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The Second International Celestial Reference Frame (ICRF2)

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Abstract

The ICRF2 catalog was constructed by the IERS/IVS Working Group with oversight by the IAU Working Group. Derived using data from August 1979 through March 2009, it is a great improvement over the original ICRF with 3414 extragalactic radio source positions, a noise floor of 40 microarcsec, and axis stability of 10 microarcsec. Significant refinements were made in the selection of defining sources, modeling, and the integration of CRF, TRF, and EOP. The adoption of the ICRF2 was approved by the IAU in Resolution B3 at the XXVII IAU General Assembly and became effective 1 January 2010.

1. Introduction[1]

The ICRF (International Celestial Reference Frame) [1], adopted by the IAU in 1997 and effective on 1 January 1998, embodied a fundamental conceptual change from the previous optical, stellar, geocentric (equator, ecliptic), and epoch-dependent realization of celestial coordinates based on 1535 fundamental stars [2]. It used instead a smaller number of extragalactic radio objects measured by VLBI with much higher accuracy and established celestial coordinate axes independent of equator, ecliptic, and epoch. Although the ICRF was extended and improved using newer data as available in ICRF-Ext.1 and ICRF-Ext.2 [3], a decade after the ICRF analysis it was evident that much better astrometric and source structure data as well as refined geophysical models were in hand for a second realization. The analysis task was given to a joint IERS/IVS Working Group for the Second Realization of the ICRF and oversight on behalf of the astronomical community was provided by an IAU Working Group. Both groups were formed following discussions in Commission 19 and Division 1 at the XXVI IAU General Assembly in Prague in 2006. The charters and membership of the IERS/IVS Working Group and IAU Working Group are as follows.

IERS/IVS WG Charter: The purpose of the working group is to generate the second realization of the ICRF from VLBI observations of extragalactic radio sources, consistent with the current realization of the ITRF and EOP data products. The working group will apply state-of-the-art astronomical and geophysical models in the analysis of the entire relevant S/X astrometric and geodetic VLBI data set. The working group will carefully consider the selection of defining sources and the mitigation of source position variations to improve the stability of the ICRF. The goal is to present the second ICRF to relevant authoritative bodies, e.g. IERS and IVS, and submit the revised ICRF to the IAU Division I working group on the second realization of the ICRF for adoption at the 2009 IAU General Assembly.

[1] This paper represents the work of the IERS/IVS Working Group for the Second Realization of the ICRF and an IAU Working Group tasked with oversight of the IERS/IVS Working Group.

Table 1. Members of the IERS/IVS Working Group.

O. Titov, Australia	R. Heinkelmann, Austria	G. Wang, China
F. Arias, France	P. Charlot, France	A.-M. Gontier, France
S. Lambert, France	J. Souchay, France	G. Engelhardt, Germany
A. Nothnagel, Germany	V. Tesmer, Germany	G. Bianco, Italy
S. Kurdubov, Russia	Z. Malkin, Russia	E. Skurikhina, Russia
J. Sokolova, Russia	V. Zharov, Russia	S. Bolotin, Ukraine
D. Boboltz, USA	A. Fey, USA	R. Gaume, USA
C. Jacobs, USA	C. Ma, USA (Chair)	L. Petrov, USA
O. Sovers, USA		

IAU WG Charter: The purpose of the working group is to oversee the generation of the second realization of the ICRF from VLBI observations of extragalactic radio sources. The reference frame will apply state-of-the-art astronomical and geophysical models in the analysis of the entire relevant S/X astrometric and geodetic VLBI data set. The working group will ensure the selection of defining sources and the mitigation of source position variations and the consistency with the ITRF and the IERS EOP to improve the stability of the ICRF. The goal is to present the second ICRF at the 2009 IAU General Assembly.

Table 2. Members of the IAU Working Group.

Alexandre Andrei, Brazil	Felicitas Arias, France
Bob Campbell, Netherlands	Patrick Charlot, France
Alan Fey, USA	Ed Fomalont, USA
Ralph Gaume, USA	Chopo Ma, USA (Chair)
Jean Souchay, France	Yaroslav Yatskiv, Ukraine
Norbert Zacharias, USA	

The IERS/IVS Working Group accomplished its work through correspondence and in-person meetings, the last in Bordeaux in March 2009. Significant contributions were also made, especially in the later stages, by C. Barache, S. Böckmann, A. Collioud, J. Gipson, D. Gordon, S. Lytvyn, D. MacMillan, and R. Ojha. The finished work was described in IERS Technical Note 35 [4], which was made available electronically to the IVS and IERS. After approval by the IVS and IERS, the IAU Working Group agreed that the ICRF2 was satisfactory, drafted the supporting resolution B3, led the discussions in Division 1 and Commission 19, and presented the resolution to the XXVII IAU General Assembly on August 13, 2009, where it was accepted without dissent. The effective date of the ICRF2 was 1 January 2010.

2. Data

The ICRF2 included 30 years of simultaneous S/X-band (2.8/8.4 GHz) observing from a heterogeneous global network, ~6.5 million group delays from more than 4500 24-hr sessions. The data quality clearly improved in the early 1990s, but the older data were included for continuity with the first ICRF and to extend the source position time series. The VLBA contributed ~28% of the observations, an indication of its importance to global astrometry. In addition to its participation in the IVS observing program, the VLBA was also used for the VLBA Calibrator Survey (VCS) [5], which observed a large number of sources but each target source only in a single session. More details can be found in section 2 of IERS TN 35.

3. Software

Several software packages have been developed independently over the years by different groups for analysis of VLBI geodetic and astrometric data. Four such packages were used in studying the data included in the ICRF2 and in the preliminary and final solutions: CALC/SOLVE (NASA's Goddard Space Flight Center), SteelBreeze (Main Astronomical Observatory (MAO) of the National Academy of Sciences of Ukraine), OCCAM (Geoscience Australia), and QUASAR (Institute of Applied Astronomy of the Russian Academy of Sciences). Preliminary solutions were submitted by seven analysis centers using these analysis packages, and a combination catalog was also generated at MAO. Comparisons of individual catalogs and the combination catalog were used to investigate systematic effects, which were found to be at the 50 microarcsec level. Additional details can be found in section 8 of IERS TN 35.

4. Special Handling Sources

Source position time series generated by several analysis centers were examined to identify sources so variable as to require special handling. Some characteristics of such sources were irregular apparent motion and excessive noise in the time series. These apparent motions are related to changes in source structure or the position of the brightest component rather than physical translations. Unfortunately no single statistical test was found that could unambiguously identify such poorly behaved sources, in large part because the temporal density and continuity of observations varied so widely from source to source. Using several criteria, D. Gordon selected 39 special handling sources whose positions were treated as "arc" parameters in subsequent analysis, i.e. estimated independently for each session in which the source was sufficiently observed, in order to mitigate the effect of these source position variations on the overall catalog. Further details are given in section 4 of IERS TN 35.

5. Modeling and Catalog Solution

State-of-the-art geophysical and astronomical models were used in the solution that generated the (relative) source positions that are in the ICRF2 catalog. These included estimated tropospheric gradients with appropriate a priori starting values and constraints, the VMF1 tropospheric mapping function, thermal variation in antenna structures, and atmospheric pressure loading. The goal was to achieve the greatest consistency among the CRF, TRF, and EOP without propagating systematic errors of one into the others. Consequently the full treatment of station position anomalies was included in the analysis, and CRF, TRF, and EOP were estimated simultaneously. Comparisons of the integrated CRF, TRF, and EOP solutions with CRF-only solutions showed insignificant differences. Additional details are in section 6 of IERS TN 35.

The culminating solution of the ICRF2 analysis was performed with CALC/SOLVE at Goddard

Space Flight Center rather than through a combination of solutions from various analysis centers. There were a number of factors behind this choice including the desire to preserve the consistency of CRF, TRF, and EOP, the marginally better quality of earlier Goddard solutions compared to others, and the absence of a tested mechanism and experience with "rigorous" combination in the mode of the ITRF.

The catalog solution includes 4540 sessions from 1979 August 3 through 2009 March 16 with 6.5 million group delays, 3375 "global" source positions, and 39 "arc" sources. Based on decimation tests and comparisons, the final source position uncertainties were derived from the solution formal errors by a multiplicative factor of 1.5 and a root-sum-square addition of 40 microarcsec. More detail can be found in sections 7 and 9 of IERS TN 35.

6. Selection of Defining Sources

The selection of defining sources balanced two conflicting conditions: the need for uniform coverage of the entire sky and the uneven distribution of source position quality systematically by declination and by source. These limitations arise from the skewed geographic distribution of VLBI observing stations (overwhelmingly in the Northern Hemisphere) and the unequal allocation of observing ($>$ 95% of observations on a limited ($\sim$150) set of sources used for geodesy). Consequently the minimum criteria for defining sources are still rather weak, $\geq$ 10 sessions and $>$ 2-yr span of observations. The sources were ranked by position stability from the position time series, formal errors from the culminating solution, and the continuous source structure index, which was developed specifically for the ICRF2 analysis. A separate analysis determined the optimum number of defining sources accounting for the actual distribution of source position uncertainties. To populate the sky evenly, the ranking was performed independently in five declination bands. Otherwise the defining sources, those with the highest overall ranking, would be largely in the northern sky. There was structure information for 707 sources, much more than for the first ICRF through the long-term efforts of USNO and Bordeaux Observatory, although only a single epoch for 337 sources. In general the position and structure rankings agreed, but sources with index $>$ 3.0 were rejected. The source structure and ranking analysis are described in detail in sections 5 and 11 of IERS TN 35, respectively.

7. Alignment of ICRF2 Onto ICRS

To align the ICRF2 positions with the ICRS as realized by the initial 1997 ICRF, 138 sources were used. Of these 97 were defining sources in both ICRF and ICRF2 (mostly in the north) and 41 were ICRF2 defining sources with positions in ICRF-Ext.2 (mostly in the south). Three rotation angles and a declination bias were estimated, but only the rotations were applied since the declination bias was considered to be a systematic error in ICRF. The axis stability of ICRF2 is $\sim$10 microarcsec. The details of the alignment are given in section 12 of IERS TN 35.

8. ICRF2 Summary

Figure 1 shows the 295 ICRF2 defining sources. Figure 2 shows the 1448 sources in the catalog with multiple sessions. Figure 3 shows the 1966 sources observed in only one session, largely from the VCS program. Figure 4 shows the distribution of uncertainties for the non-VCS sources.

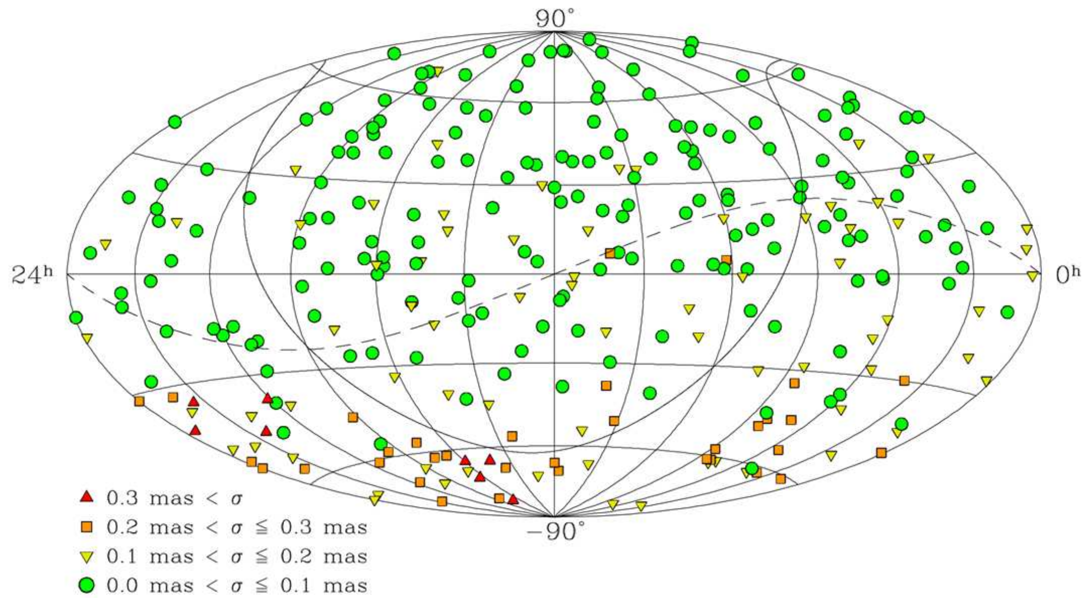

Figure 1. The 295 ICRF2 defining sources.

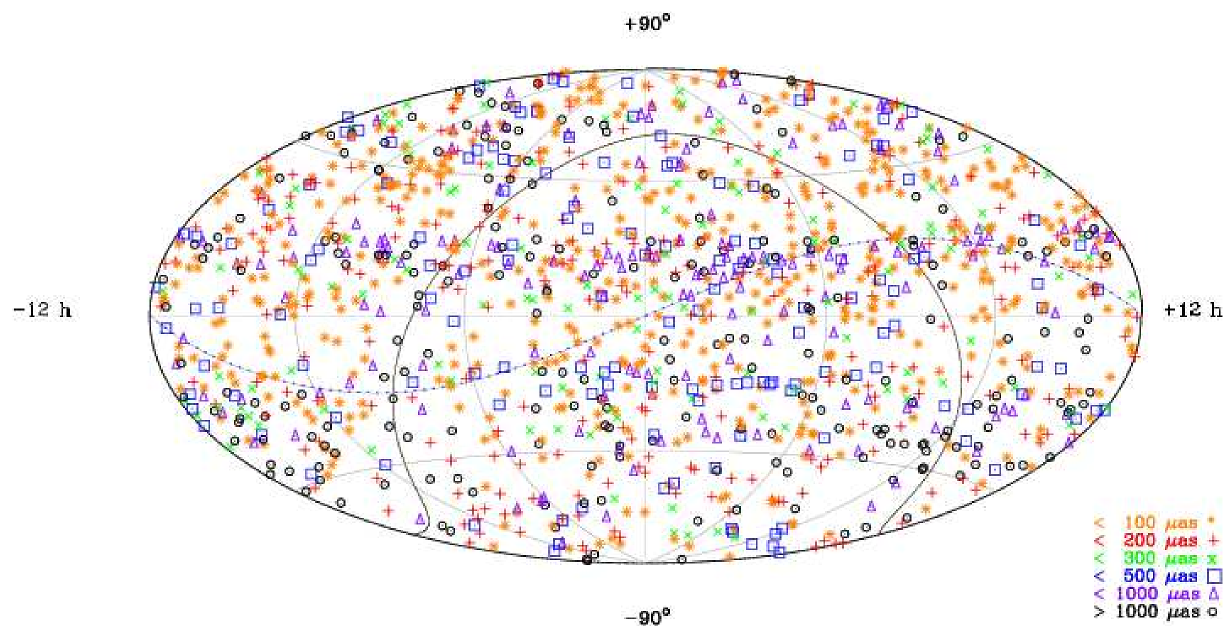

Figure 2. 1448 ICRF2 sources observed in multiple sessions. The formal errors are indicated by the key.

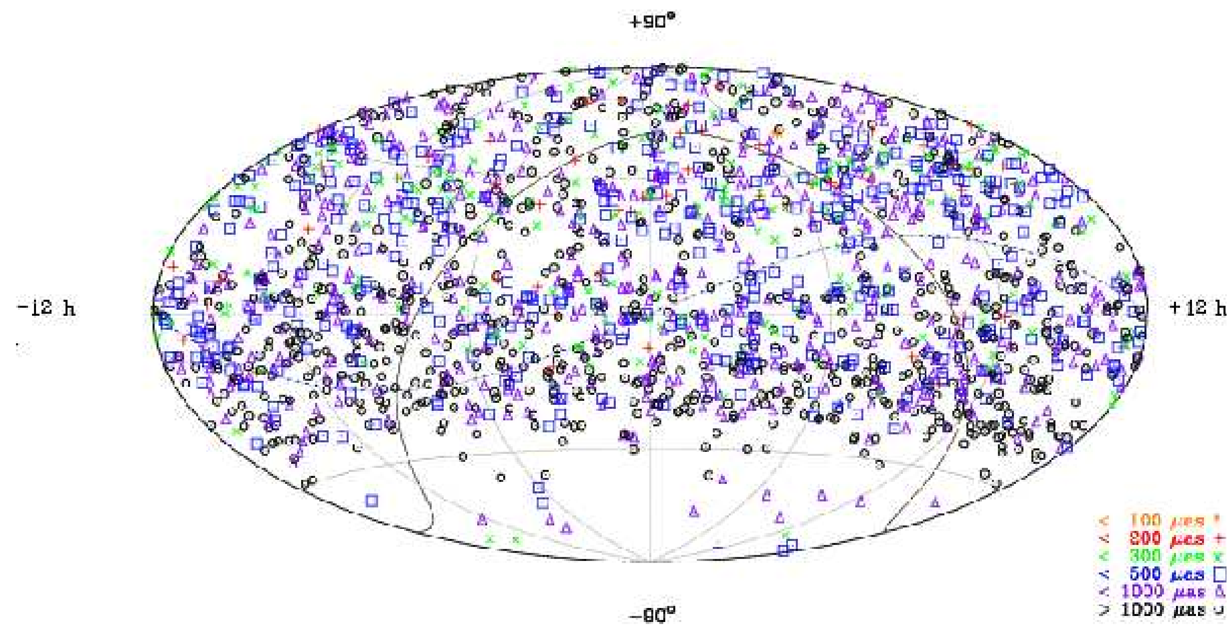

Figure 3. 1966 ICRF2 sources observed in only one session. The formal errors are indicated by the key. These are mostly VLBA Calibrator Survey (VCS) sources.

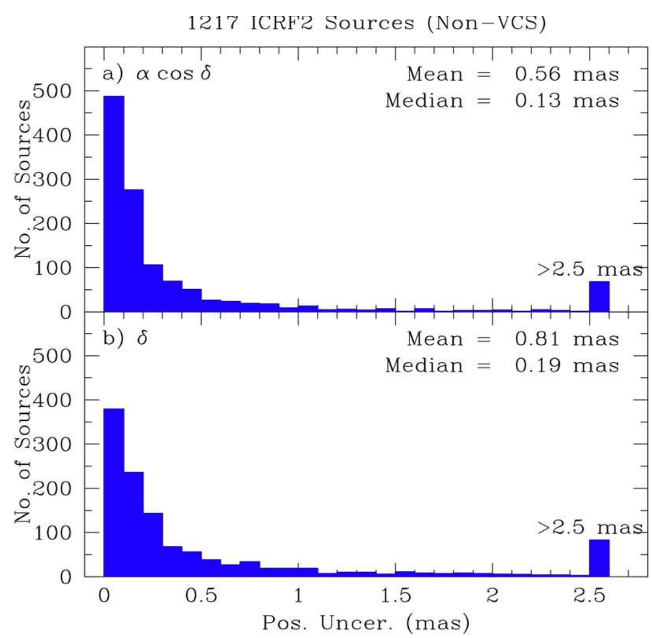

Figure 4. Histograms showing the inflated position uncertainties for the 1217 non-VCS ICRF2 sources.

9. Acknowledgements

The ICRF2 was completed under a very tight schedule through the careful, creative thinking, detailed analysis, and burning the midnight oil by the members of the working groups and the other contributors, whose assistance was invaluable. There was a can-do spirit and collaboration that pushed forward despite difficulties. In particular the editors A. Fey, D. Gordon, and C. Jacobs made the IERS Technical Note 35 a coherent document. The work of the IERS Central Bureau in preparing the final version of TN 35 and making it available was an essential and critical step to the success of the ICRF2 effort. As with all such endeavors the results are not perfect, but they are a significant step forward.

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