions for a total of 47 southern hemisphere sources (Fey et al., 2004c, Fey et al., 2004d). The positions for all 47 sources are south of $\delta = -30°$. Images at 8.4 GHz for a total of 69 southern hemisphere extragalactic sources in the ICRF have been presented by Ojha (2004). These imaging observations represent the first large, comprehensive VLBI survey in the southern hemisphere, significantly extending the existing limited VLBI surveys and, along with some well-known objects, contain many sources that have never been imaged at milliarcsecond resolution.

1.6 Densification of the ICRF in the Northern Hemisphere

The ICRF suffers from a deficit of sources with an average of only one object per 8x8 degrees on the sky (Charlot et al., 2000). Additionally, the distribution of the 667 ICRF-Ext.1 sources is found to be largely non-uniform. For example, the distance to the nearest ICRF source for any randomly-chosen sky location is up to 13 degrees in the northern hemisphere and 15 degrees in the southern hemisphere. In many cases, this precludes the use of the ICRF as a catalog of calibrators serving as fiducial points to determine the relative positions of nearby weaker objects (radio stars, pulsars, weak quasars) with the phase-referencing technique, because the separation between the calibrator and the target source should be a few degrees at most in such observations. The non-uniform source distribution also makes it difficult to assess and control any local deformations in the ICRF. Such deformations might be caused by tropospheric propagation effects and the apparent motions of the sources due to variable intrinsic structure.

To address these concerns, an observing program was proposed (Charlot et al, 2000) and is currently underway to densify the ICRF using an approach that will also improve the overall sky distribution of the sources. A secondary objective of the program is to identify new sources of high astrometric value which could potentially be used as defining sources in a future realization of the ICRF. This program concentrates on observations of northern hemisphere sources using the existing standard VLBI networks such as the European VLBI Network (EVN) and the VLBA.

1.7 Connecting the ICRF to Future Optical Realizations Through Stars

Although the present day ICRF is based on the VLBI determined radio positions of extragalactic sources, astrometric positions of galactic and extragalactic sources from future space-based missions at optical wavelengths will likely surpass the accuracy of the current ICRF, and may define the next generation ICRF. However, there will continue to be a need for an accurate link between a radio reference frame and future optical realizations of the ICRF. Of the proposed future astrometric missions, only GAIA will accurately measure astrometric positions of a large number of extragalactic sources. Proposed missions such as SIM will be limited to a small number of only the brightest extragalactic sources. As a result, it is still desirable to obtain the astrometric positions of a number of galactic sources visible in both the radio and the optical to provide a connection between the two frames. Personnel at the U.S. Naval Observatory continue to build upon a program of radio star astrometry begun in the late 1970's using the NRAO Very Large Array (VLA) (Johnston et al., 1985, Johnston et al., 2003). Recent observations using the VLA in its A-configuration in conjunction with the Pie Town VLBA antenna (Boboltz et al., 2003) were used to determine the astrometric positions of 19 radio stars in the ICRF. Average values for the errors in our derived positions for all sources were 13 and 16 mas in $\alpha \cos \delta$ and δ, respectively. U.S. Naval Observatory personnel will continue work on this radio star observing program. Additional VLA observations and observations recorded with the Multi-Element Radio Linked Interferometer Network (MERLIN) are currently being reduced.

2 The Future of the ICRF: Optical

The accuracy level of the current radio wavelength based ICRF significantly surpasses the accuracy of any existing optical astrometric catalog derived from ground based observations. However, the promised astrometric accuracy and target density of future space-based optical astrometric missions will likely motivate a future redefinition of the ICRF at optical wavelengths. Hipparcos was the world's first, and up to this point only, dedicated space astrometry mission. Owing in part to the great success of the Hipparcos mission, a number of follow-up space astrometry missions have been discussed, planned, proposed, funded, scheduled for launch, rescoped, descoped, and in some cases, canceled. These missions include DIVA, AMEX (SMEX), AMEX (MIDEX), FAME, JASMINE, SIM-PlanetQuest, Gaia, and OBSS. It is often difficult to keep track of the current status of the various space astrometry missions due in part to the quickly changing nature of the organizational priorities and funding resources of the major national and international space astronomy agencies. Currently, the list of funded space astrometry missions progressing toward launch has been reduced to two: SIM-PlanetQuest and Gaia. The salient features of these two missions are outlined below:

2.1 SIM PlanetQuest

- **Synopsis:** SIM PlanetQuest is a space-based optical interferometer operating in an earth-trailing orbit.
- **Acronym:** **S**pace **I**nterferometer **M**ission
- **Funding Agency:** NASA
- **Launch:** 2010 (planned). Five year baseline mission, potential ten year extended mission.
- **ConOps:** SIM PlanetQuest is a pointed mission with predefined targets
- **Number of Objects:** about 10,000 stars (1,300 grid stars)
- **Magnitude Range:** brighter than (a limiting magnitude of) about 20^{th}.
- **Astrometric Accuracy:** 4 microarcseconds wide angle, 1 microarcsecond narrow angle
- **Reference Frame:** Should SIM achieve 4 microarcseconds wide angle astrometric accuracy, the resultant grid will form the basis of the most accurate reference frame ever produced, easily exceeding the accuracy of the current radio-based ICRF. SIM will also be capable of observing a fair number of extragalactic sources. Detailed plans are currently being developed with regard to SIM observations of the extragalactic frame sources.
- **Additional Information:** SIM Planetquest is currently in mission development Phase B (Preliminary Design phase).[1]

Fig. 1. Artist's conception of the SIM-PlanetQuest spacecraft

[1] See: http://planetquest.jpl.nasa.gov/SIM

2.2 Gaia

- **Synopsis:** Gaia is a funded space astrometry mission intended to launch in 2010-2012. Operating at L2, Gaia consists of three instruments which provide astrometric, photometric, and spectroscopic data.
- **Funding Agency:** ESA
- **Launch:** before 2012 (planned). Five year operation phase.
- **ConOps:** Continuous scanning. Two optically combined fields of view.
- **Number of Objects:** 10^9
- **Magnitude Range:** 7-20^{th} magnitude
- **Astrometric Accuracy:** 15-20 microarcseconds @ 15^{th} m_v
- **Reference Frame:** The stated accuracy goal of Gaia (Perryman, 2004) is somewhat less than that of SIM-PlanetQuest. What Gaia loses in accuracy, however, is easily overcompensated in the number of mission objects, of order 10^5 more than SIM-PlanetQuest. Gaia will also detect and measure the positions of about 400,000 QSOs, enabling an extremely rigid attachment of the impressively dense Gaia stellar frame to the extragalactic frame.
- **Additional Information:** In addition to astrometry, Gaia will provide 12 band millimagnitide photometry, radial velocity data for brighter stars to an accuracy of a few km/s and spectrophotometry in the visible and near-IR to m_v 17.5.[2]

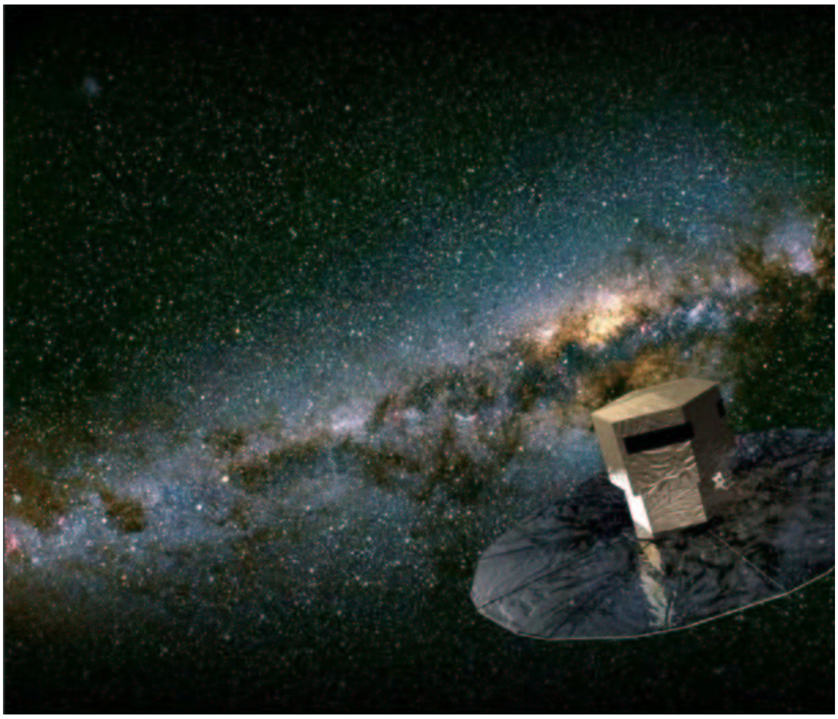

Fig. 2. Artist's conception of the Gaia spacecraft, on orbit

[2] See: http://www.rssd.esa.int/gaia/

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