Multi-epoch Study of Source Morphology in the Southern Hemisphere

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Abstract The International Celestial Reference Frame (ICRF) has been constructed using catalogs of radio quasars observed using the Very Long Baseline Interferometry (VLBI) technique. The VLBI technique defines the current ICRF and helps to improve its precision. The angular resolution available from VLBI measurements is on a scale of milliarcseconds to submilliarcseconds and provides the highest accuracy available at present. On this scale most extragalactic radio sources exhibit extended structures. In order to define the ICRF with the highest accuracy, observational efforts are required to find more compact sources and to monitor them. We report here our efforts to provide multi-epoch VLBI maps for southern sources observed through existing astrometric sessions. These images will be used to identify compact southern sources and to correct observations for source structure, thereby allowing improved relative astrometric accuracy.

Keywords Celestial Reference Frame, VLBI, imaging, astrometry, quasar

1 Introduction

Since the late 1970s, Very Long Baseline Interferometry (VLBI) observations have been used to determine the positions of radio sources with milliarcsecond precision. In recent years, the accuracy of the VLBI technique has improved substantially, and high precision VLBI measurements of positions of extra-galactic radio sources are now used to define and maintain celestial radio reference frames with sub-milliarcsecond precision. The current realization of the International Celestial Reference Frame (ICRF2, [9]), 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, and it forms the basis for positional astronomy. Catalogs of positions of radio reference sources with the highest precision are needed for many applications, for example, the imaging of faint radio sources in phase-referencing mode, accurate differential astrometry, spacecraft tracking, space navigation, and space geodesy.

The primary sources used as reference sources in VLBI are radio-loud quasars. In radio-loud quasars, the radio emission originates with a relativistic jet launched from the vicinity of the black hole. The ones useful as reference sources are those where the scale of this jet is small compared to the resolution such that the radio emission is compact or core-dominated and appears almost point-like. Unfortunately, many of the radio-loud quasars that make up the ICRF exhibit spatially extended intrinsic structures, with VLBI imaging showing jets in addition to compact cores. The extended emission structures in these sources may also evolve significantly over time on scales of months to years, and in addition they also exhibit flux density variations on timescales of years to weeks.

Charlot *et al.* [2] showed that the effect of source structure on VLBI astrometric positions can be significant, where any departure from the point source approximation, commonly made in astrometric analysis, introduces errors in the observable quantities of group delay and delay rate. It is therefore important to map the structures of these sources on a regular basis. Reg-

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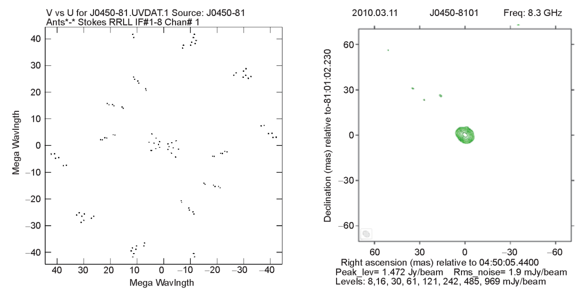
ular imaging of Northern hemisphere ICRF sources is made through the ongoing astrometric and geodetic Research and Development VLBI (RDV) experiments using the Very Long Baseline Array (VLBA) (e.g. [3, 6]). The results of the imaging and analysis of these studies prove to show the importance of continual observing and analysis in order to monitor the sources for variability or structural changes so that their astrometric quality can be continuously evaluated.

Catalogs of compact radio sources, including the ICRF2, are weak in the south, 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 Southern hemisphere reference sources, in particular the astrometric observations from the Long Baseline Array (LBA) Calibrator Survey (LCS), which has already produced a significant improvement at X-band [12]. Dedicated astrometric observations at S/X band to densify the ICRF in the south are currently underway, as proposed in Lovell *et al.* [8]. There have also been a few dedicated imaging observations of southern sources (e.g., [7, 10, 11]), and the first images from the LCS astrometric experiments have been produced [5].

However, dedicated imaging observations to map the structures of sources on a regular basis have proven to be very resource intensive, with the availability of antennas being one of the most limiting factors in the south. Based on these considerations, we have investigated the possibility of imaging source structure from existing geodetic or astrometric observations in the south. Imaging of source structure from the LCS experiments has proven to be successful, and we will continue to image more of the LCS experiments. The details of the LCS experiments are discussed in more detail in Section 2. We have also identified the Celestial Reference Frame Deep South (CRDS) astrometric VLBI observations (see Section 3) to be potentially suitable for mapping purposes, and in this paper we present our first imaging results. In addition to yielding source structure information for astrometric purposes, such images will also allow us to study the properties of such sources that will be valuable in the investigation of a wide range of astrophysical phenomena.

2 LBA Calibrator Survey (LCS)

The LCS[1] is an ongoing VLBI project to observe at 8.4 GHz a list of flat-spectrum radio sources below $-30°$ declination using the LBA. This array is stretched out along Australia's east coast in a north-south direction, which limits the uv-coverage (Figure 1 (a)).



(a) (b)

Fig. 1 uv-coverage (a) and source structure (b) of the source J0450-8101. Image credit: de Witt *et al.* [5].

The LCS seeks to systematically increase the density of compact extra-galactic radio sources in the Southern hemisphere and to determine their positions with milliarcsecond accuracy. To date, the positions of 924 new objects have been determined from analysis of 14 LBA experiments, and a total of 170 sources from two of these experiments have been successfully imaged to determine the structure at 8.4 GHz. Figure 1 (b) shows an example of source structure which was imaged from LCS experiment v271e [5].

The main aim of the LCS project is to determine the suitability of potential new sources for phase referencing observations and as target for astrometry and geodesy observations. Most sources are observed at a single epoch only, and so variability and structural changes cannot be monitored. However, the LCS provides a very valuable pool of potential new sources that can be added to existing observing projects, such as the CRDS sessions, that will provide observations of such sources on a continual basis.

In our efforts to complete the imaging and determine the source morphology of all LCS sources, we selected as our first target the most recent experiment

[1] Information on the LCS is available on the Web at *http://astrogeo.org/lcs/*

from the LCS, V271m. Observations for LCS experiment V271m were made on 15–16 June 2013 at a central frequency of 8.344 GHz and a total bandwidth of 128 MHz, and they were recorded at RCP. The antennas that participated were ASKAP, ATCA, Ceduna, Tidbinbilla 34-m, Parkes, Mopra, Hobart 26-m, Hobart 12-m, HartRAO 26-m, and Warkworth. A total of 101 sources were observed in this experiment with 2–4 scans of 2–6 minutes duration per source. The data were correlated at the Curtin University of Technology using the DiFX correlator [4]. Data reduction for v271m is still in progress.

3 Celestial Reference Frame Deep South (CRDS)

The CRDS[2] astrometric observing sessions are part of a program to strengthen the 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 dual frequency (S/X band) observations for improving the current ICRF, but also to extend and densify the ICRF by observing new sources. The CRDS observing program started in 2011 with six sessions scheduled per year. Since 2013, observations have been scheduled using a regular network of six southern stations: the HartRAO 26-m telescope in South Africa; the Hobart 26-m and the Hobart, Katherine, and Yarragadee 12-m telescopes in Australia; and the Warkworth 12-m telescope in New Zealand.

A total of 97 sources have been observed through CRDS sessions with the majority of sources being south of -30° declination. On average, most sources are observed in at least two to three sessions per year with around two to seven scans of nine minutes duration per source. As opposed to more typical astrometric sessions where only two-station scans are required, the majority of scans in the CRDS sessions observed since 2013 include at least four to six stations per scan, making these observations more suitable for mapping purposes.

In order to test the suitability of CRDS sessions for imaging of source structure, we have chosen the most recent CRDS session at the time, which is CRDS63. Observations for CRDS63 were made on 14–15 June 2013 and 38 sources were observed. All six stations as mentioned above were scheduled for observing, but, unfortunately, in the end both the Hobart 12-m and Warkworth 12-m antennas did not participate. Data was recorded at RCP with six IFs at 2.3 GHz and eight IFs at 8.4 GHz with a bandwidth of 4 MHz per IF[3]. The data was correlated at the Washington Correlator (WACO) in Washington, DC.

4 Data Reduction and Preliminary Results

The data reduction for the CRDS 8.4-GHz data was done using AIPS. The correlated data was fringe-fitted with `fourfit` using the '-X' option which is used to produce data suitable for import into AIPS. The correlated data was then imported into AIPS using `MK4IN` [1].

Amplitude gains were derived from nominal system temperatures. Thereafter, data inspection, initial editing, and fringe fitting were done in the standard manner. We did an initial round of fringe-fitting to find approximate residual rates and delays. The main editing was carried out using this approximate calibration, and then, using the edited data, we proceeded to a second round of fringe-fitting to refine the calibration, with each source being fringe-fitted individually. The visibility data for source J1427-4206 were Fourier inverted and deconvolved using the CLEAN algorithm, and the amplitude gains were further refined by self-calibration using CLEAN models. For the final CLEAN image, we used complex weighting using the square root of the statistical visibility weights, which increases the robustness of the image.

So far we have only produced preliminary imaging results for source J1427-4206 at 8.4 GHz (see Figure 2). We have chosen source J1427-4206 for our initial attempt, as this source has the highest flux density from the sample of sources in CRDS63 and was observed during four scans that included all four antennas. J1427-4206 has also previously been observed with both the VLBA and LBA (see Figure 2) which

[2] Information about the CRDS sessions is available on the IVS Web site at *http://ivscc.gsfc.nasa.gov*

[3] Bandwidth was increased to 8 MHz from CRDS66 session in June 2013.

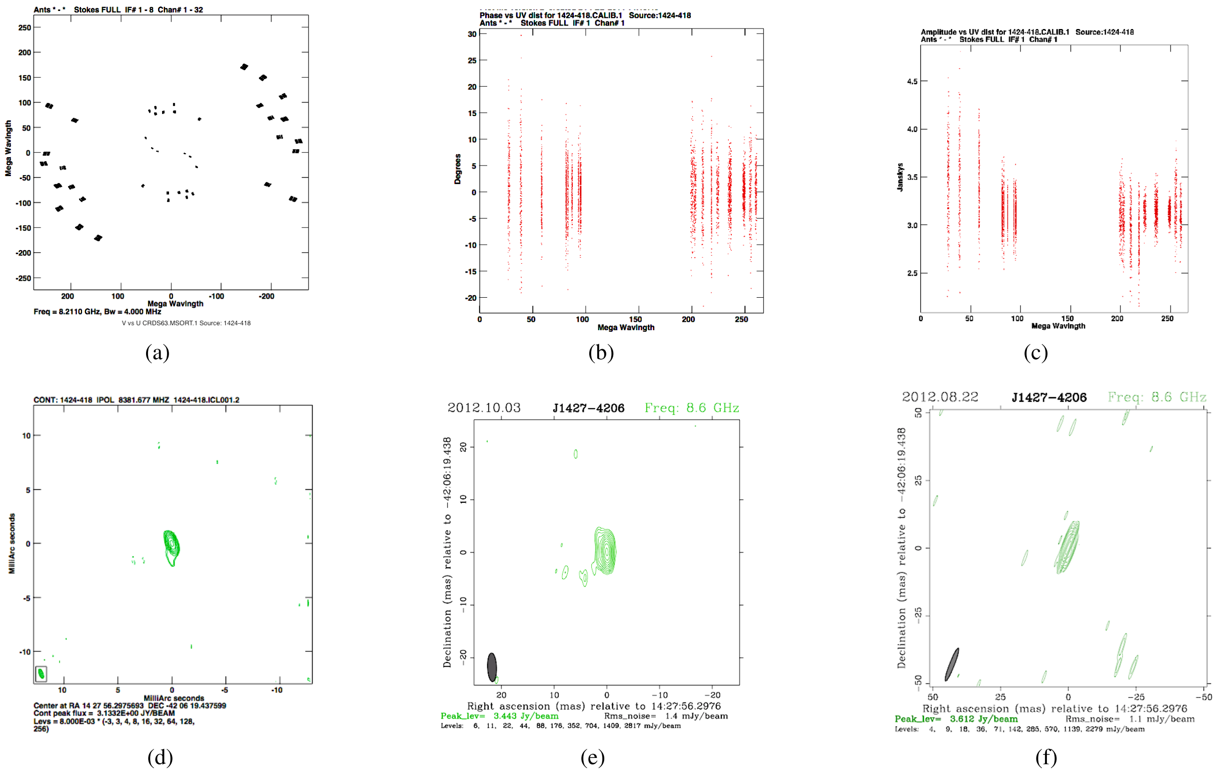


Fig. 2 (a) uv-coverage plot for source J1427-4206 from the CRDS63 experiment. (b) Phase vs. uv-distribution plot of the source J1427-4206. (c) Amplitude vs. uv-distribution plot of the same source. (d) Map of source J1427-4206 from the CRDS63 experiment. (e) and (f) Multi-epoch source structure images of J1427-4206 available from the RFC VLBI Global Solution Catalogue (available on the Web at http://astrogeo.org/vlbi/solutions/rfc_2014b/). North is UP and East is to the LEFT in all of the above maps.

provides us with an opportunity to compare our results with available images from existing experiments.

We show a representative contour plot of the CRDS63 image of J1427-4206 at 8.4 GHz in Figure 2. The total CLEAN flux density is 3.33 Jy, and the image background rms is 7.9 mJy beam^{-1}.

5 Summary and Outlook

We present preliminary imaging results for one source from the CRDS63 astrometric observing session. Our aim is to complete imaging of all CRDS sessions in order to evaluate the astrometric quality of these ICRF sources for future astrometric and geodetic use.

At present we are working on the calibration and imaging of the remaining sources in the CRDS63 session at 8.4 GHz. We also plan to analyze the 2.3-GHz data from the CRDS63 session. In the future we plan to set up a pipeline for automated imaging of CRDS sessions. These dual-frequency observations will give us an opportunity to test the frequency dependence of the source structure and to monitor the sources for variability or structural changes on a continuous basis.

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