THE STATUS AND FUTURE OF THE ICRF

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ABSTRACT. The International Celestial Reference Frame is currently defined by the radio positions of 212 extragalactic objects. Since its inception there have been two extensions to the ICRF. These extensions included revised positions of ICRF candidate and "other" sources, based on inclusion of additional observations, as well as positions of an additional 109 "new" sources. With continued applicable VLBI observations and improvements in analysis a better realization of the ICRF is now possible and an even better realization is feasible in the foreseeable future. Planning for a second realization of the ICRF is currently underway with a projected completion date concurrent with the 2009 IAU General Assembly. Within the next decade, optical astrometric satellites will present serious competition to the radio based ICRF. Reevaluation of the spectral regime at which the ICRF is defined will then be necessary.

1. THE STATUS OF THE ICRF

At the XXIII General Assembly of the International Astronomical Union (IAU) held on 20 August 1997 in Kyoto, Japan, the International Celestial Reference Frame (ICRF) [9] was adopted as the fundamental 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of the axes of the celestial reference system are no longer related to the equator or the ecliptic but have been superseded by the defining coordinates of the ICRF.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. The positional accuracy of the ICRF sources is better than about 1 mas in both coordinates. The ICRF "defining" sources set the direction of the ICRS axes and were chosen based on their observing histories and the stability and accuracy of their position estimates. The sky distribution of the ICRF defining sources is shown in Figure 1. In addition to the 212 defining sources, positions for 294 less observed candidate sources along with 102 less suitable "other" sources were also given by [9] to densify the frame. The final orientation of the frame axes was obtained by a rotation of the positions into the system of the International Celestial Reference System (ICRS) [1] and is consistent with the FK5 J2000.0 optical system, within the limits of the latter system accuracy.

There have been two extensions [6] of the ICRF since its initial definition in 1998. The primary objectives of extending the ICRF were to provide positions for the extragalactic radio sources observed since the definition of the ICRF and to refine the positions of candidate and "other" sources using additional observations. There were 59 new sources in ICRF-Ext.1 and 50

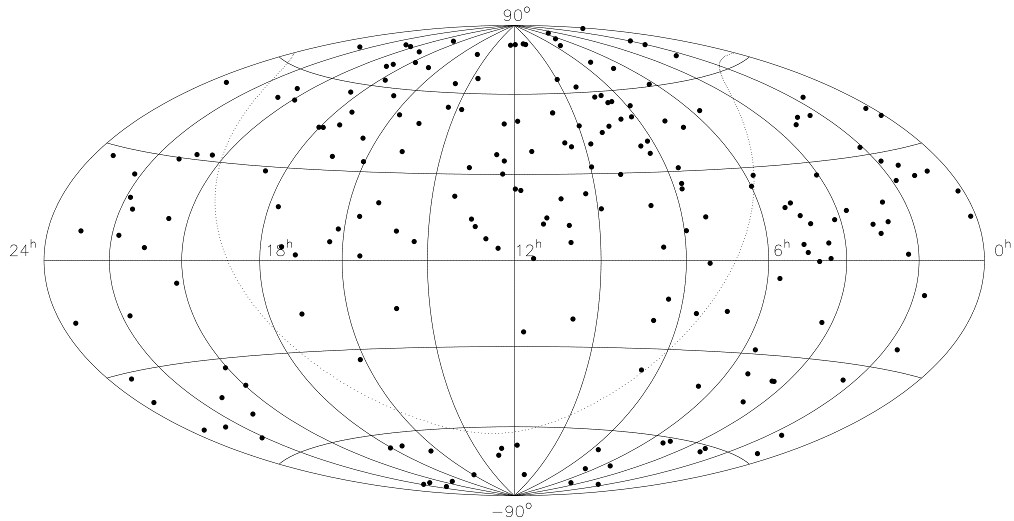

Figure 1: Distribution of the 212 ICRF Defining sources on an Aitoff equal-area projection of the celestial sphere. The dotted line represents the Galactic equator.

new sources in ICRF-Ext.2. Coordinates consistent with the ICRF were estimated for these 109 new sources. The distribution on the sky of the new sources is shown in Figure 2. Positions of the ICRF defining sources have remained unchanged.

2. ICRF MAINTENANCE

The International Astronomical Union (IAU) has charged the International Earth Rotation and Reference Systems Service (IERS) with the maintenance of the ICRF. Maintenance activities are run jointly by the IERS ICRS Product Center and the International VLBI Service (IVS).

The IERS ICRS Product Center is directly responsible for the maintenance of the ICRS and ICRF. The Center is run jointly by the Observatoire de Paris and the U.S. Naval Observatory (USNO). More information can be obtained from the Product Center Web page at `http://www.iers.org/iers/pc/icrs/`.

The IVS is an international collaboration of organizations which operate or support VLBI. The IVS provides a service which supports geodetic and astrometric work on reference systems, Earth science research, and operational activities. Many of the observing programs for maintenance of the ICRF are coordinated by the IVS. More information about the IVS can be obtained from the IVS Web page at `http://ivscc.gsfc.nasa.gov/`.

Various observing programs contribute astrometric data for maintenance of the ICRF. These include but are not limited to:

- *IVS CRF Experiments:* These 24^{hr} duration VLBI experiments, coordinated by the IVS, concentrate primarily on observation of southern hemisphere ICRF sources for monitoring and to increase the sky density of ICRF defining sources.

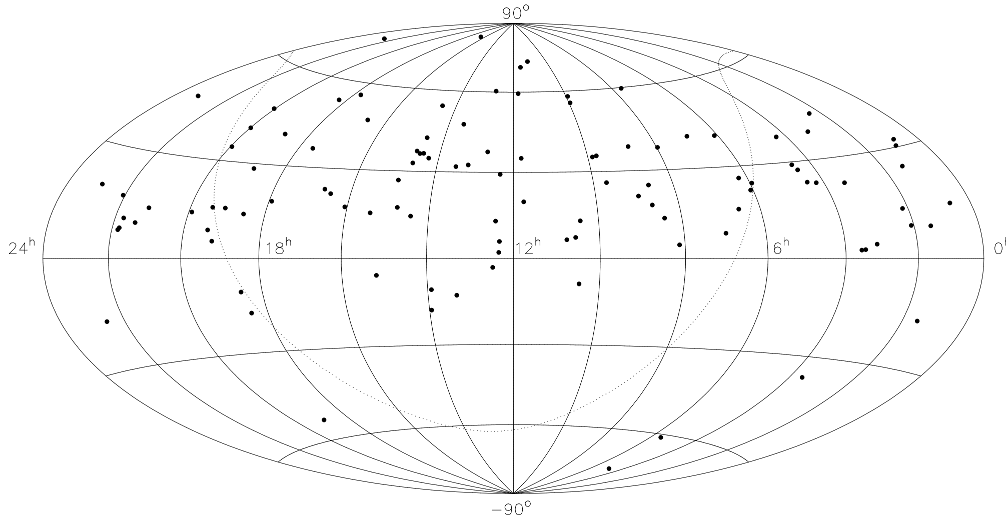

Figure 2: Distribution of the 109 new sources in ICRF-Ext.1 and ICRF-Ext.2 on an Aitoff equal-area projection of the celestial sphere. The dotted line represents the Galactic equator.

- *VLBA RDV Experiments:* These 24^{hr} duration VLBI experiments are part of a collaborative program of geodetic and astrometric research between the USNO, Goddard Space Flight Center (GSFC) and the National Radio Astronomy Observatory (NRAO). These Very Long Baseline Array (VLBA) experiments concentrate primarily on observation of northern hemisphere ICRF sources ($\delta > -30°$). Intrinsic source structure information is also obtained from these experiments.

- *IVS Geodetic/Astrometric Experiments:* These 24^{hr} duration VLBI experiments, coordinated by the IVS, concentrate primarily on observation of sources for geodetic purposes and for Earth Orientation Parameter estimation but are also useful for astrometric purposes.

- *VLBA Calibrator Surveys:* These 24^{hr} duration VLBI experiments are part of a joint NRAO/GSFC program to expand both the list of high quality geodetic sources and the list of phase reference calibrators for imaging.

- *EVN Experiments:* These 24^{hr} duration VLBI experiments are part of a Bordeaux Observatory program to expand the list of ICRF defining sources in the northern hemisphere using the European VLBI Network (EVN).

- *LBA:* These 24^{hr} duration VLBI experiments are part of a joint USNO/ATNF program to expand the list of ICRF defining sources in the southern hemisphere using the Australia Telescope National Facility (ATNF) Long Baseline Array (LBA). Intrinsic source structure information is also obtained from these experiments. The distribution on the sky of 74 new southern hemisphere sources added by this program is shown in Figure 3.

3. ASTROMETRIC ANALYSIS IMPROVEMENTS

Modeling and analysis capabilities have advanced significantly since the ICRF was defined, particularly for handling the troposphere and source structure. While the charged particle media propagation effects are effectively calibrated using two observing frequencies, the modeling of the troposphere has improved in discrete steps associated with development of new troposphere mapping algorithms [11, 12] and modeling of asymmetry and variability [10]. Current research

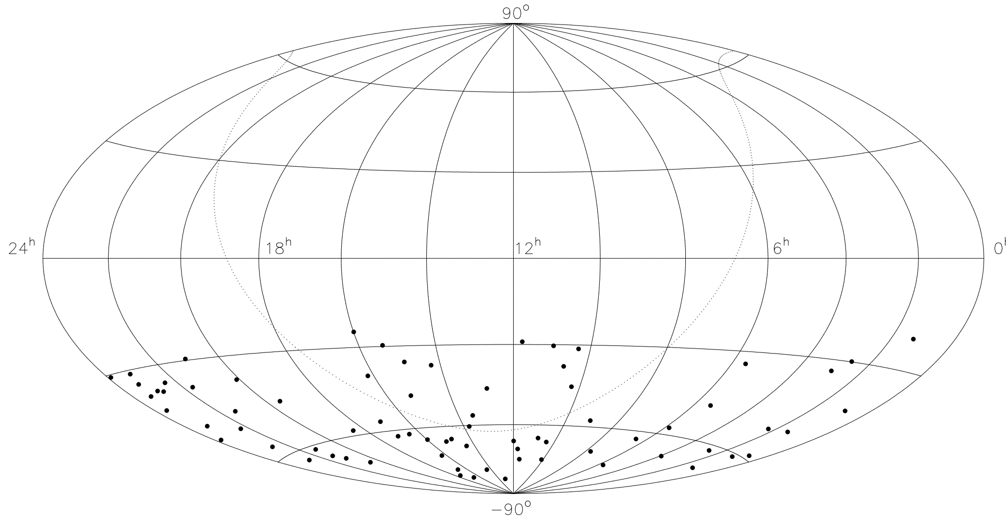

Figure 3: Distribution of 74 new southern hemisphere sources with milliarcsecond accurate astrometric VLBI positions which are now available for inclusion in the next realization of the ICRF.

is directed toward the use of global weather data in computing the mapping function through ray tracing or a proxy.

Source structure and changes in source structure put a floor on the stability of source positions. Modeling such effects has been tested on massive scales by [13]. Results of this analysis showed that the effects of intrinsic source structure on astrometric position estimation amounts to a significant fraction of the systematic error budget, thus confirming that source structure does affect VLBI analysis even though it is not currently the dominant error. An investigation of the astrometric suitability of a large sample of ICRF sources based on intrinsic source structure by [3, 4] found correlations between the observed radio structure and the astrometric position accuracy and stability of the sources indicating that the more extended sources have larger position uncertainties and are less positionally stable than the more compact sources.

Refinements in modeling the motion of the stations, especially in various loading effects, should permit the unification of analysis for the celestial reference frame, the terrestrial reference frame and Earth orientation parameters, which were separated in the ICRF analysis. As shown by [2], it should now be possible to include the station positions and velocities as global parameters (i.e. parameters dependent upon the data from all observing sessions) in the analysis without contamination of the celestial reference frame.

About one-third of the ICRF defining sources were found by [3, 4] to be somewhat spatially-extended and thus may not be appropriate for defining the celestial frame with the highest level of accuracy. This suggests that revision of source categories would be mandatory upon realization of a new ICRF. In order to address the question of finding an improved method of selecting stable and potential defining sources in a subsequent ICRF realization, [2] used position time series, computed in parallel with the ICRF-Ext.2 analysis, to derive a global source stability index based on the repeatability of the source positions from epoch to epoch. This analysis showed that over long time intervals the ICRF defining sources are not as positionally stable as could be hoped. The analysis also identified a set of sources that could potentially be better and which could be used to improve the next realization of the ICRF.

As a consequence of changes in observing strategy and networks over the lifetime of astrometric/geodetic VLBI, the stability of source positions derived from individual year data sets has improved significantly since about 1990 [7]. A considerable improvement in the ICRF can be expected by using only the data obtained after 1990. The source stability analysis of [2] found that only about half of the available sources had sufficient data for a time series analysis. The lack of data for stability analysis is most pronounced in the southern hemisphere. Consequently, special emphasis by the IVS is now being placed on observations of the stable and potentially stable sources, especially in the southern hemisphere, identified as possible defining sources for a next realization of the ICRF.

Technical innovations incorporated into newer VLBI recording systems now allow the use of both wider spanned bandwidths and higher recorded data rates. The consequent increased sensitivity will allow observations of weaker sources not previously accessible. As these systems are more widely deployed, much higher sensitivity observations will become the norm, increasing the number of observations and increasing the number of observable radio sources.

4. THE NEXT RADIO REALIZATION OF THE ICRF

The institution of the IVS has significantly improved the organization and coordination of global geodetic/astrometric VLBI observations. With continued applicable VLBI observations and improvements in analysis, a better realization of the ICRF is now possible and an even better realization is feasible in the foreseeable future. Under the direction of the ICRS Product Center, which is responsible for the maintenance of the ICRF, planning for a second *radio* realization of the ICRF is currently underway with a projected completion date concurrent with the 2009 IAU General Assembly.

5. THE FUTURE OF THE ICRF

VLBA observations to extend the ICRF to radio frequencies of 24 GHz and 43 GHz began in 2002 May. The use of this frequency pair was motivated by the National Aeronautics and Space Administration (NASA) decision to move future spacecraft telemetry from the current 8.4 GHz to 32 GHz and the availability of 24 GHz and 43 GHz receivers on the VLBA. One of the goals of these observations was to study whether the sources were more compact at 24 GHz and 43 GHz in order to improve the astrometric accuracy at these frequencies. Initial imaging results [5] show that sources are indeed more spatially compact at these higher frequencies than those currently used for the ICRF. The initial reference frame derived from these data [8] shows agreement with the ICRF to roughly the 0.3 mas level with zonal errors dominating the differences. The accuracy of a celestial reference frame defined at these higher observing frequencies has the potential of exceeding that of the current ICRF.

In the coming decades, there will be significant advances in the area of space-based optical astrometry. Planned missions such as the NASA SIM PlaneQuest and the European Space Agency GAIA will achieve positional accuracies well beyond that presently obtained by any ground-based radio interferometric measurements. SIM PlaneQuest will be a space-based optical interferometer that will be able to determine the positions of stars with a precision approaching the microarcsecond (μas) level but is a pointed mission with a limited number of target objects and limited sensitivity. The SIM astrometric grid, which will consist almost entirely of stellar sources (and of order 100 extragalactic objects to remove the global rotation of the stellar frame), will ultimately be more accurate than the current ICRF but will not be quasi-inertial as the stars that will be observed are nearby objects in comparison to the quasars that make up the radio frame. GAIA on the other hand is planned as a survey mission and will make observations of order 10^9 objects and, with a limiting magnitude of $m_v \approx 20$, will be able to observe almost all known extragalactic sources. Because of the large number of extragalactic objects accessible by GAIA, the astrometric grid defined by GAIA can be constructed in such a way as to be quasi-inertial. If the projected accuracies for GAIA are realized, the GAIA astrometric grid will be serious competition for the radio realization of the ICRF and must prompt reevaluation of the spectral regime at which the ICRF is defined.

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