2 The Data (DG)

The celestial reference frame results presented in this Technical Note come from nearly 30 years of accumulated geodetic/astrometric VLBI sessions organized and scheduled by many groups in many regional and worldwide campaigns. The major organizers have included NASA's Goddard Space Flight Center (GSFC) and Jet Propulsion Laboratory (JPL), the National Geodetic Survey (NGS), the U.S. Naval Observatory (USNO), the Naval Research Lab (NRL), the Geodetic Institute University of Bonn, Bundesamt für Kartographie und Geodäsie (BKG), and the Geographic Survey Institute (GSI) of Japan. The International VLBI Service (IVS) was formed in 1999, and took over coordination of the geodetic/astrometric campaigns, but the scheduling and analysis of individual sessions is still done by the individual member groups.

The earliest data used in this report is from 1979 August 3 and the latest is from 2009 March 16. All sessions used were dual frequency S/X-band (2.3/8.4 GHz) VLBI sessions taken either with the Mark III, Mark IV, VLBA, K4, K5, or combinations of these VLBI hardware/software systems. The participating antennas were all either dedicated geodetic stations or radio astronomical telescopes which spend most of their time doing astronomical research. The fixed antennas used here are located on all continents – with antennas in Antarctica, Australia, Brazil, Canada, Chile, China, Germany, Italy, Japan, Norway, Russia, Spain, South Africa, Sweden, Ukraine, and the USA. Most of the VLBI data used here was taken primarily for geodetic purposes, but is also well suited for astrometric analysis. A typical VLBI geodetic/astrometric experiment uses several antennas during a typical 24-hr data taking session.

The S/X-band systems record simultaneously several narrow channels (2–8 MHz) spanning broader bandwidths ($\sim$ 100–700 MHz). The combination of both bands allows for a first order correction for the dispersive effects of the Earth's ionosphere. In most of the VLBI sessions used, there were eight individual channels at X-band and six at S-band. Exceptions are the VLBA sessions, which use only four channels each at of S- and X-bands.

There were a total of 4540 sessions used for the final ICRF2 catalog, with approximately 6.5 million S/X-band ionosphere-corrected group delay measurements. The VLBI sessions used for ICRF2 include:

- Most fixed station sessions that are 18 hours or longer.
- Most of the Western U.S. and Alaska Crustal Dynamics Project (CDP) Mobile sessions, plus other sessions with mobile antennas – provided at least two large fixed antennas also participated. The three mobile systems were small transportable antennas of 3, 5, and 9 meter aperture. The two smaller systems occupied several dozen sites in the U.S., Canada, the Caribbean, and Europe during the 1980's and early 1990's.
- Most VLBA-correlated and AIPS-fringed S/X-band VLBA and VLBA +Mark IV sessions, a total of 168 such sessions. This includes 72 RDV sessions (January 1997 to December 2008) and 24 VCS sessions (August 1994 to January 2007).
- Most one-baseline southern hemisphere Celestial Reference Frame sessions, coordinated by USNO.
- 74 one-baseline NASA Deep Space Network sessions from 1988 August 20 – 1994 September 04 that were used in ICRF1 for consistency with ICRF1, even though some are of shorter duration than 18 hrs.

Sessions that were not used include various small and regional sessions (JADE, Canadian regional, most European mobiles), various "ties" sessions, several short one-baseline sessions, and other special sessions not

suitable for astrometric analysis. Also, no single band data (S-band only, X-band only, K-band, Ka-band, Q-band, etc.) was used.

It is important to note that the data used in this work is a very heterogeneous data set. The networks involved ranged from as little as 2 stations (1 baseline) to as large as 20 stations (190 baselines). Antenna sizes ranged from 3 meters up to 100 meters. The distribution of the fixed antennas was also very uneven. Out of some 53 antennas used over the past 30 years, only 10 have been in the southern hemisphere. Currently, there are some 34 fixed antennas that regularly or occasionally participate in geodetic/astrometric sessions, but only seven of those are in the southern hemisphere. This distribution directly affects the data available for the ICRF2. The amount of data begins to drop off quickly for sources south of around $-30°$ declination. In recent years, the USNO has made great efforts to observe new sources in the far south using the HARTRAO and HOBART antennas and this has added several dozen such sources. However, with the mechanical failure of HARTRAO in 2008, further progress in this area has been severely curtailed.

Worth mentioning is the contribution of the VLBA in improving the precision of the ICRF2. The VLBA[3] is an astronomical VLBI array of ten 25-meter antennas, all on U.S. territory. The VLBA antennas are some of the most sensitive and phase stable systems available. Details of their geodetic/astrometric use are given by Petrov et al. [2009]. Use of the Pietown VLBA antenna began in 1988 followed by the Los Alamos (LA-VLBA) antenna in 1991. Use of all 10 VLBA antennas, and correlation on the VLBA correlator began in 1994. In a 2004 study, Gordon [2004] found that the regular VLBA (non-VCS) observations accounted for some 30% of the available geodetic/astrometric VLBI data and its usage improved the TRF at non-VLBA sites by typically 10-40% and reduced the average source position formal errors by $\sim$62% in R.A. and $\sim$54% in declination for sources north of $-30°$ declination. This means the formal errors are roughly cut in half by a combination of more data and higher data quality due to VLBA usage. Currently, VLBA data comprises $\sim$28% of all the data used in this report.

The VCS were a series of six multi-session S/X-band astrometry campaigns designed to map and find precise positions of as many new compact radio sources as possible for use as phase referencing calibrators by the radio astronomical community. The first of these, VCS-1, was observed 1994–1997, and its 10 sessions are described and analyzed by Beasley et al. [2002]. An eleventh VCS-1 session, initially considered a failure, was later found and analyzed successfully. Five follow up VCS campaigns were made between 2002 and 2007 by Fomalont et al. [2003], Petrov et al. [2005], Petrov et al. [2006], Kovalev et al. [2007], and Petrov et al. [2008]. These added another 13 VCS sessions for a total of 24. The observing mode was much different from regular geodetic/astrometric sessions. The VCS sessions concentrated on making short observations of many new sources. They were not optimized for full sky coverage or atmospheric calibration, although the later ones were better calibrated than the first. The VCS sessions add nearly 2200 additional sources to the catalog with most of those observed in only one VCS session. In spite of that, many of the VCS source positions are as precise as many non-VCS sources.

[3]The VLBA is operated by the National Radio Astronomy Observatory, which is a facility of the National Science Foundation, and operated under cooperative agreement by Associated Universities, Inc.