Improving the S/X Celestial Reference Frame in the South: A Status Update

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Abstract Catalogues of positions of compact extragalactic radio sources, including the ICRF-3, are generally weaker in the south by factors of 2 or more in both density and precision. In 2018 we started a campaign to improve the S/X celestial reference frame in the south by upgrading existing IVS astrometric observing programmes. Our efforts were mainly focused on the Celestial Reference Frame (CRF) and Celestial Reference Frame Deep South (CRDS) sessions, which are dedicated astrometric observing programmes of sources at mid- and southern declinations. In particular, the data rate of the CRF and CRDS sessions were increased from 256 Mbps to 1 Gbps and the pool of sources were increased by a factor of two. The scheduling was also optimised to allow for simultaneous astrometric and imaging observations, and the CRF network was revised for improved uv-coverage. We provide details of our efforts, to date, to improve both the density and precision of the southern celestial reference frame, as well as our efforts to map and monitor the sources to quantify non-point-like structure and measure jet directions. We also discuss planned changes and upgrades, noting that the Australian 12-m telescopes are transitioning to broadband and may not be available for S/X astrometric observing in future. We also present the ideas and role of the newly-established IVS-CRF committee to improve the celestial reference frame in the south.

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1 Introduction

At present there are still only a few VLBI-capable radio telescopes in the Southern Hemisphere and even fewer that regularly participate in astrometric and geodetic VLBI experiments. For this reason current radio astrometric catalogues remain weak in the south, with a significant hemispheric disparity in source distribution, density, and source coordinate accuracy. The second realization of the International Celestial Reference Frame (ICRF-2, Ma et al., 2009) was dominated by data from the north, and despite many efforts in recent years to improve this imbalance, current radio astrometric catalogues are still weaker in the south by factors of 2 or more in both density and precision.

The efforts toward the realisation of the third International Celestial Reference Frame (ICRF-3, Charlot et al., 2020), placed specific emphasis on improving the southern celestial reference frame. However, while the ICRF-3 shows significant improvements in the south, the south has not yet reached parity with the north. Various efforts are currently underway to correct this. In particular, a dedicated campaign was started in 2018 to improve the S/X celestial reference frame in the south by upgrading record rates and improving source lists and schedules for existing IVS astrometric observing programmes (e.g. de Witt et al., 2019). In future, the newly established IVS-CRF Committee[1] will coordinate these efforts to improve the celestial reference frame in the south.

It is also important to map the structures of the celestial reference frame sources on a regular basis, as the effect of source structure on astrometric VLBI positions can be significant and the structure and flux density variability are directly related to the precision of geodetic solutions (e.g. Charlot, 1990). Unfortunately there have only been a few imaging sessions of reference sources in the far south ($\lesssim -45°$) and dedicated programmes to map and monitor source structure are difficult to obtain on astronomical VLBI networks. However, dedicated campaigns to map and monitor the sources in the far-south are underway, and efforts to image source structure from existing astrometric observations in the south have shown that dedicated imaging campaigns may indeed be possible for southern sources (e.g. Basu et al., 2018).

This paper provides an update on recent progress that was made towards improving the southern celestial reference frame, with specific emphasis on the progress made towards improving the southern astrometric IVS observing programmes, in particular the Celestial Reference Frame Deep South (CRDS) sessions. It also provides an update on the sources observed as part of the astrometric sessions of the Asia-Oceania VLBI group for Geodesy and Astrometry (AOV). An update on the progress towards improving the Celestial Reference Frame (CRF) sessions will be provided in a follow-up paper.

[1] https://ivscc.gsfc.nasa.gov/about/com/crfc/index.html

2 Current Status

The most recent S/X astrometric solution from August 2020 (sx-gsfc-200827, David Gordon) show some improvement over previous solutions (e.g. de Witt et al., 2019). However, the number of sources is still a factor of 2 less in the far-south ($\leq -30°$), and while the number of sessions per source are roughly the same in the north and the south, the average number of observations per source is also factor of 2 less in the far-south. Figure 1 shows the sky coverage from the latest S/X astrometric solution, colour coded by the Right Ascension ($\alpha \cos(\delta)$) and declination (δ) precision. We find that the median σ in $\alpha \cos(\delta)$ is almost 1.5 times weaker in the far-south and that the median σ in δ is a factor of 2.53 weaker in the far-south. It is clear that not only do we need more southern baselines, but we also need more sources in the far-south, and we also need to improve the spatial coverage in the south. It should be noted that the declinations are consistently worse than the right ascensions, even at the equator, and it is clear that we also need more north-south baselines.

3 CRDS Sessions

The CRDS sessions (now abbreviated to CRD sessions) are part of an IVS astrometric program focussing on the Deep Southern Sky. In November 2013 the data rate of these sessions was increased from 128 to 256 Mbps. On 24 January 2018 (starting with CRDS-93), the data rate was further increased to 1 Gbps, which allowed for the detection of weaker sources and more efficient scheduling (for more details see de Witt et al., 2019). With the increase in the data rate to 1 Gbps, the frequency sequence was also revised and was optimised to avoid S-band RFI.

The CRDS source list was also updated to include an additional 216 southern sources (before CRDS-93 only ICRF-2 defining sources were included), which at the time were sources observed in less than 10 sessions and that had a flux density of > 350 mJy. Priority was given to the 124 sources from this list that are in the far-south and for which no VLBI images were available (note that CRDS-94 was a special session that was used to image and analyse potential defining sources for the ICRF-3). At the same time, the scheduling of these sessions was optimised for both astrometry and

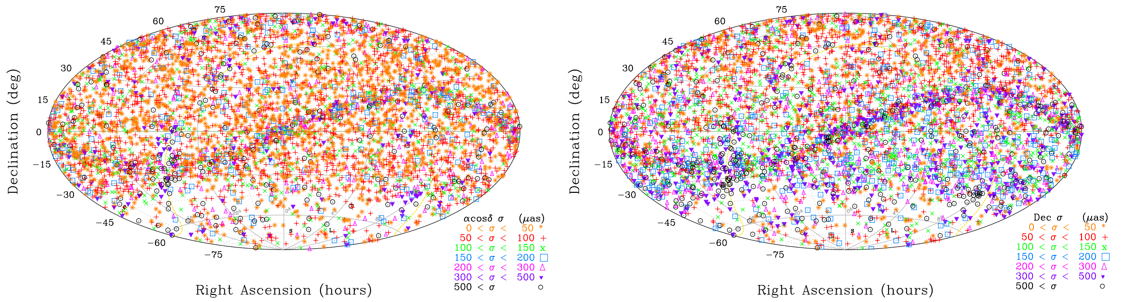

Fig. 1 The distribution of sources from the most recent S/X astrometric solution (sx-gsfc-200827) showing the formal uncertainties in $\alpha\cos(\delta)$ on the left and δ on the right.

imaging. The new schedules were generated using the NRAO scheduling software SCHED[2]. From June 2019 onward, starting with CRD-102, the schedules were generated using the new VLBI scheduling software for geodesy and astrometry, VieSched++ (Schartner and Böhm , 2019).

The CRDS network has always consisted of only a few stations, and prior to CRDS-89, there were six stations that regularly participated in the CRDS sessions. In July 2017 (CRDS-89), the Hobart 12-m antenna (Australia) was upgraded to a VGOS-style broadband receiver, leaving only five stations. More recently, in May 2019 (CRD-102) the O'Higgings 9-m antenna (Antarctica) was added to the CRDS network, but in June 2019 the Katherine 12-m antenna (Australia) was also converted for VGOS. In February 2020 (CRD-105) the Aggo 6-m antenna (Argentina) was added to the CRDS network, bringing the total number of stations back to six (see Figure 2), although at some point the Yarragadee 12-m antenna (Australia) will also move to broadband, However, both the Hobart and Katherine 12-m antennas have been used in locally organised mixed-mode observations together with the traditional S/X telescopes and hopefully the Australian 12-m antennas will re-join the CRDS sessions in the near future.

The statistics obtained from the IVS analysis reports for the CRDS sessions (e.g. the number of sources scheduled per session or the number of observations per source), provide valuable information in terms of the performance of these sessions. From CRDS-93 onward the statistics show that the majority of sources in a session were scheduled to be observed in at least 4 scans and with four or more stations per scan, to enable imaging. However, from a scheduling perspective, achieving at least 4 scans per source is a very hard scheduling constraint to achieve with a small network. One of the open problems, evident from the session statistics, is that only a small percentage of the observations from the CRDS sessions are actually used for analysis (on average $\sim 44\%$). However, closer inspection of the analysis reports show that the main contributor to this high failure rate is the long baseline observations to smaller antennas. The Aggo and O'Higgins antennas both have small dishes with large SEFD's ($>$ 10000 Jy) and are mostly tagged along in CRDS schedules. Some proposed solutions to improve the CRDS sessions include:

- increasing the scan length for weak sources (this has already been done for CRD-114 onward).
- moving to SNR based scheduling (only if correct flux information is available).
- increasing the data rate to 2 Gbps.
- adding more large, sensitive antennas.

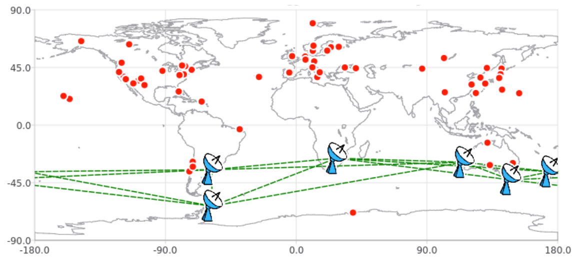

Fig. 2 The distribution of the six antennas that currently make up the CRDS network; the Aggo 6-m antenna in Argentina, the HartRAO 26-m antenna (Hh) in South Africa, the Hobart 26-m antenna (Ho) in Australia, the O'Higgins 9-m antenna (Oh) in Antarctica, the Warkworth 12-m antenna (Ww) in New Zealand, and the Yarragadee 12-m antenna (Yg) in Australia.

[2] http://www.aoc.nrao.edu/software/sched/index.html

One of the biggest issues in moving to SNR based scheduling for the CRDS sessions, is that many of the southern sources have either unreliable or no flux density information available. Figure 3 shows an example of the flux density information available for the source 1424-418 at X-band. The available flux density information was obtained from the *sked* flux catalogue[3] (these values are empirical fluxes based on the individual IVS sessions' SNRs and averaged over time). The *sked* flux catalogue is currently used for SNR-based scheduling of all IVS geodetic and astrometric sessions. Flux density information was also obtained from available images of 0424-418 in the Bordeaux VLBI Imaging Database[4] (BVID) and from the CRDS imaging campaign (one epoch only). The flux time series in Figure 3 shows some big differences between the IVS values and the flux densities obtained from the BVID (in particular after 2010), while the CRDS flux density values seem to agree well with the BVID. The source 1424-418 is an example of a well observed source with multi-epoch images, but for many sources further south there are very little or no images available and it is uncertain (as evident from this example) how accurate the available flux densities from the *sked* flux catalogue would be.

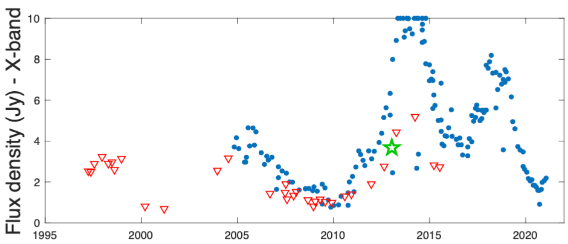

Fig. 3 Flux values in X-band of the source 1424-418 as reported in the *sked* flux catalogue (blue dots), and from the BVID (red triangles) and CRDS imaging campaign (green star).

A campaign to image southern celestial reference frame sources using the CRDS sessions started in January 2013 (see e.g. Basu et al., 2018), and the imaging of eleven CRDS sessions has been completed to date. Imaging of the older sessions, prior to CRDS-93, was challenging because of poor sensitivity and poor uv-coverage. Amplitude calibration is also difficult, in general, since system temperature and gain curve information is not available for all of the stations. In addition, because of the already small network, some sessions end up with only three or four participating stations (e.g. CRDS-93 and 99), and some these sessions are not useful for imaging. Figure 4 shows the contour maps for a representative sample of five sources, taken from more recent CRDS sessions that were observed during 2018 and 2019. Three of these sources, 0302-623, 0454-810 and 1925-610 are ICRF-2 defining sources. The source 0302-623 shows poor astrometric quality due to its extended structure and was subsequently removed as a defining source. The sources 0454-810 and 1925-610 are also ICRF-3 defining sources. However, the source 1925-610 shows a secondary component and its status as a defining source should be revisited in future, as indicated in the ICRF-3 paper.

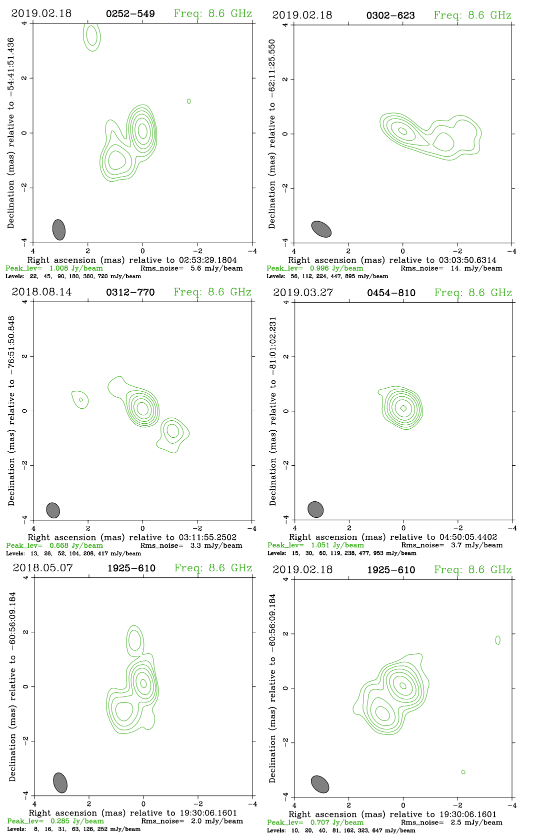

Fig. 4 Contour plots for sources 0252-549 and 0302-623 (top panel), 0312-770 and 0454-810 (middle panel), and 1925-610 (bottom panel) at 8.6 GHz from CRDS sessions between 2018 and 2019. North is Up and East is to the Left. The FWHM beamsize is graphically indicated in the bottom left corner.

[3] https://github.com/nvi-inc/sked_catalogs

[4] http://bvid.astrophy.u-bordeaux.fr/

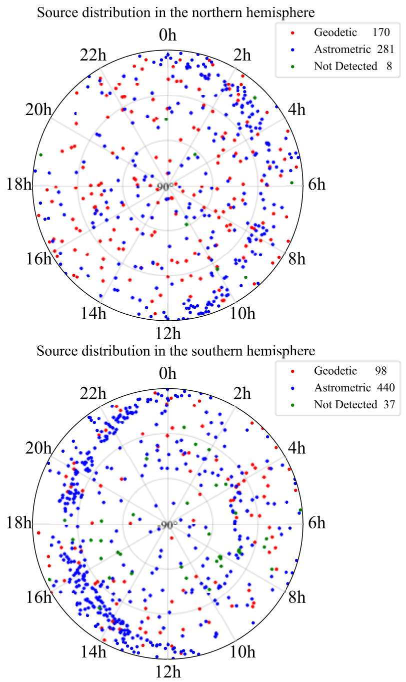

Fig. 5 Distribution of the 1034 sources observed as part of the AOV astrometric sessions. The astrometric sources that were detected are shown in blue, and the sources that were not detected are shown in green. The sources shown in red are sources that are listed as good geodetic sources in the *sked* source catalogue.

4 AOV Sessions

The AOV group is composed of 5 countries (New Zealand, Australia, Japan, China and South Korea) and 17 participating telescopes. The programme was launched in 2015 and one of the goals is the astrometry of weak sources with an emphasis on the ecliptic plane and Southern Hemisphere. All of the astrometric sessions were observed at a data rate of 1 Gbps. So far 1034 sources have been observed, including 861 ICRF-3 sources and a few radio stars. From the original 1034 sources a total of 989 were detected at S/X dual band. The median values of the flux densities are 0.26 Jy at X-band and 0.24 Jy at S-band. Figure 5 shows the Northern and Southern Hemisphere distribution of the 1034 sources observed as part of the AOV astrometric sessions. The AOV is now considering the source list for the next AOV astrometric sessions.

5 Conclusions and outlook

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, in order to reach parity with the north. To achieve this, the IVS-CRF committee recommends these actions:

- Increase southern IVS session data rate to 2 Gbps.
- Increase the number of south-south but also north-south baseline observations.
- Image all southern sources to quantify non-pointlike structure and to measure jet directions.
- Expand the southern source list and improve spatial coverage following ICRF-3 recommendations.
- Add more sensitive antennas in the south e.g. the Tidbinbilla 70-m antenna in Australia, the VLBA Saint Croix and Mauna Kea 30-m antennas, and the Kunming 50-m antenna in China.
- Add the Warkworth 30-m antenna in New Zealand in single-frequency mode (X-band only and using external ionosphere data).
- Address RFI issue by using single-frequency mode for the Hobart 26-m antenna in Australia and other stations that suffer from severe S-band RFI issues.

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