How Good is the Deep Southern Sky

S. Basu[1,2,3], A. de Witt[2], S. Shabala[3], J. McCallum[3], J. Quick[2], A. Bertarini[4,5]

Abstract The Celestial Reference Frame Deep South (CRDS) observing sessions are part of a program to strengthen the International Celestial Reference Frame (ICRF) in the South and are coordinated by the International VLBI Service for Geodesy and Astrometry (IVS). The aim of the CRDS sessions is to provide astrometric results from Very Long Baseline Interferometric (VLBI) observations for improving the current ICRF, but also to extend and densify the ICRF by observing new sources. The effect of source structure variability on VLBI astrometric positions can be significant, and it is important to map these sources on a regular basis. In this paper we present our most recent results from our efforts to provide VLBI maps from the CRDS astrometric observations. In the future, continual analysis of CRDS observations will allow us to monitor the sources for structural changes so that their astrometric quality can be evaluated regularly.

Keywords VLBI, IVS, ICRF: quasars, CRDS, imaging

1. University of South Africa, Pretoria, South Africa
2. Hartebeesthoek Radio Astronomy Observatory, Krugersdorp, South Africa
3. School of Physical Sciences, University of Tasmania, Australia
4. Institute for Geodesy and Geoinformatics, University of Bonn, Germany
5. Max Planck Institute for Radioastronomie, Germany

1 Introduction

High-precision Very Long Baseline Interferometry (VLBI) measurements of positions of extra-galactic radio sources are used to define and maintain celestial reference frames (CRF) with sub-milliarcsecond (sub-mas) precision. Early efforts at defining a celestial reference frame using VLBI observations of extra-galactic radio sources led to the realization of the International Celestial Reference Frame (ICRF) [10]. The second extension of the ICRF (ICRF-Ext.2) [4] contained 212 'defining' sources (sources of high astrometric quality) along with 294 'candidate' sources (sources with insufficient observations) and 102 'other' sources (sources with excessive position variations).

The current realization of the celestial reference frame (ICRF-2) [6] is based on dual frequency 2.3-GHz (S-band) and 8.4-GHz (X-band) VLBI observations of 3,414 extra-galactic radio reference sources, including 295 'defining' sources which determine the orientation of the frame axes. In 2012, the need for a more uniform spatial coverage of sources and uniform accuracy in source coordinates led to the formation of an International Astronomical Union (IAU) working group, with the goal of the realization of the next generation celestial reference frame (ICRF-3) [9], to be completed by 2018.

The primary sources used to define and maintain the ICRF are radio-loud quasars. To maintain the highest accuracy in astrometry and geodesy, it is desired to use sources where the radio emission is compact or core-dominated with a point-like structure. However, many of the extra-galactic sources that make up the ICRF exhibit spatially extended intrinsic structures on mas scales. The extended emission structures in these

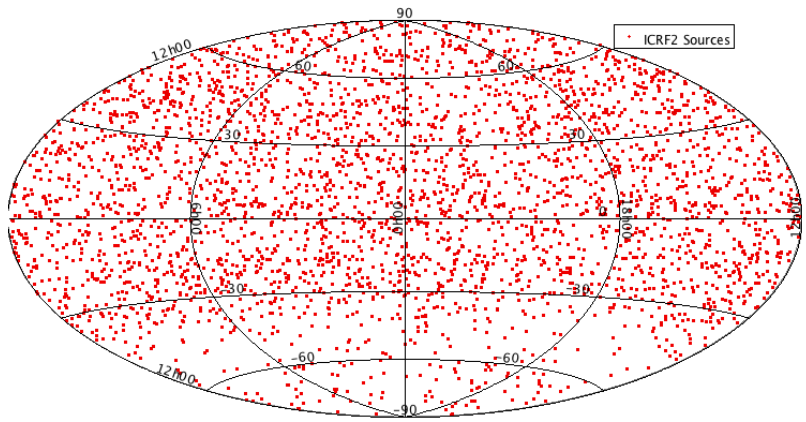


Fig. 1: Distribution of sources in the ICRF-2 catalog on an Aitoff equal plane projection of the celestial sphere. The deficit of sources south of $-30°$ can clearly be seen.

sources may also change with observing frequency and can evolve significantly over timescales of months to years. It is well-known that the effect of source structure on astrometric VLBI positions can be significant and that structure and flux density variability are directly related to the precision of geodetic solutions [14]. It is therefore important to map the structures of these sources on a regular basis.

Another method to assess astrometric source quality for application to the ICRF is the source structure index (SI), which is the median value of the structure delay corrections computed from VLBI source maps [3]. The ICRF sources are categorized according to their SI value, where the best astrometric sources receive a structure index of 1 and sources with an SI of 3 and 4 are considered not suitable for geodetic or high-precision astrometric VLBI observations. A list of SI values for all ICRF-2 sources can be found in Fey et al. [5]. Flux density information can also be used as an estimate of the compactness of a source, e.g. [11], where source compactness (SC) is defined as the ratio of core flux density to total flux density.

Catalogs of compact radio sources, including the ICRF-2, are weak in the south (see Figure 1), especially at declinations south of $-45°$, the limit of the reach of northern baselines. There have been many efforts in recent years to increase the number of known reference sources and to densify the ICRF in the south e.g. [13, 8]. There have, however, only been a few imaging observations of reference sources in the south, e.g. [7, 11, 12], and dedicated campaigns to map and monitor source structure prove to be difficult, with the availability of antennas being one of the most limiting factors in the south. As a result, we investigated the possibility of imaging source structure from existing astrometric and geodetic observations in the south. We identified the Celestial Reference Frame Deep South (CRDS[1]) astrometric VLBI observations to be suitable for mapping purposes, and first imaging results were obtained in 2014 [1].

In this paper we present multi-epoch imaging results as well as the calculated structure indices and source compactness values for two of the sources in our sample. Results were obtained from CRDS astrometric observations at both 2.3 and 8.4 GHz.

2 Session Selection

We selected the CRDS astrometric sessions for imaging purposes based on the following criteria:

- The majority of sources observed are south of $-40°$ declination.
- Sessions from 2013 onwards have at least four stations per scan, as opposed to more typical astrometric sessions where only two-station scans are required.

[1] Information about the CRDS is available on the Web at *http://ivscc.gsfc.nasa.gov/program/master*

Fig. 2: Map of station positions from the CRDS experiments.

- All sessions have at least two scans per source, with a maximum of seven scans per source.
- The scan duration is not based on minimum SNR per baseline, but set at a minimum of five minutes per scan.
- On average, most sources are observed in at least two to three sessions per year.

The CRDS observing program started in 2011 with six sessions scheduled per year. Since 2013, from CRDS63 onwards, observations have been scheduled using a regular network of six southern stations. In June 2013 the bandwidth was also increased from 4 to 8 MHz (CRDS66 onwards). The telescopes that take part in CRDS sessions are the Hartebeesthoek Radio Astronomy Observatory (HartRAO) 26-m telescope in South Africa, the Hobart 12- and 26-m and the Katherine and Yarragadee 12-m telescopes in Australia, and the Warkworth 12-m telescope in New Zealand. A map of CRDS station positions is shown in Figure 2. Representative plots of the *u*-*v* coverage for two sources at similar declinations but from different CRDS sessions are shown in Figure 3.

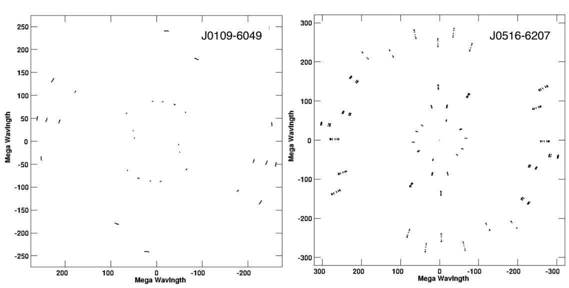


Fig. 3: The *u*-*v* plane coverage for two sources at similar declinations but from different CRDS sessions. The *u*-*v* coverage plot on the left is from the CRDS63 session in which only four antennas participated, resulting in very poor sampling in the *u*-*v* plane. The *u*-*v* coverage plot on the right is from the CRDS68 session in which all six antennas participated. The gap in the *u*-*v* coverage clearly shows the missing intermediate baseline lengths that results from the absence of telescopes between Australia and South Africa.

For the purpose of this study we reduced and analyzed data from the CRDS66 session as well as the CRDS68 session for both 2.3 and 8.4 GHz. Observations for CRDS66 were made on 30–31 July 2013, and observations for CRDS68 were made on 27–28 November 2013. Data was recorded at right circular polarization (RCP) with six IFs at S-band and ten IFs at X-band with a bandwidth of 8 MHz per IF. Data was correlated at the Washington Correlator (WACO) in Washington, DC.

3 Data Reduction and Results

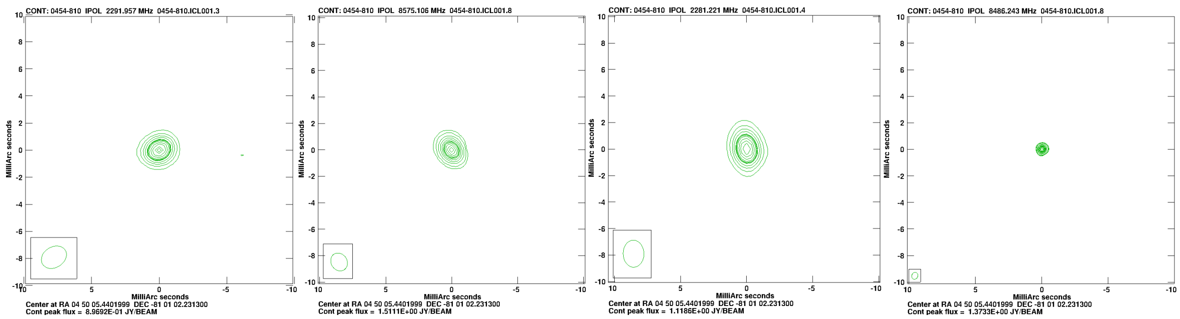
The data reduction was done using the NRAO's Astronomical Image Processing System (AIPS) [2] and included data inspection, editing, and fringe-fitting. Our earlier work on VLBI imaging of CRDS63 proved to be successful, and hence we followed a similar approach in reducing the data for CRDS66 and CRDS68 [1].

In Figure 4 we show representative contour plots at both 2.3 and 8.4 GHz for two of our sources, J0450-8101 and J0538-4405. Plots from two epochs, July 2013 (CRDS66) and November 2013 (CRDS68) are shown. The contour plots for both sources, at both frequencies and epochs, show a compact central object with no extended structure or additional components. Both of these sources are among the ICRF-2 defining sources.

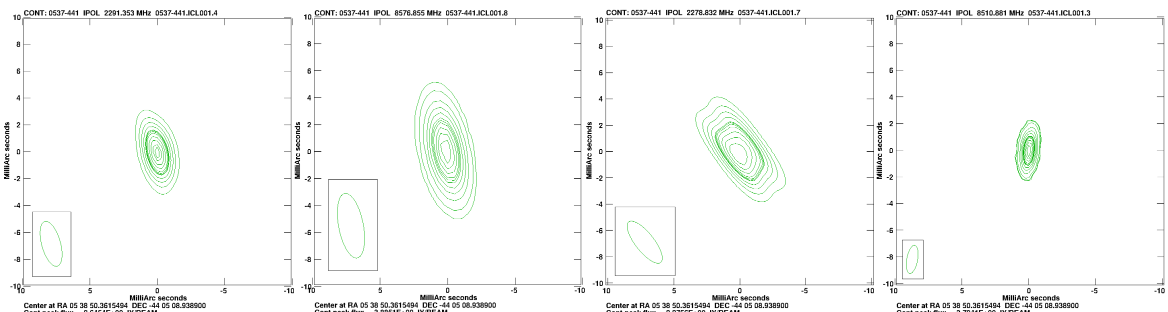
Observations from the LCS experiments at 8.4 GHz also show J0450-8101 to be a very compact source with no extended structures. For J0538-4405, imaging results from the Bordeaux VLBI Image Database (BVID)[2] using the Very Long Baseline Array (VLBA) show a central compact object with no extended structure at both frequencies.

In Table 1 we also list the SI and SC values for each of the sources, at both frequencies and epochs.

[2] The Bordeaux VLBI Image Database (BVID) is available from *http://www.obs.u-bordeaux1.fr/BVID/*



(a) J0450-8101 (2.3 GHz) July 2013
(b) J0450-8101 (8.4 GHz) July 2013
(c) J0450-8101 (2.3 GHz) November 2013
(d) J0450-8101 (8.4 GHz) November 2013



(e) J0538-4405 (2.3 GHz) July 2013
(f) J0538-4405 (8.4 GHz) July 2013
(g) J0538-4405 (2.3 GHz) November 2013
(h) J0538-4405 (8.4 GHz) November 2013

Fig. 4: Contour plots for J0450-8101 (top) and J0538-4405 (bottom) at 2.3 and 8.4 GHz, both for two epochs, July 2013 (CRDS66) and November 2013 (CRDS68). North is up, and East is to the left. The FWHM beamsize is graphically indicated in the bottom left corner. The contour levels are a percentage of the peak brightness and are at 5, 10, 20, 30, 40, 50, 60, 70, 80, and 90%, with the 50% level represented by a thick contour.

For the SC we have taken the core flux density as the CLEANed flux density within one synthesized beam (labelled as Jy/beam for each source in Figure 4) and the total flux density as the sum of all CLEANed components. It should be noted that the source compactness can be greater than 1 for inclusion of negative CLEAN components.

Table 1: SC and SI values for J0450-8101 and J0538-4405 at 2.3 and 8.5 GHz for both epochs, July and November 2013.

Source Name	2.3 GHz (July)	2.3 GHz (Nov.)
J0450-8101	**SI**=1.48, **SC**=0.95	**SI**=1.68, **SC**=0.85
J0538-4405	**SI**=1.78, **SC**=0.85	**SI**=1.90, **SC**=0.48
Source Name	8.5 GHz (July)	8.5 GHz (Nov.)
J0450-8101	**SI**=1.42, **SC**=1.04	**SI**=1.07, **SC**=1.07
J0538-4405	**SI**=2.03, **SC**=0.91	**SI**=1.96, **SC**=0.90

4 Conclusions

In this paper we provided an overview of the CRDS astrometric observing sessions and we presented some results from our efforts to image sources structure. In order to verify the reliability of our results it is important that we continue to compare the images of those sources also observed in other VLBI programs. In order to further verify the astrometric quality of these sources we will also take into consideration the visibility plots as well as the size of the source. A reasonable estimate of the source size can be obtained by fitting a Gaussian model to the visibility data. Considering all aspects of the CRDS experiment, we believe this project will contribute significantly to future work regarding ICRF source densification in the Southern Hemisphere.

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