1 Introduction (DG, CM)

The International Celestial Reference Frame (hereafter referred to as ICRF1) was the realization of the International Celestial Reference System (ICRS) at radio frequencies [Ma et al., 1997, 1998]. It was defined by the Very Long Baseline Interferometry (VLBI) positions of 212 "defining" compact radio sources. These positions were independent of the equator, equinox, ecliptic, and epoch, but were made consistent with the previous stellar and dynamical realizations within their respective errors. The usage of VLBI for celestial reference frames was outlined by Gontier, Feissel & Ma [1997]. The ICRF1 used most geodetic/astrometric VLBI data taken between August 1979 and July 1995, and contained 608 sources. It was adopted by the IAU in 1997 and became official on 1 January 1998 [IAU General Assembly XXIII, 1997]. Two extensions, adding 109 additional sources [Fey et al., 2004] were later made using several years of newer VLBI data, including the first of a series of Very Long Baseline Array (VLBA) Calibrator Surveys (VCS) [Beasley et al., 2002].

ICRF1 had an estimated noise floor of 250 micro-arc-seconds (μas) and an estimated axes stability of $\approx$ 20 μas. This represented roughly an order of magnitude improvement over the previous stellar celestial reference frame, the FK5 [Fricke et al., 1988]. Even so, it had its limitations and deficiencies. The distribution of defining sources was very non-uniform, with most being in the northern hemisphere. Additionally, several of the original defining sources have been found to be unstable (showing significant systematic position variations).

Significant developments and improvements in geodetic/astrometric VLBI have been made since the generation of ICRF1. Geodetic/astrometric VLBI sensitivity and quality have improved significantly due to developments such as wider single channel bandwidths, wider spanned bandwidths, receiver improvements, and better observing strategies. Also, the use of newer and more sensitive antennas and arrays, such as the 10 station VLBA, has greatly improved the sensitivity and quality of the data as well. And additional new observing programs, such as the VLBA Research and Development VLBI (RDV) sessions, the southern hemisphere celestial reference frame (CRF) sessions, the weekly large network R1 and R4 Earth Orientation Parameter (EOP) sessions, and the VCS sessions have greatly improved the quality and quantity of the available VLBI data. Also, better geophysical modeling and faster computers have allowed for significant improvements in the data analysis. The additional 14 years of data now allow us to select a set of stable sources distributed more uniformly on the sky to more precisely define the axes. The additional data also allows us to filter out the most unstable sources for special handling, avoiding possible distortion of the frame that might occur otherwise. Additionally, there is now also a large amount of imaging data (e.g., the USNO Radio Reference Frame Image Database[1] and the Bordeaux VLBI Image Database[2]), mostly from analysis of the RDV sessions. Sources with extensive structure can thus be identified and eliminated from use in defining a reference frame. The ICRF1 used ~1.6 million group delay measurements. At the current time, there are ~6.5 million VLBI S/X-band group delay measurements available for use. The number of sources has also increased substantially. The ICRF1 contained 608 sources and was later expanded to 717. There are currently over 1200 sources whose positions can be obtained from the regular geodetic / astrometric sessions, and the number of far-southern sources has increased greatly. When we include the purely astrometric VCS sessions, nearly 2200 additional sources can be added, for a total of over 3400 sources. As previously mentioned, the sensitivity and quality

[1] http://rorf.usno.navy.mil/RRFID/
[2] http://www.obs.u-bordeaux1.fr/BVID/

of the data has also improved, and a conservative estimate is that the current noise floor has been reduced by a factor of 5 or more over ICRF1. Thus, there are many reasons for a new realization of the ICRF.

Greater accuracy and stability of the ICRF has benefits in at least two areas. It allows improvements in spacecraft navigation using differential VLBI relative to a nearby ICRF source. Also benefiting would be the VLBI monitoring of Earth orientation parameters, particularly of precession/nutation and UT1, which are the unique domain of VLBI. Enhanced stability and accuracy are needed for studies of the small, variable effects of deep structures of the Earth. Also, the upcoming Gaia mission will require much more precise positions of bright quasars in order to get the best optical-radio registration.

Since the adoption of ICRF1 by the IAU in 1997, the work of maintaining the ICRS was given to the IERS with the International VLBI Service for Geodesy and Astrometry (IVS) having operational responsibility for the VLBI realization. An IERS/IVS Working Group was established specifically for the second realization of the ICRF. This Working Group is truly an international team, with members from the USA, France, Germany, Italy, Russia, Ukraine, Australia, and China. This report describes the work of that team towards the generation of the second realization of the ICRF, hereafter referred to as ICRF2. The report is organized as follows: Sec. 2 describes the data used to construct the ICRF2, Sec. 3 describes the various software packages used in the analysis, Sec. 4 presents the selection and treatment of special handling sources, Sec. 5 discusses the characterization of source structure, Sec. 6 gives various model and data comparisons, Sec. 7 documents the configuration of the catalog solution, Sec. 8 describes and compares multiple preliminary catalog solutions, Sec. 9 evaluates the realistic uncertainties, Sec. 10 provides several tests of external validation for the ICRF2, Sec. 11 documents the selection of the final axes-defining sources, Sec. 12 describes how the ICRF2 was aligned onto the ICRS, Sec. 13 presents the ICRF2 catalog, Sec. 14 provides statistics of the ICRF2, and Sec. 15 gives conclusions and prospects for the future.

The Working Group studied the VLBI data using several independent software analysis packages, including Calc/Solve, OCCAM, SteelBreeze, and Quasar, all of which will be described briefly later in this report. Preliminary work with all the software packages included the generation and study of source position time series to identify stable and unstable sources, the generation and inter-comparison of preliminary catalogs, and the creation and study of a combination catalog. In the end, it was decided to use a single catalog rather than a combination for several reasons. The solutions going into the combination catalog all had some small differences in geophysical modeling, in editing criteria, and/or in data used. Also a combination catalog loses certain information, such as the full covariance matrix, and the links to the EOP and the Terrestrial Reference Frame (TRF) solutions. Although the final ICRF2 catalog is based on a single solution done at the NASA Goddard Space Flight Center (GSFC), the generation of ICRF2 has truly been an international group effort. The ICRF2 could not have been realized as accurately and with as much understanding of the limiting errors and noise levels without the participation of all the analysis centers and software packages involved.