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Evaluation of Terrestrial and Celestial Reference frames estimated from VGOS data

T. Nilsson, R. Haas, K. Le Bail

Abstract We use the VGOS data from 2017 until the beginning of 2025 to estimate a Terrestrial Reference Frame (TRF) and a Celestial Reference Frame (CRF). These reference frames are then compared to ITRF2020_u2023 and ICRF3, as well as to a TRF/CRF solution calculated based on legacy S/X VLBI data up to the beginning of 2025. For the TRF, we find agreements on the level of a few millimeters for the VGOS stations with the longest observation spans. For the CRF, the differences are in general a few 100 μas.

Keywords VLBI, VGOS, Terrestrial Reference Frame, Celestial Reference Frame

1 Introduction

The VLBI Global Observing System (VGOS) is the new geodetic VLBI system (Petrachenko et al., 2009). The first publicly released VGOS data are from five days during the CONT17 campaign in December 2017. In 2019 biweekly VGOS sessions were observed, and since 2020 operational VGOS sessions have been observed biweekly or weekly. Thus, for the VGOS stations with the longest time-spans, it should now be possible to estimate velocities with good accuracy from the VGOS observations.

Furthermore, it is likely that that the radio source positions estimated from VGOS will be slightly different from those estimated from the legacy S/X VLBI system. The reason for this is that VGOS since 2017 uses other frequencies than S/X (four bands in the range between 3.0 GHz and 10.6 GHz, instead of two bands centered around 2.3 GHz and 8.5 GHz). Thus, a celestial reference frame (CRF) for the currently observed VGOS frequencies is needed.

In this work, we estimate a Terrestrial Reference Frame (TRF) and a CRF from the VGOS observations between late 2017 and early 2025, called oso2025_vgos_trf and oso2025_vgos_crf, respectively. We compare these frames to ITRF2020_u2023, which is the 2023 update of ITRF2020 (Altamimi et al., 2023), as well as to ICRF3 (Charlot et al., 2020). We also compare the results to a TRF/CRF solution estimated from S/X VLBI observations from the period 1979–2025 (oso2025_sx_trf and oso2025_sx_crf).

2 Data analysis

The VGOS sessions between late 2017 until early 2025 were analyzed with the ASCOT software (Artz et al., 2016). First, each session was analyzed individually. Then, the datum-free normal equations from all sessions were combined in a global solution (using the global solution module of ASCOT) to estimate a TRF (oso2025_vgos_trf) and a CRF (oso2025_vgos_crf). In total, 216 sessions were included in the solution. In this global solution we explicitly estimated radio source coordinates, station coordinates, and station velocities, while Earth Orientation Parameters, tropospheric parameters and clock parameters were reduced from the single-session normal equations.

The datum of the TRF was realized by imposing No-Net-Translation (NNT) and No-Net-Rotation (NNR)

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constraints relative to the ITRF2020_u2023 coordinates and velocities for seven stations: GGAO12M, KOKEE12M, MACGO12M, ONSA13NE, RAEGYEB, WESTFORD, and WETTZ13S. These stations were chosen because they were found to be stable and have at least five years of observational data. The velocities of two stations, HARTVGS and YARRA12M, were constrained to their ITRF2020_u2023 values, and the velocity of WETTZ13N was constrained to be equal to that of WETTZ13S. This was done because these stations had too short observation intervals for reliable velocity estimation. For the CRF, the datum was realized by NNR constraints relative to the ICRF3 for the ICRF3 defining sources that were observed in at least 50 sessions.

For comparison, we also calculated a TRF/CRF solution (oso2025_sx_trf and oso2025_sx_crf) using ASCOT based on data from the legacy S/X VLBI network. This solution contained 7255 sessions from 1979 until early 2025.

3 Results

3.1 Terrestrial Reference Frame

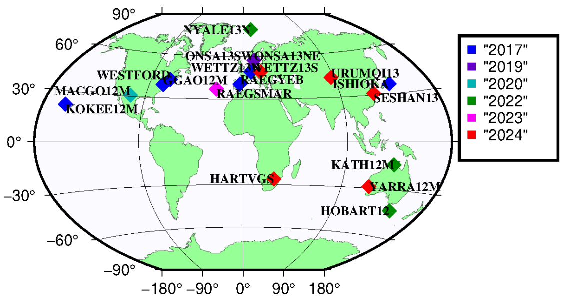

Fig. 1 Map of the stations participating in the VGOS sessions 2017–2025. The stations are color-coded with the year they joined the network.

A map of the stations of the VGOS network is shown in Fig. 1. Currently, the network consists of 18 stations. As can be seen, there is an uneven station distribution with most stations located in the northern hemisphere. Furthermore, the few stations located in the southern hemisphere joined the network quite recently (after 2022).

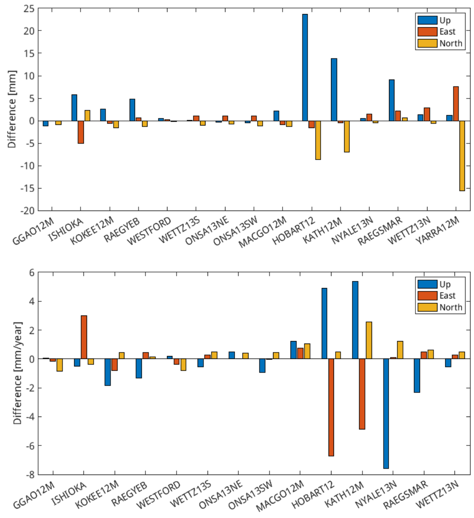

Fig. 2 Coordinate differences at epoch 2023.0 (top) and velocity differences (bottom) between oso2025_vgos_trf and ITRF2020_u2023.

Figure 2 shows the coordinate and velocity differences between oso2025_vgos_trf and ITRF2020_u2023. For the longest operating stations (>5 years, the nine leftmost stations in Fig. 2) there is in general an agreement on the level of a few millimeters or better. For the other stations, however, larger deviations can be seen. One reason for this is that the velocity estimations for these stations are uncertain due to the short time span. Another issue is that no stations in the southern hemisphere were included in the datum of oso2025_vgos_trf (because of their short time spans). This also makes the uncertainties larger for those stations (HOBART12, KATH12M, and YARRA12M).

The largest differences are seen for HOBART12. This station has problems with weak phase-cal signal, causing the observations to be very noisy (about a factor 5–10 worse than a typical station). This makes the estimated coordinates and velocities more uncertain. There have been similar problems at KATH12M, although not as severe.

Rather large differences in velocity (3 mm/year in the East direction) can be be seen for ISHIOKA. One reason for this may be that this station was affected by the Noto earthquake on January 1, 2024. The effect of this earthquake was not considered when estimating oso2025_vgos_trf. Furthermore, the large difference in the Up velocity seen for NYALE13N (7.5 mm/year) is possibly caused by the non-linear uplift of Ny-Ålesund caused by present-day ice-melting (Kierulf et al., 2022). In ITRF2020_u2023 the velocity of NYALE13N is constrained to be equal to that of NYALE13S, which has a longer observation time span which is different from that of the VGOS observations of NYALE13N.

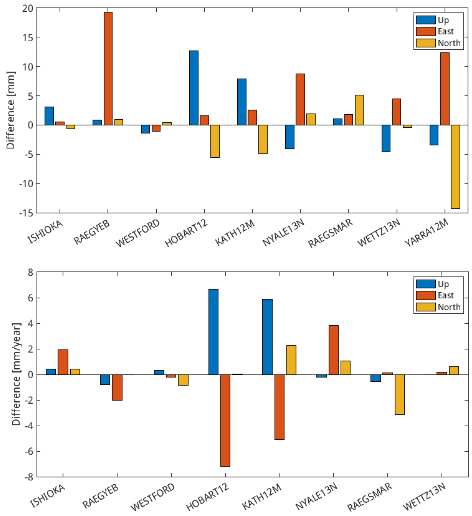

Fig. 3 Coordinate differences at epoch 2023.0 (top) and velocity differences (bottom) between the VGOS TRF and the S/X TRF.

Figure 3 shows the coordinate and velocity differences between the oso2025_vgos_trf and oso2025_sx_trf, i.e., stations that have a history of S/X observations and were later converted to VGOS. The results are in general similar as to the case when comparing to ITRF2020_u2023, i.e., larger differences for stations with short time spans and for HOBART12. Furthermore, there is a big difference of about 2 cm in the East component for RAEGYEB. This station has observed for less than one year in S/X (in 2015), hence the velocity (and thus also the coordinate at epoch 2023.0) is very uncertain in oso2025_sx_trf.

3.2 *Celestial Reference Frame*

The radio sources included in oso2025_vgos_crf are shown in Fig. 4. In total, 481 sources are included. Some of these (61) have been observed in more than

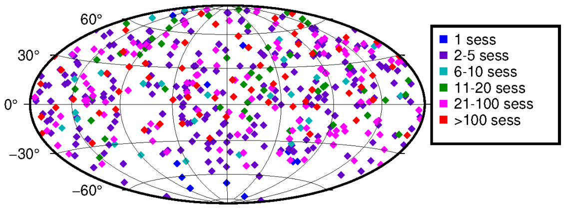

Fig. 4 The radio sources included in the VGOS CRF. The sources are color-coded with the number of sessions they were observed in.

100 sessions, while 11 sources have been observed in just one session. There are fewer sources in the far south (below -60° declination), and the sources there have been observed only in a few sessions. The reason for this is the lack of stations in the southern hemisphere.

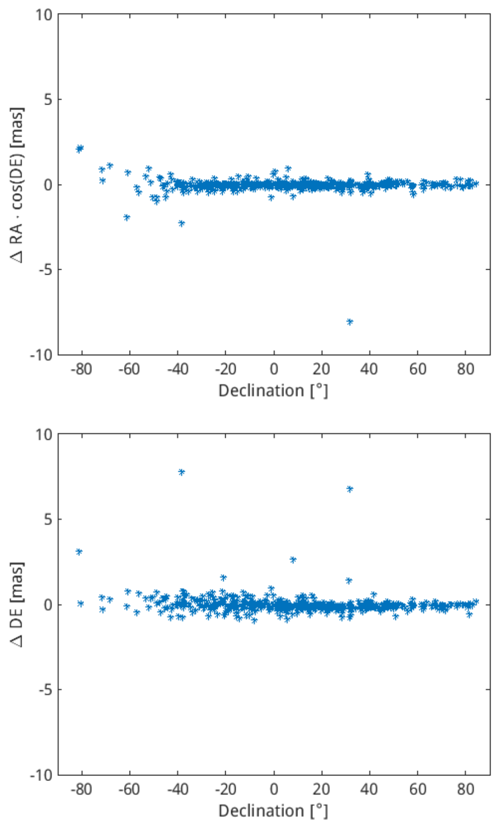

Fig. 5 Radio source coordinate differences between oso2025_vgos_crf and ICRF3.

Figure 5 shows the differences between the radio source coordinates (right ascension, RA, and declination, DE) between oso2025_vgos_crf and ICRF3. In general, there is a good agreement; the weighted root-mean-square (WRMS) differences are 153 μas for $\mathrm{RA} \cdot \cos \mathrm{DE}$ and 224 μas for DE. There are, however, sources where the differences are reaching several milliarcseconds.

Three of these sources (1323+321, 1947+079, and 0738+313) have significant source structure. They are sources consisting of two components separated by several milliarcseconds (for the first two even several tens of milliarcseconds). Since no source structure corrections were applied in our analysis, the estimated position of one of these radio sources will be, more or less, the barycenter of the two components. Thus, any variation in the relative intensity of the two components, either as a function of frequency or in time (or both), will cause a change in the source position.

One source with large coordinate difference (0405-385) was only observed in one session and only in six observations. It is located in the southern hemisphere, but was observed only with telescopes in the northern hemisphere, making the observation geometry bad and thus the estimated coordinates uncertain. Furthermore, we can see larger differences for radio sources far south. These are also observed in a somewhat bad observation geometry and mostly with the Australian telescopes. As reported in Sec. 3.1, these stations, especially HOBART12, suffered from phase-cal problems, resulting in very noisy observations.

We also compared oso2025_vgos_crf to oso2025_sx_crf. The results are shown in Fig. 6. As can be seen, the results are similar to the comparison of oso2025_vgos_crf with ICRF3. The WRMS differences were 115 μas for $\mathrm{RA} \cdot \cos \mathrm{DE}$ and 132 μas for DE. However, the deviations for the three sources with huge source structure were smaller. The reason for this could be that the structure of these sources are varying with time. ICRF3 includes observations up to March 2018. Hence, if the source structures have changed after 2018, this would affect both oso2025_vgos_crf and oso2025_sx_crf in a similar way.

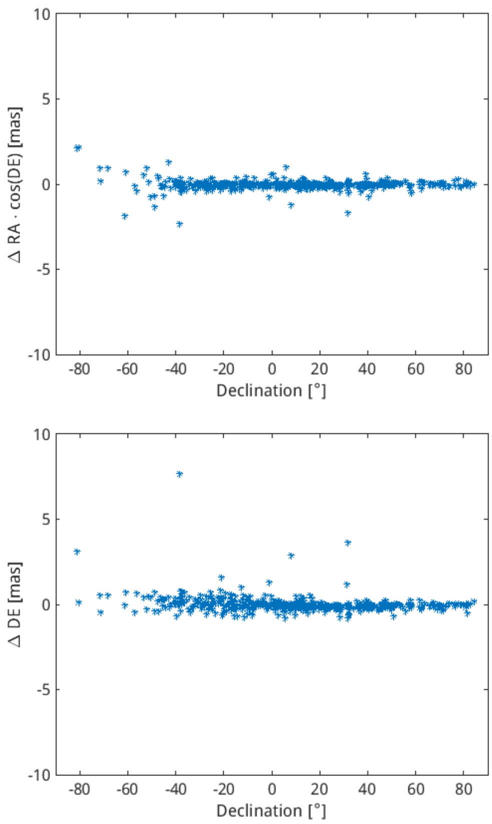

Fig. 6 Radio source coordinate differences between oso2025_vgos_crf and oso2025_sx_crf.

4 Conclusions

The TRF solution oso2025_vgos_trf estimated in this work agrees with ITRF2020_u2023 on the level of a few millimeters for coordinates and 1–2 mm/years for velocities for good stations with observation time spans of at least five years. A weakness of oso2025_vgos_trf is the lack of stations in the southern hemisphere. Furthermore, the existing southern hemisphere stations have all relatively short observation time spans (three years or less) and some of them are quite noisy due to phase-cal problems. The situation will improve with time as the time-series of the southern stations get longer and hopefully the problems with phase-cal are solved.

For the CRF, we find that oso2025_vgos_crf agrees with ICRF3 on the level 150–200 μas. There are a few larger deviations of several milliarcseconds found for sources with huge source structure, what could be expected. Furthermore, we found worse agreement for the sources with declination below -60° due to the low number of stations in the southern hemisphere. This latter issue is likely to improve as more southern stations join the network.

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