Imaging & Study of VLBI Reference Frame Sources in the Southern Hemisphere

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Abstract. The International Celestial Reference Frame (ICRF) was adopted by the International Astronomical Union (IAU) in 1997. The current standard, the ICRF-2, is based on Very Long Baseline Interferometric (VLBI) radio observations of positions of 3414 extragalactic radio reference sources. The angular resolution achieved by the VLBI technique is on a scale of milliarcsecond to sub-milliarcseconds and defines the ICRF with the highest accuracy available at present. An ideal reference source used for celestial reference frame work should be unresolved or point-like on these scales. However, extragalactic radio sources, such as those that define and maintain the ICRF, can exhibit spatially extended structures on sub-milliarsecond scales that may vary both in time and frequency. This variability can introduce a significant error in the VLBI measurements thereby degrading the accuracy of the estimated source position. Reference source density in the Southern celestial hemisphere is also poor compared to the Northern hemisphere, mainly due to the limited number of radio telescopes in the south. In order to define the ICRF with the highest accuracy, observational efforts are required to find more compact sources and to monitor their structural evolution. In this paper we show that the astrometric VLBI sessions can be used to obtain source structure information and we present preliminary imaging results for the source J1427-4206 at 2.3 and 8.4 GHz frequencies which shows that the source is compact and suitable as a reference source.

Keywords: Celestial Reference Frame, Quasar, VLBI, IVS, Astrometry, Imaging

1. Introduction

Very Long Baseline Interferometry, or VLBI, radio observations are almost unique in providing us with milliarcsecond or even sub-milliarcsecond resolution, and also allow us to do astrometry with sub-milliarcsecond accuracy (e.g. Walker, 1999; Thompson et al. 2007). VLBI achieves its resolution by using radio telescopes hundreds or thousands of kiliometers apart simultaneously to form an interferometer. The received signals are amplified at the participating antennas and are sent to a correlator by storing them on disk packs or by using network links. The received signals from each pair of antennas are then cross-correlated and Fourier transformed in order to determine the sky brightness distribution at the observed radio frequency. Most VLBI applications rely on having reference sources, for example, the imaging of faint radio sources in phase-referencing mode, accurate differential astrometry, spacecraft tracking, space navigation and space geodesy.

Since the late 1970s, 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 extragalactic radio sources are now used to define and maintain celestial radio reference frames with sub-milliarcsecond precision. Various radio source catalogs have been constructed from a number of high accuracy, dual frequency 8.4 GHz and 2.3 GHz observations which have been collected from different networks for geodetic and astrometric purposes. Ma et al. (1990) produced the first catalog of 182 sources with a positional accuracy of 1 milliacrsecond. All of these sources are located north of -30^0 declination. The source density was increased significantly in the Northern hemisphere with more observing campaigns and a few sources were also added in the Southern hemisphere (e.g. Reylonds et al. 1994; Russell et al. 1994; Johnston et al. 1995).

The realisation of the radio celestial reference frame was adopted by the 23rd International Astronomical Union (IAU) General Assembly in 1997 to replace the traditional optical fundamental celestial reference frame, the FK5 reference frame. High precision VLBI measurements of positions of extragalactic radio sources now define and maintain the International Celestial Reference Frame (ICRF), which forms the underlying basis for positional astronomy. The current realisation of the ICRF (ICRF-2, Ma et al. 2009) is based on dual frequency (8.4 GHz, 2.3 GHz) VLBI observations of 3414 radio reference sources, including 295 defining sources which determine the orientation of the frame's axes. In 2012, a working group under the IAU was formed with the goal of the realisation of the ICRF-3 by 2018 with specific emphasis on improving the accuracy and coverage in the southern hemisphere.

Extragalactic radio sources that are relatively bright at the frequency of observation, compact or core-dominated on VLBI scales and with no or little detectable motion are well suited as reference sources. The primary sources used as reference sources in VLBI are radio-loud quasars. Quasars being at great distances do not exhibit any measurable proper motion or parallax, making them ideal reference sources. 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 (1990) 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 accurate position of the source. Temporal variations of the intrinsic structure of these objects can result in apparent motion when observed at several epochs. Results from Fey, Clegg & Fomalont (1996) and Fey & Charlot (1997), show that structural variations of sources can be extreme, ranging from relatively compact core objects, to compact double sources, to complex core-jet objects. It is therefore important to map the structures of these sources on a regular basis.

Catalogues of compact radio sources, including the ICRF-2 are weak in the south, especially at declinations south of $-45°$, the limit of the reach of the Very Long Baseline Array (VLBA). Among 295 defining sources, fewer than 30% are in the Southern hemisphere. In the Northern hemisphere, ICRF sources are well distributed and regular imaging of Northern hemisphere ICRF sources are made through the ongoing astrometric and geodetic Research and Development VLBI (RDV) experiments using the VLBA (e.g. Fey & Charlot, 2000; Collioud & Charlot, 2009). 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. There have been many efforts in recent years to increase the number of known Southern hemisphere reference source, in particular the astrometric observations from the Long Baseline Array (LBA) Calibrator Survey (LCS), which has already produced a significant improvement at 8.4 GHz (Petrov et al 2011). Dedicated astrometric observations at 8.4 and 2.3 GHz band to density the ICRF in the south are currently underway, as proposed in Lovell et al. (2013). There has also been a few dedicated imaging observations of southern sources (e.g. Hungwe et al. 2011; Ojha et al. 2004; Ojha et al. 2005), and first images from the LCS astrometric experiments have been produced (de Witt & Bietenholz, 2012).

Dedicated imaging observations to map the source structures on a regular basis have proven to be very resource intensive, with availability of antennas being one of the most limiting factors in the south. Based on these considerations we have investigated the possibility of imaging sources from existing geodetic and astrometric observations in the south. Imaging of source structure from the LCS experiments have proven to be successful and we will continue to image more of the LCS experiments. We also have identified the Celestial Reference Frame Deep South (CRDS) astrometric VLBI observations to be potentially suitable for mapping purposes. Present and past surveys (e.g. Pearson & Readhead, 1988; Taylor et al. 1996) show that such surveys are an important tool for astrometry but also for investigation of a wide range of astrophysical phenomena.

2. Obseravtional data:

We have reduced the data for a single epoch, 24-hour session of one LCS (v271m) and one CRDS (CRDS63) experiment.

The LCS[1] is an ongoing VLBI project to observe a list of flat-spectrum radio sources below -30^0 declination at 8.4-GHz using the LBA array. Observations for LCS experiment v271m were made on 15-16 June 2013 at a central frequency of 8.344 GHz, recording a total bandwidth of 128 MHz, right circular polarization (RCP) only. Eight antennas (see Table 1 with lcs tag) from the LBA participated and a total of 101 sources were observed in this experiment with 2–4 scans of 2–6 minutes duration per source. The *uv*-coverage for LCS experiments is very limited due to the few scans per source and also the array configuration. The data were correlated at the Curtin University of Technology using the DIFX correlator (Deller & Tingay, 2007). Imaging of sources from experiment v271m is still in progress.

The CRDS[2] astrometric observing sessions are part of the International VLBI Service for Geodesy and Astrometry (IVS) campaign to strengthen the ICRF in the south. Since 2013 observations have been performed using a regular network of six southern stations (see Table 1 with crds tag). A total number of 97 sources have been observed through CRDS sessions with the majority of sources being south of -30°declination. Most sources are observed in at least 2-3 sessions per year with around 2-7 scans of 9 minutes duration per source. As opposed to more typical astrometric sessions where only 2-station scans are required, the majority of scans in the CRDS sessions, observed since 2013, include at least 4 to 6 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 were made on 14-15 January 2013 and a total number of 38 sources were observed. All six telescopes as mentioned in table 3 were scheduled for observations, but unfortunately the Hobart 12m and Wakworth 12m telescopes did not participate. Data were recorded at RCP with 8 IFs at X-band and 6 IFs at S-band and a bandwidth of 4 MHz per IF[3]. Data were correlated at the Washington Correlator (WACO) in Washington, DC.

[1] Information on the LCS is available on the web at *http://astrogeo.org/lcs/*
[2] Information on the CRDS sessions are available on the IVS webpage at *http://ivscc.gsfc.nasa.gov*
[3] Bandwidth was increased to 8 MHz from CRDS66 in June, 2013.

Table 1. Antennas participating in the LCS & the CRDS experiments.

Station	Location	Diameter(m)	SEFD(2.3 GHz)	SEFD(8.4 GHz)
ATCA^{lcs}(Array with 6 antennas)	Australia	6×22	106	86
Ceduna^{lcs}	Australia	30	400	600
HartRAO^{lcs,crds}	South Africa	26	2929	1978
Hobart^{lcs,crds}	Australia	26	1019	902
Hobart^{lcs,crds}	Australia	12	4000	5000
Mopra^{lcs}	Australia	22	530	430
Parkes^{lcs}	Australia	64	30	43
Tidbinbilla^{lcs}	Australia	70	16	25
Yarragedee^{crds}	Australia	12	3247	5333
Katherine^{crds}	Australia	12	4337	3286
Warkworth^{lcs}	New Zealand	12	8000	8000

***System Equivalent Flux Density (SEFD) values are in Jy.*

3. Data reduction & Results:

The data reduction for the imaging of the CRDS and LCS observations was performed using the NRAO Astronomical Processing System (AIPS; Greisen, 1988). The CRDS correlated data were fringe-fitted with *FOURFIT* which is used to produce data suitable for importing into AIPS. The correlated data was then imported into AIPS using `MK4IN` (Alef & Graham, 2002). 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 of data 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 the source J1427-4206 were Fourier inverted and deconvolved using the CLEAN algorithm, and the amplitude gains were further refined by self-calibrating using CLEAN models. For the final CLEAN image we used the square root of the statistical visibility weights, which increases the robustness of the image.

We present preliminary imaging results (see Figure 1) for the source J1427-4206 at 8.4 GHz and 2.3 GHz. We have chosen J1427-4206 for our initial attempt as this source has the highest flux density among the sample of sources in CRDS63 and was observed during 4 scans that included all 4 antennas. J1427-4206 has also previously been observed with both the VLBA and the LBA which provides an opportunity to compare our results with available images from existing experiments. Figure (a), (b), (c) indicate the source strcuture, visibility phase and visibility amplitude plots respectively. For any compact source we can expect its amplitude and phase to be steady over all the baselines which is shown by figure (b) and (c) the gap in these two plots is due to the lack of available antenna between HartRAO and Warkworth which has the longest baseline length more than 10,000 km. Figure (b) and (c) conclude that the source has a point like structure which is shown in figure (a). Figure (d), (e) and (f) shows the source structure, visibility amplitude and visibility phase plot respectively of the same source J1427-4206 at 2.3 GHz. All the plots for amplitude and phase strongly indicate that the observed source has a compact strcuture at both 8.4 and 2.3 GHz frequencies which is shown in figure (a) and (d) respectively.

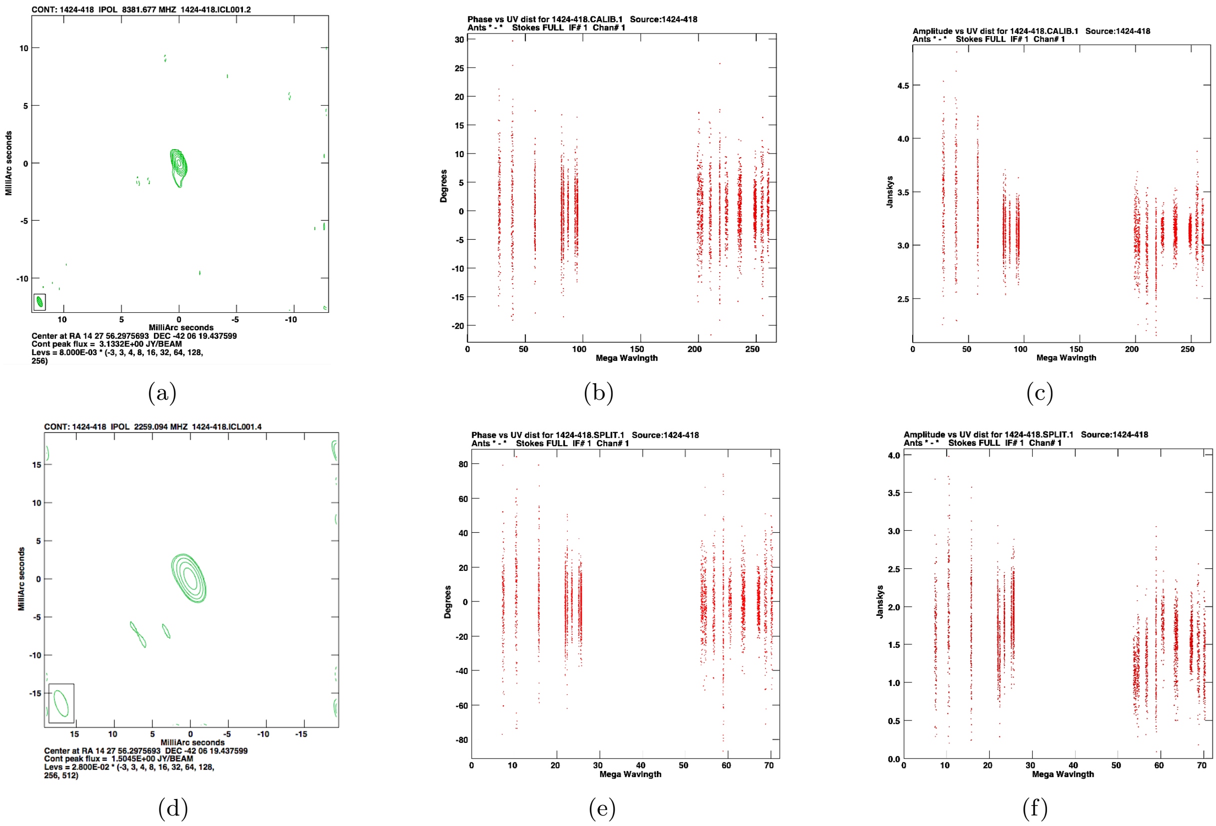

Figure 1. (a) shows a map of the source J1427-4206 from the CRDS63 experiment at 8.4 GHz. The peak flux density is 3.13 Jy/beam, the rms noise is 8 mJy/beam and the contour levels are at -3, 3, 4, 8, 16, 32, 64, 128, 256, 512 times the rms noise. North is up and East is to the left. (b) shows the visibility phase vs uv-distance plot and (c) shows the visibility amplitude vs. uv-distance plot for the source J1427-4206 at 8.4 GHz. (d) shows a map of the source J1427-4206 from the CRDS63 experiment at 2.3 GHz. The peak flux density is 1.50 Jy/beam, the rms noise is 28 mJy/beam and the contour levels are at -3, 3, 4, 8, 16, 32, 64, 128, 256, 512 times the rms noise. North is up and East is to the left. (e) is the visibility phase vs uv-distance plot and (f) is the visibility amplitude vs uv-distance plot of the source J1427-4206 at 2.3 GHz.

4. Summary & Outlook

We have presented here our preliminary imaging results of source J1427-4206 from the CRDS63 astrometric session. We aim is to complete the imaging of all the sources observed in the CRDS63 session in order to evaluate the astrometric quality of these sources for future astrometric and geodetic purposes. Efforts are also underway to image sources from the LCS and to reduce data for more CRDS sessions. In future, we plan to set up a pipeline for automated imaging CRDS sessions. These dual frequency observations will help us to test the frequency-dependence of the sources and to monitor the sources for variability or structural changes on a continuous basis.

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