The benefits of the Australian mixed-mode program (2018 - 2023) for the celestial reference frame at S/X-band

H. Krásná, L. McCallum, T. McCarthy

Abstract The current realization of the International Celestial Reference Frame at 8.4 GHz, the ICRF3-SX, is computed from very long baseline interferometry (VLBI) measurements starting in 1979 through until March 2018. The concentration of the majority of VLBI telescopes in the Northern hemisphere reflects itself in the unequal distribution of observations to radio sources over declination, causing the ICRF3-SX to be weaker in the south. One of the current VLBI observing programs active in the Southern hemisphere is the Australian mixed-mode program (AUM) which started to be organized in July 2018. In this contribution, we show the benefits of the AUM for the celestial reference frame including observation until December 2022 and also discuss its current limitations. The individual sessions were scheduled for currently available VLBI telescopes (Hb, Ke, Yg for the first block, then also including Ht and Ww in the second block). In terms of scheduling, the sessions were scheduled geodetically, i.e. aiming for a high number of scans. In AUM049-058, five target sources were observed in 4-5 scans of 10 minutes duration. This setup still ensures about 25 scans/hr/station, which is seen as a foundation for good geodetic results.

Keywords Australian mixed-mode program (AUM), celestial reference frame (CRF)

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1 Introduction

Conventional celestial reference frames (CRF) are practical realizations of the international celestial reference system (ICRS; Arias et al., 1995). The ICRS was adopted by the International Astronomical Union (IAU) as the conventional system in 1997. At its XXX General Assembly in 2018, IAU resolved in Resolution B2, "On The Third Realization of the International Celestial Reference Frame" (ICRF3 working group , 2018) that from 1 January 2019, the fundamental realization of the ICRS shall be the Third Realization of the International Celestial Reference Frame (ICRF3; Charlot et al., 2020). The ICRF3 at S/X band consists of absolute positions of extragalactic radio sources that were estimated from geodetic and astrometric very long baseline interferometry (VLBI) sessions. These sessions were organized and made available mainly by the International VLBI Service (IVS) and the Very Long Baseline Array (VLBA) across several observing programs. The substantial dominance of the telescopes in the Northern hemisphere included in these programs reflects itself in the proportionally lower number of observed radio sources in the Southern hemisphere with a lower cadence for their re-observations. Petrov et al. (2011, 2019) organized calibrator surveys of southern compact radio sources (LCS1 and LCS2) using the Australian long baseline array (LBA), with one of the objectives being to match the density of calibrator sources in the Northern hemisphere with positions accurate to a few milliarcseconds. As the measurements were carried out at X band only, without a precise access to the ionospheric contribution on the delay, the LCSs are not included in the ICRFs. One of the IVS observing programs which focuses on the increase of density and precision of the southern radio sources

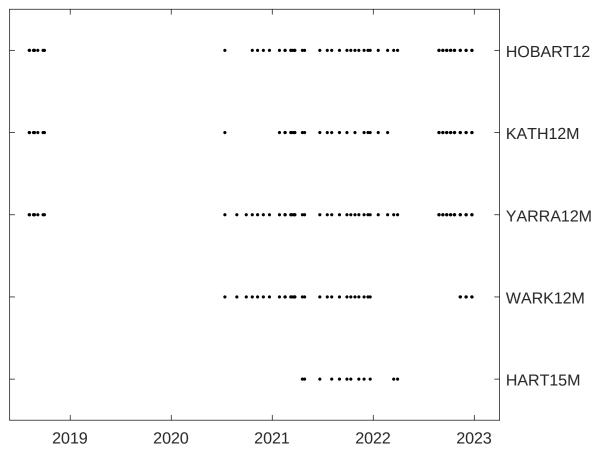

Fig. 1 Telescopes observing in the AUM001-064 sessions.

included in ICRF3, is the celestial reference frame deep south (CRDS; Weston et al., 2023) program.
The Australian mixed-mode program (AUM; McCallum et al., 2022) started in 2018 as a network of three Australian telescopes Hobart12 (Hb), Kath12m (Ke) and Yarra12m (Yg). In 2020 Wark12m (Ww) in New Zealand joined followed by Hart15m (Ht) in South Africa (Fig. 1). The mixed-mode configuration means that the upgraded VLBI Global Observing System (VGOS) stations (Hb, Ke) observe the legacy S/X configuration with the remaining telescope(s) in the network. In this paper we describe contribution of sessions AUM001-064 (2018-Jul-31 to 2022-Dec-17) to the CRF on basis of the VIE2022sx[1] solution (Krásná et al., 2023).

2 Method

The AUM sessions started to observe in July 2018 in the novel mixed-mode configuration to close the gap in the global IVS network as well as in the station time series which arised after the upgrade of Hb and Ke to VGOS telescopes. For sessions AUM049-058, we decided to exploit the potential of the strategic location of the AUM network to reobserve ICRF3 sources in the Southern hemisphere with a low number of prior observations. We scheduled dedicated sessions with 5 target sources. We included 10 min scans on each of them. We also scheduled 4 calibration blocks in each session, with 2 min scans. Still, sky coverage includes about 25 scans/hr/station, which gives similarly good geodetic results as described for sessions AUM001-033 in McCallum et al. (2022). Table 1 shows the scheduled target sources per session in detail.

[1] https://vlbi.at/data/analysis/ggrf/crf_vie2022_sx.txt

Table 1 Overview of the dedicated AUM049-058 sessions.

session	start date	target sources
AUM049	2022-Aug-19	0035-534, 0407-658, 1030-590, 1352-632, 1839-486 (target1)
AUM050	2022-Aug-20	0125-484, 0700-465, 1204-613, 1343-601, 1722-554 (target2)
AUM051	2022-Sep-02	0219-474, 0809-493, 1253-590, 1600-489, 1830-589 (target3)
AUM052	2022-Sep-03	0252-712 , 0647-475, 1556-580, 1829-718 (target4)
AUM053	2022-Sep-16	target1
AUM054	2022-Sep-17	target2
AUM055	2022-Sep-30	target3
AUM056	2022-Oct-01	target4
AUM057	2022-Oct-14	target3
AUM058	2022-Oct-15	target1

3 Results

The analysis of these dedicated sessions showed that only several scheduled scans to the target sources could be successfully observed. The limitation factor was the low flux density of the radio sources. Nevertheless, the sessions even after the loss of several scans performed well and could be used for CRF estimation in a global solution.

The global solution VIE2022sx includes the AUM001-064 sessions by default. For this investigations, we computed another global solution that is identical to VIE2022sx but without the AUM sessions denoted as VIE2022sx_noAUM. The contribution of the AUM001-064 sessions to the VIE2022sx global solution, with the number of observations per source plotted over declination (δ), is depicted in top panel of Fig. 2. The lower plot shows the percentage of AUM observations to the respective sources coming from AUM in the VIE2022sx solution. It shows that even a small number of observations to sources below -45° declination represents a significant percentage of their observations in VIE2022sx. Fig. 3 depicts the sources in AUM001-064 with a mollweide projection

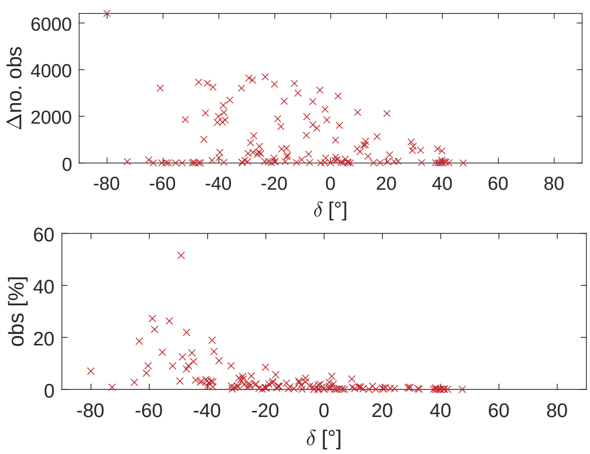

Fig. 2 Top panel: Difference in no. of observations between VIE2022sx and VIE2022sx_noAUM, i.e., no. of observations to respective sources in AUM001-064. Lower panel: Percentage of observations to sources in VIE2022sx coming from AUM001-064.

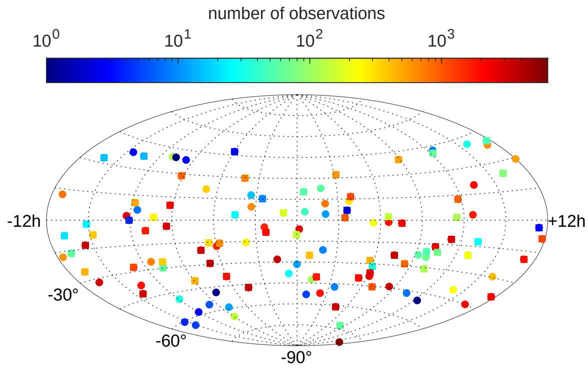

Fig. 3 No. of observations (logarithmic scale) to ICRF3 defining sources (squares) and ICRF3 non-defining sources (circles) in AUM001-064 sessions.

using a logarithmic heat color scale for the number of observations per source (ICRF3 defining sources are squares and other sources are circles).

Comparison of the two CRF catalogs (VIE2022sx_noAUM minus VIE2022sx) shows a slight systematic difference in the declination estimates plotted over declination of all southern sources included in VIE2022sx. The peak of the systematic difference in δ reaches about -10 μas at $-40°$ declination (lower plot in Fig. 4) but is within the formal errors of the estimates. The differences in the estimated right ascension (α^*) and δ for sources observed in AUM001-064 sessions, are shown in

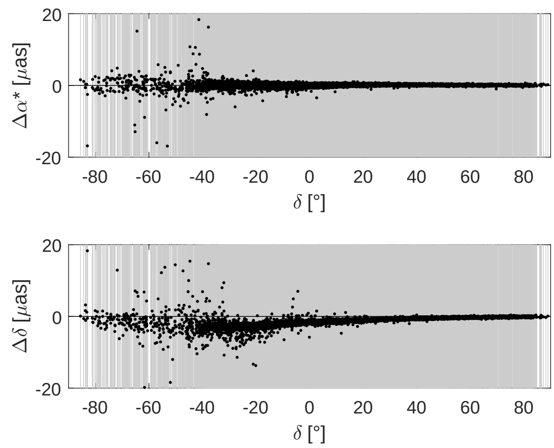

Fig. 4 Difference in right ascension (top panel) and declination (lower panel) computed as VIE2022sx_noAUM minus VIE2022sx for all sources in VIE2022sx. We use the designation α^* for right ascension scaled by declination of the source, i.e., $\alpha^* = \alpha \cdot \cos\delta$. Grey color indicates inflated formal error of the differences.

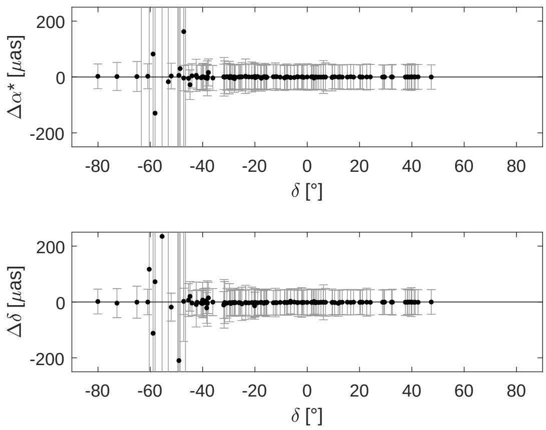

Fig. 5 Difference in right ascension (top panel) and declination (lower panel) computed as VIE2022sx_noAUM minus VIE2022sx for sources observed in AUM001-064 sessions. Grey color indicates inflated formal error of the differences.

Fig.5. The largest differences exceeding 50 μas in one or both coordinates appears for sources with declinations between $-45°$ and $-62°$. Comparison with Fig. 2 yields that the amount of observations coming from AUM sessions for these sources exceeds 10%.

In Figs. 6 and 7 we show the difference in inflated formal errors ($\Delta\sigma_{\alpha^*}$ (left panels), $\Delta\sigma_{\delta}$ (right panels)) computed as VIE2022sx_noAUM minus VIE2022sx plotted with respect to the corresponding inflated

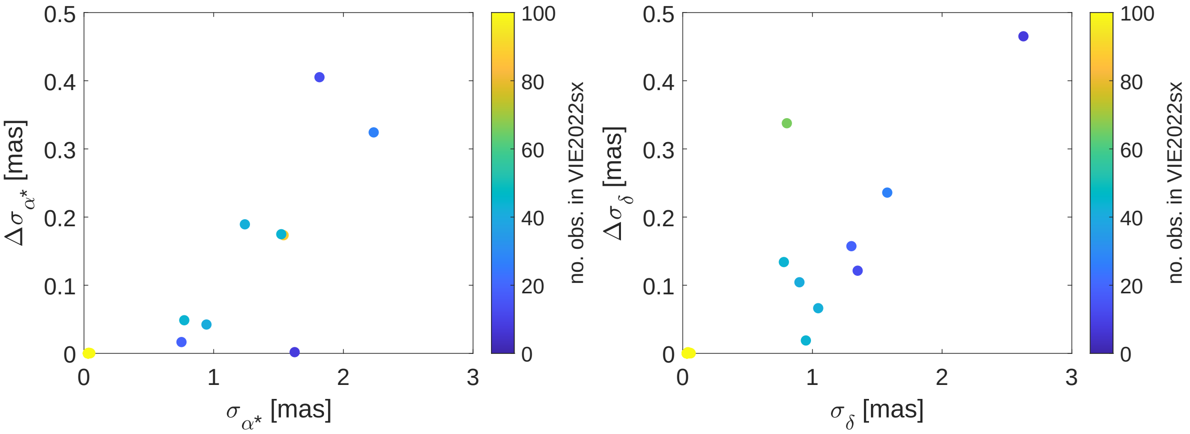

Fig. 6 Difference in inflated formal errors ($\Delta\sigma_{\alpha^*}$ (left panel), $\Delta\sigma_{\delta}$ (right panel)) computed as VIE2022sx_noAUM minus VIE2022sx w.r.t. the inflated formal error in VIE2022sx_noAUM. Color-coded is number of observations in VIE2022sx.

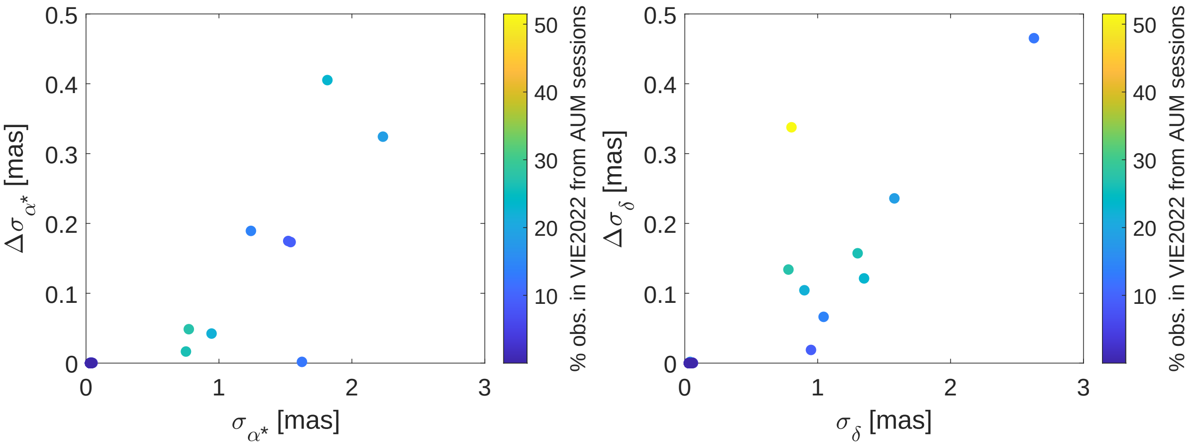

Fig. 7 Difference in inflated formal errors ($\Delta\sigma_{\alpha^*}$ (left panel), $\Delta\sigma_{\delta}$ (right panel)) computed as VIE2022sx_noAUM minus VIE2022sx w.r.t. the inflated formal error in VIE2022sx_noAUM. Color-coded is percentage of observations coming from AUM001-064.

formal error in VIE2022sx_noAUM. The inflation of errors was done following the recommendation given for ICRF3, i.e., multiplication of formal errors by scaling factor 1.5 and addition of noise floor 30 μas as RSS. The difference between Figs. 6 and 7 is in the information coded in the color scale. The color bar in Fig. 6 depicts the number of observations of the individual sources in VIE2022sx, and in Fig. 7 it shows the percentage of observations for the respective sources coming from AUM001-064 sessions in VIE2022sx. There are eleven sources which show a reduction of formal error larger than 100 μas in one or both coordinates: 0035-534, 0219-474, 0700-465, 0809-493, 1343-601, 1352-632, 1556-580, 1600-489, 1722-554, 1830-589, 1839-486. These sources have large formal error in VIE2022sx_noAUM (1–3 mas) mainly due to low number of observations (< 100) and the amount of extra observations coming from AUM sessions for these sources lays between 10% and 50% of observations in VIE2022sx.

4 Conclusions and outlook

The Australian mixed-mode program (AUM) supports the realization of the ICRS in the Southern hemisphere. We show that the dedicated AUM049-058 sessions improved inflated formal errors of eleven radio sources by $100 - 500$ μas in one or both coordinates. These sources had large formal error (1–3 mas) of their posi-

tion in CRF without AUM sessions primarily due to low number of observations (< 100).
The AUM program is ongoing with a double session (one weekend) per month. We expect Hobart26 to join the AUM sessions in 2023 which will increase the sensitivity of the baselines to the weaker radio sources.

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