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Uses of the ICRF and Implications for Future VLBI

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Abstract

Since its inception on 1 Jan 1998, the fundamental ICRF has been set by the VLBI positions of 212 "defining" extragalactic radio sources. In all, there are $\sim$ 3000 sources with usefully accurate ($<$ few mas) positions consistent with the ICRF. The uses of the ICRF include fundamental astrometry, monitoring of Earth orientation, and spacecraft navigation. For fundamental astrometry, stability and accuracy are most important, and realizations at different frequencies must be in proper registration. However, there is no preferred frequency, and the GAIA mission has the potential for an optical ICRF with 500,000 objects at the 50 microarcsec level some time after the planned 2011 launch. The radio ICRF should be properly prepared for a transition to assure long term stability and consistency. Earth orientation monitoring requires objects attached to the solid Earth, and VLBI will continue to be the fundamental technique. For this purpose it is essential that the new VLBI stations contemplated in the VLBI2010 report be capable of observing a sufficiently large and well-distributed set of stable sources, and identifying these sources is an on-going effort. Spacecraft navigation by differential VLBI is planned using the Ka-band telemetry signal, and work has begun towards an ICRF realization suitable for this purpose. The balancing of different needs related to the VLBI ICRF is discussed.

1. Introduction

Since 1 January 1998 the fundamental ICRF (International Celestial Reference Frame) has been set by VLBI positions of extragalactic radio sources, formally the 212 defining sources. The $\sim$ 3000 radio sources with accurate positions in the ICRS (International Celestial Reference System) have uses in fundamental astrometry, geodesy, spacecraft navigation, and astrophysical observing. Consequently, the observations and analysis for continued strengthening, refinement, and densification of the VLBI source catalogue as well as the development of advanced VLBI instrumentation such as VLBI2010 must balance the various needs. In addition, the transition to an optical extragalactic celestial reference frame with many more objects and significantly improved precision must be prepared.

2. Fundamental Astrometry

The ICRF-Ext.2 (Fey et al., [2]) shown in Figure 1 is the latest refinement of the original ICRF (Ma et al., [4]). It retains the positions of the 212 defining sources unchanged as well as the overall error characteristics of the ICRF while improving the positions of the remaining sources and adding $\sim$15% more. For fundamental astrometry accuracy and stability of positions and distribution over the sky are of greatest importance. The data used for the original ICRF spanned 1979.7 - 1995.6. However, Gontier et al. [3] showed that data after $\sim$1990 are considerably better for astrometry than the older data in the ICRF analysis, and Feissel-Vernier [1] showed that some of the 212 ICRF defining sources are less than ideal when considering the currently available VLBI data. The overall data distribution is deficient in the southern hemisphere, and many of the ICRF defining sources have been poorly observed since 1995. Consequently the IVS began a celestial reference frame (CRF) monitoring program in 2004 to improve the data set for high quality astrometric sources and for ICRF defining sources, which is described below.

3. Geodesy

VLBI geodesy encompasses two main areas, regular monitoring of EOP (Earth orientation parameters), for which VLBI has unique capabilities, and maintaining the ITRF (International Terrestrial Reference Frame), to which VLBI contributes scale and long term data. These observing sessions use a subset of the VLBI sources often called the geodetic catalogue. The current geodetic catalogue has ~100 sources and is shown in Figure 2. The geodetic catalogue has evolved over the years following development of VLBI instrumentation and networks, and the small number of geodetic sources constitute well over 90% of all VLBI geodetic/astrometric observations. Ideally geodetic sources should be strong, point-like and stable in position, but very few sources meet all the criteria all the time. In particular, as shown in Figure 2, there has been a trade-off between stability and source strength in some cases, and sources that are usually quite good occasionally drop in flux density or evolve structure for some period. MacMillan (this volume) shows some effects in the geodetic results caused by source instability. Maintaining and updating the geodetic catalogue has been a sporadic effort, hampered by the absence of objective criteria and sufficient data for regularly adding or removing sources. As with fundamental astrometry, the geodetic catalogue should be improved in the future by data from the CRF monitoring program.

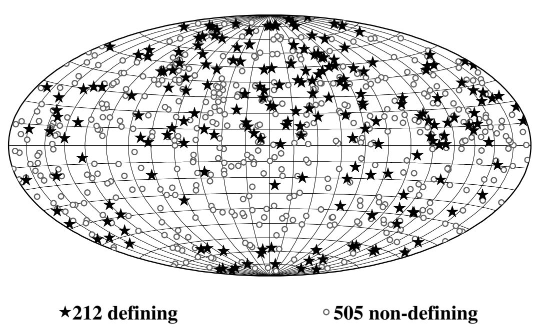

Figure 1. ICRF Ext.2 sources.

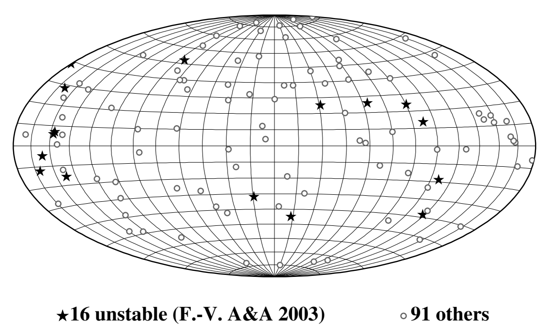

Figure 2. Geodetic sources.

4. Celestial Reference Frame Monitoring Program

The CRF monitoring program was started by the IVS in the spring of 2004 to remedy serious gaps in the astrometric observing profile, primarily the paucity of data for most of the stable sources identified in Feissel-Vernier [1] and subsequent analysis (Feissel-Vernier, personal communication). See Figure 3. Potentially stable sources, i.e., those with insufficient data to determine stability but no obvious deficiencies (Figure 4) as well as poorly observed ICRF defining sources are also included. Some stable sources and some ICRF defining sources are in the geodetic catalogue and are not included in the CRF monitoring list since they have more than sufficient observations. The current set of CRF monitoring sources is shown in Figure 5.

The CRF monitoring program uses ~10% of the observations of certain geodetic sessions (currently R1 and RDV) to systematically observe sources in the CRF monitoring list. The goal is to have at least one session per target source every six months. Figure 6 shows that this goal is being met. These data will allow the extension of the Feissel-Vernier [1] time series analysis and improvement of the positions of the ICRF defining sources. In addition, the RDV sessions, which use the VLBA and up to ten other stations, provide data for structure maps. The CRF monitoring data will be essential to properly select defining sources for the next radio-frequency ICRF realization. To increase the data in the southern hemisphere, the IVS has focused its astrometric observing program on mid and far southern sources.

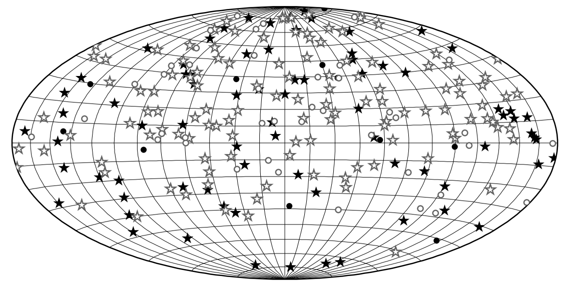

Figure 3. Total stable sources.

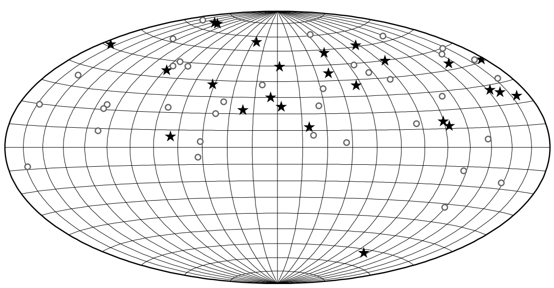

Figure 4. Potentially stable sources from M. Feissel-Vernier (personal communication).

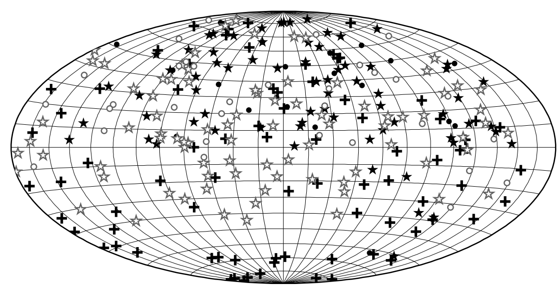

Figure 5. Total CRF monitoring sources.

5. Spacecraft Navigation

Spacecraft navigation using differential VLBI has become a standard technique for NASA spacecraft equipped with delta-DOR (Differential One-way Range) at X-band and has been tested at Ka-band. The Cassini-Huygens probe was tracked while descending to Titan in January 2005 by a global array of astronomical VLBI stations using phase referencing at S-band. Such spacecraft navigation requires a high density of sources near the ecliptic with positions at the telemetry frequency. As the telemetry frequency has evolved from S-band (2 GHz) to X-band (8 GHz) to Ka-band (30 GHz) to provide greater signal bandwidth, the source catalogues must also evolve.

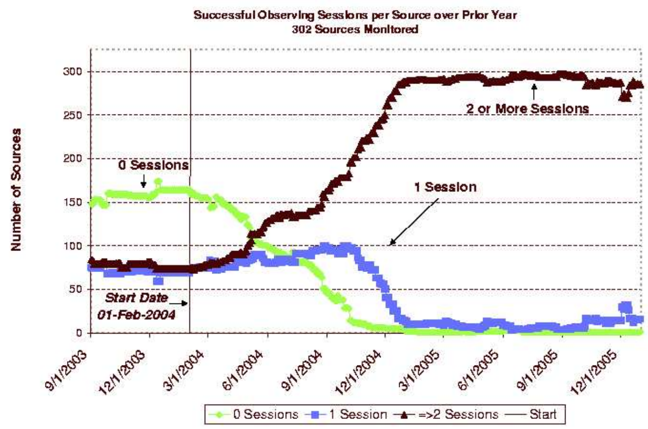

Figure 6. Source monitoring.

Since there is not yet sufficient observing capability to build a true Ka-band catalogue, K-band (22 GHz) and Q-band (43 GHz) observations have been used as proxies. See Jacobs et al. (this volume). These higher frequency observations have shown that sources are generally more compact but weaker than at S/X-band.

6. Astrophysical Observing

A standard technique for observing weak radio sources with VLBI is phase referencing, i.e., integrating the differential VLBI signal between a weak target source and a nearby calibrator. Many sources of error are cancelled or sharply reduced in this mode. For this purpose the spatial density and distribution of the calibrator catalogue are most important, and the requirements for absolute position accuracy are somewhat relaxed. Figure 7 shows the VLBA Calibrator Survey (VCS) sources up through the third VCS densification. These positions at the ~1 mas error level are the result of a series of VLBA sessions begun in 1994 (Petrov et al., [5]). The finished catalogue should be essentially complete at the 200 milliJansky level for S/X-band sources above -30 deg.

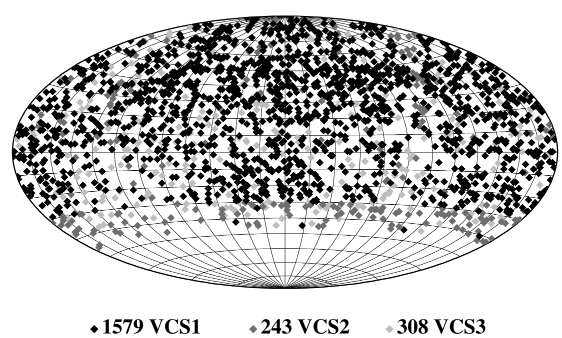

Figure 7. VCS sources.

7. Future Fundamental ICRF at Optical Wavelengths

The GAIA mission is scheduled for launch at the end of 2011 and has the potential for an optical ICRF with 500 000 extragalactic objects at the 50 microarcsec level. See Andrei (this volume). Transferring the orientation of the radio ICRF precisely and accurately to such an optical ICRF will not be trivial since most of the radio ICRF objects are at the faint end of the sensitivity planned for GAIA. In addition, nonregistration of the radio and optical emission points and source structure in the radio (and possibly in the optical at the planned GAIA precision) will add noise to the orientation transfer. It may be desirable to focus some VLBI observing over the coming years on a small set of quasars where the balance of radio and optical strength and position precision make them the best candidates for the tie. However, it is possible that the best tie will come from using the largest number of objects although the radio and/or optical positions are not the best.

8. Considerations for Future Observing and Technical Developments

Since there is not an infinite amount of VLBI observing at all relevant radio frequencies with global networks of large antennas, it is impossible to improve all aspects of ICRF use equally. In the abstract, a better radio ICRF would use higher frequencies than S/X-band for source compactness (and probably source position stability) and large, geographically well distributed antennas to cover the full sky more densely by observing weaker sources. In practice, it is likely that the past and future S/X-band data will continue to be the basis for the best radio ICRF, and the existing large antennas will be needed for catalogue maintenance and source monitoring. For EOP monitoring, which can never be done using the optical GAIA ICRF, a limited but well distributed set of strong, stable sources observable by the smaller, faster antennas envisioned by VLBI2010 is required. For spacecraft navigation sources along the ecliptic must be found and accurate positions at the telemetry frequencies must be determined. Observations for this purpose may become a separate effort from the general astrometric program. Phase reference observations will continue to be well served by the VCS catalogue. This set of sources may also provide the link to the GAIA optical frame if a larger number of tie objects with larger uncertainties is better than a severely limited set of sources optimized at both the radio and the optical wavelengths.

References

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