Improving the S/X Celestial Reference Frame in the South

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Abstract We believe that the S/X celestial reference frame (CRF) can be improved in the far-south by a factor of 2 in density and a factor of 2.5 in precision. We have started a collaboration to meet these goals. We have increased the data rates on existing IVS astrometric sessions in the south from 256 Mbps to 1 Gbps. We will use this sensitivity to detect weaker sources and to improve the precision of sources in the southern S/X CRF, while simultaneously increasing the number of sources, in particular the overlap with other frames such as K- and Ka-band in the radio and the Gaia frame in the optical. VLBI observations in the southern celestial hemisphere have always been more difficult both because there are fewer radio telescopes in the south than in the north, and because there are fewer known reference sources in the south. There have been many efforts in recent years to increase the number of known reference sources in the south, in particular the LBA calibrator Survey (LCS), which has already produced a significant improvement at X-band. The ICRF-3 is expected to make significant improvements in the south, however the south has not yet reached parity with the north and much work remains to be done. Therefore dedicated astrometric and imaging observations have already begun to improve the southern CRF at S/X-bands.

Keywords Astrometry, VLBI, Celestial Reference Frames, Southern Hemisphere, quasars

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1 Introduction

Geodetic and astrometric VLBI observations have always been more difficult in the south, with the availability of antennas being the most limiting factor. The second realization of the International Celestial Reference Frame (ICRF-2 [7]) was dominated by data from the north. However, despite many efforts to improve the north/south imbalance of observations (e.g. the AUSTRAL observing program that was started in 2011 [9]), current radio astrometry catalogs are still weak in the south, with a significant hemisphere disparity in source distribution and density.

In recent years there have been many efforts to increase the number of known reference sources in the south, with the most significant contribution coming from the Australian Long Baseline Array (LBA) Calibrator Survey (LCS, [8]), that observed more than 1500 candidate extragalactic radio sources, (declination below $-30°$), from 16 VLBI experiments with the LBA at 8.4 GHz.

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, [6]). Specific emphasis was placed on improving the southern CRF as well extending the frame to higher radio frequencies, chiefly at 24 GHz (K-band [4]) and 32 GHz (Ka-band [5]). Although the ICRF-3 is expected to show significant improvements in the south, the south has not yet reached parity with the north and much work remains to be done.

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 [3, 10]. It is therefore important to map the structures of these sources on a regular basis. There have, however, only been a few imaging sessions of reference sources in the south and dedicated campaigns to map and monitor source structure have proven difficult to obtain. However, recent investigations to image source structure from existing astrometric and geodetic observations in the south have proven that dedicated imaging campaigns may indeed be possible [1].

In this paper we present the current status of the S/X CRF as well as our proposed plans to improve the S/X CRF in the south. We also present some recent results from these efforts, including a multi-epoch campaign to image source structures in the south.

2 Current Status: North Versus South

At present there are only a few VLBI-capable radio telescopes in the Southern Hemisphere and even fewer that regularly participate in astrometric and geodetic VLBI experiments. The Very Long Baseline Array (VLBA) significantly contributes to CRF work in the north, but unfortunately there is no VLBA to compensate in the south. Currently there are only five radio telescopes in the south that regularly participate in astrometric experiments (∼12 % of total); a 15 & 26m telescope in South Africa, three 12m telescopes and one 26m in Australia and one 12m telescope in New Zealand. There are two radio telescopes in Antarctica, but these are very small in size and can only detect a few of the brightest sources. There is also a radio telescope in Brazil, but it is close to the equator and does not contribute significantly to southern observations.

In figure 1 we show the evolution of geodetic and astrometric observations for the period 03 August 1979 to 27 March 2018. The plot shows the distribution between northern-only baselines, southern-only baselines and north-south or mixed baselines. The distribution has evolved from mainly northern-only baselines to ∼10 % southern-only and almost 20% mixed baselines.

The growth of astrometric and geodetic observations between the period 03 August 1979 and 27 March 2018 are shown in figure 2. Southern-only baselines and mixed baselines have increased noticeably in recent years, but still represent only ∼15 % of the total number of baselines.

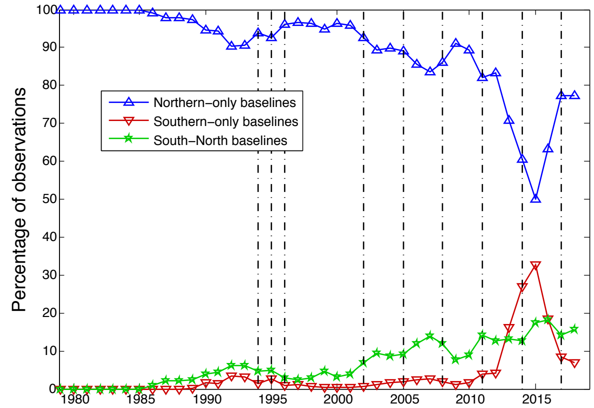

Fig. 1 The evolution of the observation distribution for 03 August 1979 to 27 March 2018 between northern-only baselines (blue traingles), southern-only baselines (red inverted triangles) and mixed baselines (green stars).

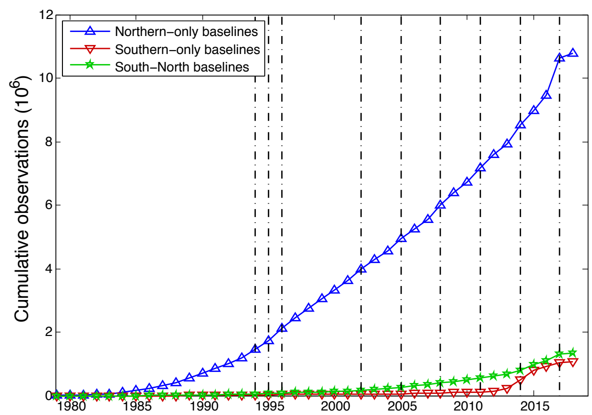

Fig. 2 Cumulative growth of northern-only observations (blue traingles), southern-only baselines (red inverted triangles) and mixed baseline observations (green stars) for the period 03 August 1979 to 27 March 2018.

The ICRF-2 is based on high precision Very Long Baseline Interferometric (VLBI) measurements of positions of 3414 extragalactic radio sources. This includes the 295 defining sources which determine the orientation of the frame axes. The ICRF-2 has a noise floor of 40 μas in the individual source coordinates, and an axis stability of 10 μas. The positions were determined from dual-frequency VLBI observations at 2.3 GHz (S-band) and 8.4 GHz (X-band), mostly organized under the auspices of the International VLBI Service for Geodesy and Astrometry (IVS).

The ICRF-2 was generated from 4,726 VLBI sessions and 6.5 million measurements acquired for geodetic and astrometric purposes between 1979 and 2009 and was dominated by data from the north (e.g. figures 1 & 2). The most recent S/X astrometric solution (sx-gsfc-180521, David Gordon) was generated from 6,206 VLBI sessions and 13.2 million measurements from all available sessions up to 27 March 2018, and includes significantly more southern-only and north-south baseline observations than the ICRF-2.

The sky distribution plot of the formal position uncertainties, from the most recent S/X CRF, is shown in figure 3. Although this solution shows significant improvement over the ICRF-2, it is clear that we still need more sources in the south and that we also need to improve the spatial coverage, especially for declinations south of $-30°$. Both the number of sources and the average number of observations per source are a factor of 2 less in the far-south ($\leq -30°$) compared to the far-north. The median formal uncertainties are a factor of 1.5 weaker in $\alpha\cos(\delta)$ in the far-south and a factor of 2.7 weaker in δ. It is evident from these plots that we need more southern baseline observations as well as more north-south baselines.

From the most recent S/X CRF we identified 124 sources (37 ICRF-2 defining sources) in the far-south (below $-45°$ south), with no VLBI images—almost half the total number of sources in the far-south! Multi-epoch maps are essential to assess the astrometric suitability of CRF sources. Extended intrinsic source structures can introduce significant errors in the VLBI measurements, thereby degrading the accuracy of the estimated source positions. The lack of images will severely limit the potential for further improvements in the accuracy of VLBI source positions in the far-south and thus the improved stability of future S/X-band CRFs.

3 Proposed Plans and Progress to Date

3.1 Increase data rates

Currently the only dedicated astrometric programs at S/X in the Southern Hemisphere are the IVS Celestial Reference Frame (IVS-CRF) and Celestial Reference Frame Deep South (IVS-CRDS) sessions. Up to 2017, the data rates of these were only 128 Mbps for the IVS-CRF sessions and 256 Mbps for the IVS-CRDS sessions and included only observations of ICRF-2 defining sources. We propose to increase the data rates of these session by factor of 4 or more by increasing the data rate to 1–2 Gbps. This in turn will allow an increase in the sensitivity by a factor of 2 or more which will allow the detection of weaker sources down to $\sim$350 mJy or less. Scheduling will also become more efficient, since there will be more sources to choose from and scan times will be shorter which will result in more scans and/or sources per schedule.

We tested and implemented a 1 Gbps observing mode for the IVS-CRDS sessions and a 1 Gbps narrowband mode was tested for the IVS-CRF sessions. The IVS-CRDS sessions were officially upgraded to 1 Gbps mode starting with crds93 on 24 January 2018. The IVS-CRF sessions switched to 1 Gbps on 4 April 2018 with crf106.

3.2 Scheduling optimised for astrometry

We propose to change the scheduling of the IVS-CRF and IVS-CRDS sessions to be optimised for astrometry and imaging instead of geodesy. This would imply using the full network of stations when possible for every scan and with no sub-netting as is used routinely for geodesy schedules. There should also be at least 3–8 scans per source spread evenly over hour angle range, to allow for optimal *u*-*v* coverage for imaging without compromising the astrometric goals of the experiment. The schedule should also include blocks with tropospheric calibrators, that will also be used as astrometric ties and for amplitude calibration for imaging. In addition, we propose astrometric sessions be scheduled as part of a campaign rather than individual sessions. This will ensure that each source will receive the required amount of observing time and that the ultimate astrometric goals of the project be reached.

We have optimised the scheduling of all of the IVS-CRDS sessions from crds93 onwards. Figure 4 compares the *u*-*v* coverage for a source observed in both crds68 (27 November 2013) and crds94 (21 March 2018). The improvement in *u*-*v* coverage going from 2 scans (crds68) to 7 scans (crds94) is clearly evident from these two plots. The overall number of sources also increased from 38 to 51 and the overall number of scans from 144 to 304, from crds68 to crds94.

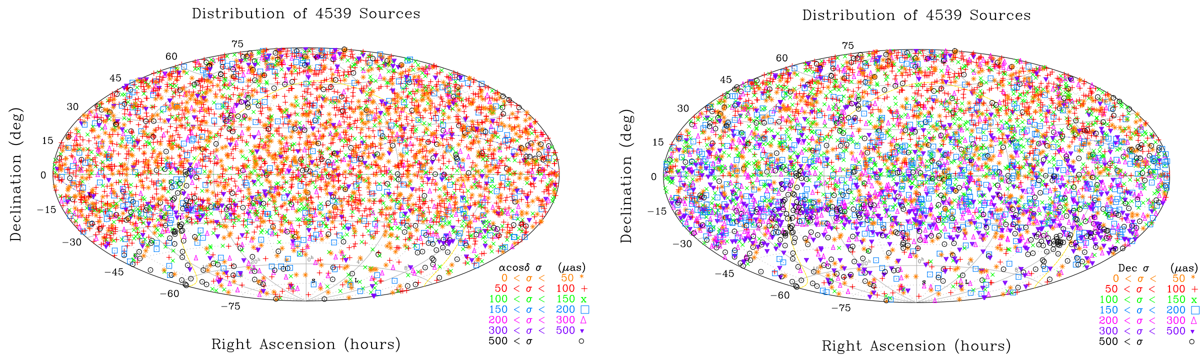

Fig. 3 The distribution of sources from the most recent S/X astrometric solution (sx-gsfc-180521) showing the formal uncertainties in $\alpha\cos(\delta)$ on the left and δ on the right.

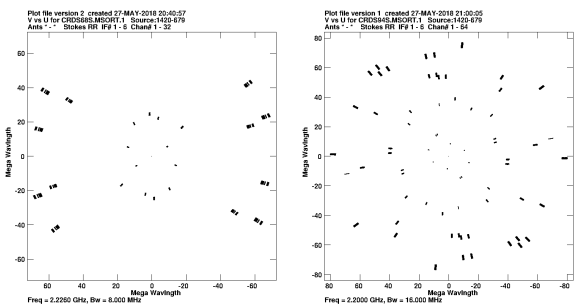

Fig. 4 The *u*-*v* plane coverage for the source 1420-679, observed in different IVS-CRDS sessions. The *u*-*v* coverage plot on the left is from the crds68 session (27 November 2013) and the plot on the right, showing a much improved sampling of the *u*-*v* plane, is from the crds94 session (21 March 2018). In both sessions five antennas participated. In crds68 the source was only observed in two scans and in the crds94 it was observed in seven scans.

3.3 Improve precision

Up to 2017, only ICRF-2 defining sources were observed in IVS-CRF and IVS-CRDS sessions. We propose to re-observe all southern sources in the current S/X CRF to improve the source position accuracy in both coordinates. We propose to improve the overall precision by a factor of 2.5 in the south. From the 1344 sources south of -15°, we have 1091 sources with ≤ 10 observing sessions. We will prioritise the 216 of these sources with flux density > 350 mJy that will be easily detectable with current instruments and data rates. Since December 2017, we started to include some of these 216 sources as part of the IVS-CRDS and IVS-CRF sessions.

3.4 Improve density and spatial coverage

We propose to improve the far-south by a factor of 2 in density by expanding the source list in the south, specifically in the far-south (below -30° south). In addition, we also propose to improve the overlap with K- and Ka-band frames and the Gaia optical frame. We identified $\sim$80 K- and Ka-band sources that are not in the current S/X frame at declinations south of -15°. From these we have $\approx$20 sources with flux density > 350 mJy at S/X-band. In addition, we also propose follow-up observations of candidate CRF sources brighter than 350 mJy from the pool of LCS sources. Priority will be given to $\sim 1/2$ of the target sources that have a counterpart with Gaia. Since December 2017, we started to include those K- and Ka-band sources that are not currently in the S/X CRF into the IVS-CRDS sessions.

3.5 Imaging

We propose to produce multi-epoch maps at both 2.3 and 8.4 GHz for all sources observed in the IVS-CRDS and IVS-CRF sessions. These maps will be used to quantify the non-pointlike structure and jet directions in these CRF sources. First priority will be given to those 124 sources in the far-south with no VLBI images. In figure 5 we show representative contour plots from recent imaging results obtained from the crds94 session from 21 March 2018 [2].

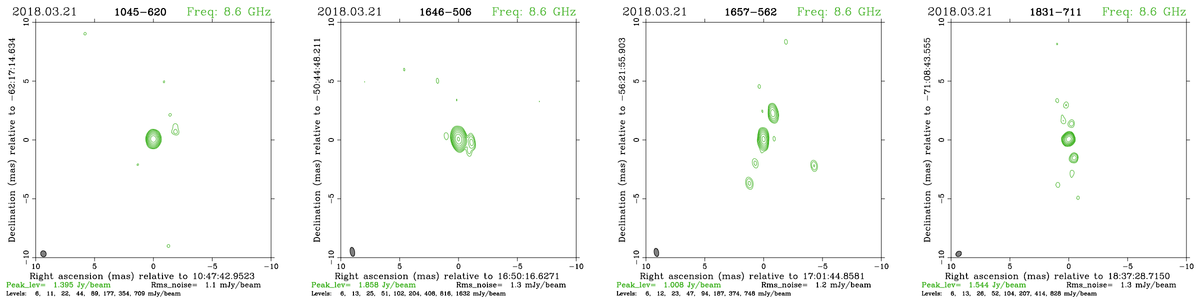

Fig. 5 From left to right, contour plots for sources 1045-620, 1646-506, 1657-582 and 1831-711 at 8.6 GHz from 21 March 2018 (crds94). North is Up and East is to the Left. The FWHM beamsize is graphically indicated in the bottom left corner [2].

4 Conclusions

Our goal is to improve the S/X-band frame in the south by at least a factor of 2 in density and 2.5 in precision, to be about as good as the north.

In order to achieve this, we propose to increase the data rate of southern IVS sessions to at least 1 Gbps and to optimise the scheduling of these sessions for astrometry and imaging versus geodesy. We further propose to increase the number of well observed sources (Nsess > 10) in the south and to increase both the number of southern-only and north-south baseline observations. We also propose to expand the southern source list and improve spatial coverage. In addition, we propose multi-epoch imaging of southern CRF sources to quantify non-pointlike structure and measure jet directions.

Our initial steps are succeeding: all IVS southern astrometric sessions are now at 1 Gbps, non-defining sources were added to the IVS-CRDS and IVS-CRF source list, and we produced first imaging results from and IVS-CRDS sessions at 1 Gbps.

Acknowledgements

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