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Refinement of the ICRF

Chopo Ma

NASA Goddard Space Flight Center
e-mail: cma@virgo.gsfc.nasa.gov

Abstract

Since the ICRF was generated in 1995, VLBI modeling and estimation, data quality, source position stability analysis, and supporting observational programs have improved markedly. There are developing and potential applications in the areas of space navigation, Earth orientation monitoring and optical astrometry from space that would benefit from a refined ICRF with enhanced accuracy, stability and spatial distribution. The convergence of analysis, focused observations, and astrometric needs should drive the production of a new realization in the next few years.

1. Introduction

The ICRF (International Celestial Reference Frame) is the first realization of the ICRS (International Celestial Reference System) at radio frequencies and consists of 212 defining sources whose positions are independent of the equator, equinox, ecliptic and epoch but consistent with the previous stellar and dynamical realizations within their respective errors. The accuracy of individual positions has a floor of 0.25 milliarcseconds based on an extensive error analysis while the orientation stability of the axes is $\sim$20 microarcseconds. Initially the ICRF positions of 608 sources were estimated (Ma et al., 1998). While the ICRF did not come into official use until 1 January 1998, the catalog positions were used before that date to orient and stabilize the HIPPARCOS catalog, the ICRS realization at optical frequencies. Since then the radio positions have been improved for non-defining sources and the catalog extended by 109 sources in ICRF-Ext.1 and ICRF-Ext.2 (Fey et al., submitted) using newer data from conventional geodetic/astrometric sessions along with $\sim$1200 sources from a series of VLBA sessions devoted to the VLBA Calibrator Survey (Beaseley et al., 2002).

2. Considerations for Generating the Next ICRF

The process for introducing and adopting the ICRF was detailed and lengthy. A firm theoretical framework, sufficient observational data, established VLBI analysis, an expectation of order of magnitude improvement over the stellar celestial reference frame, and preparation of the astronomical community were all important in a smooth transition from FK5 to ICRF. The rationales for the next radio realization are rather different and the process may be less formally structured.

One rationale and a prerequisite is useful improvement in the intrinsic quality of a new realization. The limitations of the ICRF are the error floor (related to modeling, estimation, and data imperfections), the defining sources (too sparse, unevenly distributed spatially, insufficiently stable in retrospect), and data distribution (overall sparseness of sources and particular deficiency in the southern hemisphere). Each of these weaknesses can be significantly ameliorated by developments since 1995 and expected changes in analysis and CRF observing in the next few years.

There are two areas that would directly benefit by a more accurate and stable realization. Spacecraft navigation using differential VLBI relative to a nearby ICRF object is now a standard technique in the NASA solar system exploration program and is also planned for the Japanese and Chinese lunar probes. This measurement type is dependent on the accuracy of ICRF positions as well as ICRF objects in the relevant parts of the sky. The second area is VLBI monitoring of Earth orientation parameters, particularly precession/nutation and UT1. These measurements will continue to be the unique domain of VLBI. Enhanced stability and accuracy are needed to detect the small, variable effects of deep structures of the Earth.

A prospective development in optical astrometry, the GAIA mission, may prove to be the most stringent requirement for the radio realization. Expected to be launched within a decade, GAIA is projected to achieve 10 microarcsecond precision for brighter quasars. To achieve the best optical-radio registration and to insure the highest accuracy for the transfer from radio to optical realizations, the radio CRF must be pushed to the limit. A particular VLBI observing effort may be needed for the common sources since the current ICRF sources are generally weaker than desirable in the optical band.

The process for adopting the ICRF was quite formal, culminating in an IAU resolution at the IAU General Assembly at Kyoto in 1997. Since then the responsibility for the maintenance of the ICRS has been given to the IERS (International Earth Rotation and Reference Systems Service) while the IVS has operational responsibility for the VLBI realization. The IAG (International Association of Geodesy) is forming a working group in Subcommission 1.4 Interaction of Celestial and Terrestrial Reference Frames to investigate the systematic errors in the ICRF because of the impact on Earth orientation parameters and indirectly on the satellite celestial reference frames. While the work for the ICRF was accomplished within an IAU working group, the work for the next VLBI realization may be more loosely coordinated or placed under a different organization. The process for preparing the astronomical community and for formal adoption remains to be decided.

3. Areas of Refinement

There are four main areas in which the VLBI realization of the ICRS can be improved: analysis, data, defining sources, and observing programs.

Since 1995 considerable progress has occurred in VLBI modeling and estimation. New analysis software has been developed (Titov et al., this volume; Tesmer et al., this volume). The largest source of errors is probably the troposphere, so improved troposphere mapping functions that use weather model information such as the IMF (Isobaric Mapping Function) (Niell, 2002) and the VMF (Vienna Mapping Function) (Boehm et al, this volume) and better gradient estimation should reduce systematic errors and temporal noise. Refined loading models for ocean, atmosphere and hydrology effects should permit the unified solution for CRF, TRF and EOP to exploit the unique capability of VLBI. In constrast, the ICRF analysis estimated station positions for each session to reduce contamination from the TRF. However, analysis methods to properly model nonlinear station motions as well as apparent sources motions and other instabilities need to be tested and compared. Treating unstable sources as arc parameters as was done for the ICRF may unnecessarily weaken the results. It should be noted that the ICRF-Ext.1 and ICRF-Ext.2 analysis were consistent with the analysis for the ICRF.

The ICRF used all available geodetic/astrometric VLBI data from 1979 to 1995.6. The sources observed, the number of sources and observations in each session, the network sizes and geometries, and the sensitivity of the VLBI equipment evolved over the period and have continued to improve since then. Instead of ~15 sources with a network of 3-4 stations producing several hundred observations in the earliest years, the most extensive modern sessions use 20 stations and up to 80 sources resulting in several tens of thousands of observations. In addition, Gontier et al. (2001) showed that the stability of the CRF improved noticeably around 1990. Consequently the next realization probably will discard early sessions as well as those unsuitable for astrometry. Figure 1 shows that the 792 sources observed since 1990 in conventional geodetic/astrometric sessions cover the sky with reasonable uniformity. It will remain true, however, that the bulk of the data will come from geodetic sessions, ~200 "geodetic" sources most frequently observed, and the northern hemisphere. Sessions using the VLBA together with up to 10 other stations will contribute a significant fraction of the total observations.

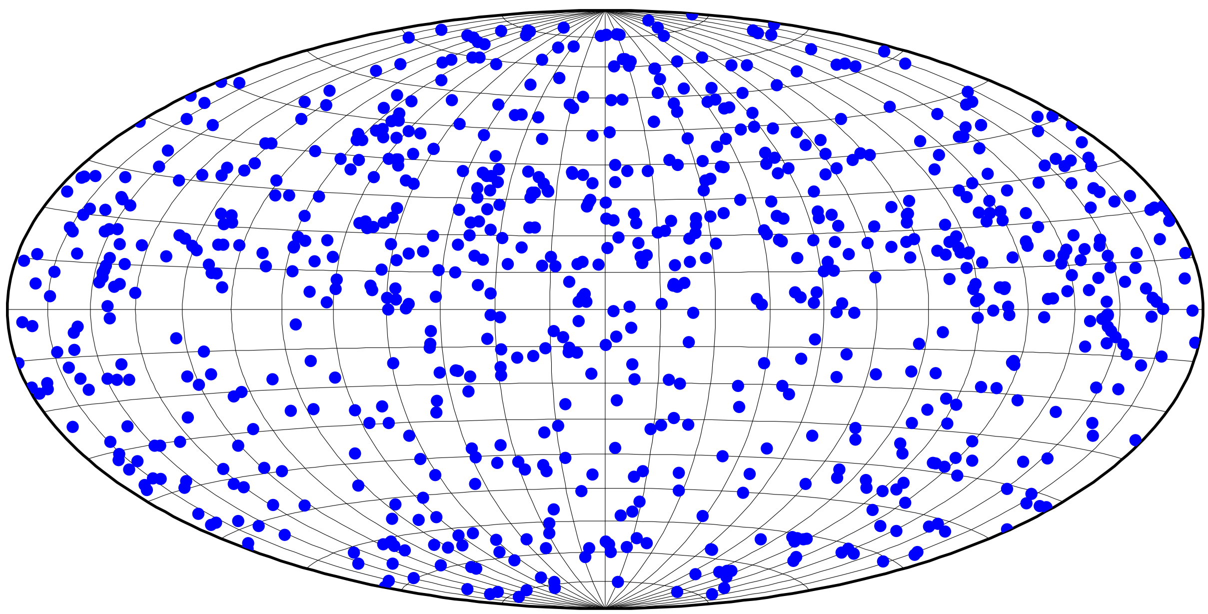

Figure 1. 792 sources observed since 1990.

The positions of the 212 defining sources are the formal realization of the ICRS called the ICRF. These sources were chosen with the best information available in 1995 based largely on number of observations and position stability. However, the distribution of the data over sources and over the sky was extremely nonuniform with most of the observations from fewer than 100 "geodetic" sources used in the regularly scheduled geodetic sessions in the northern hemisphere. In order to have over two hundred defining sources with somewhat more extensive and uniform sky distribution, the selection criteria could not be too severe. Even so, less than 30% of the defining sources are in the south. On the other hand, some frequently observed sources were not selected as defining sources because they had sufficient data to detect anomalous behavior. Recent analysis by Feissel-Vernier (2003) looking at annual VLBI source position time series from 1990 to 2002 and using very different criteria from the ICRF identified a different set of sufficiently observed sources with stable positions. A number of ICRF defining sources failed these stability criteria. It is clear that the next realization should reexamine the defining sources and ensure that the data set is robust enough to make a new selection.

While the Feissel-Vernier analysis showed that better defining sources can now be found, the number and distribution of such sources still leaves something to be desired. In the planned IVS observing program the vast majority of the sessions are primarily geodetic in nature. The VLBA sessions contribute to both geodesy and astrometry by design. Recognizing the data deficiencies, the astrometric sessions will concentrate on the southern hemisphere, particularly to provide sufficient temporal coverage to identify stable sources. In addition, a small fraction of each geodetic session will be allocated to observing stable and potentially stable sources to accumulate data more rapidly for time series analysis and estimation of apparent proper motion. Potentially stable sources are those whose current time series have insufficient data to establish stability but do not show disqualifying motions or scatter. Over the next few years these observing efforts should significantly augment the potential defining sources for the next realization.

4. Summary

The next VLBI realization of the ICRS, perhaps to be designated ICRF-200x, will differ significantly from the ICRF. It will utilize the state of the art VLBI analysis as of the end epoch 200x, correcting known systematic errors in the ICRF and reunifying the CRF, TRF and EOP. The data set will most likely include only astrometrically relevant data from 1990 to 200x. The defining sources will be more extensive and uniformly distributed than those of the ICRF, relying on the geodetic data augmented by recent directed astrometric observations for stable sources and the southern hemisphere.

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