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Assessment of Parameters Describing the Signal Delay in the Neutral Atmosphere Derived from VGOS Observations

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Abstract We use the VGOS session VR2101 to assess parameters describing the signal delay in the neutral atmosphere. VGOS results are compared to corresponding results derived from co-located GNSS stations for all sites, and additionally to results from a ground-based microwave radiometer for the Onsala Space Observatory. For the first time all three independent techniques can be compared with the same high temporal resolution of 5 min. Zenith total delays from VGOS and GNSS reveal correlation coefficients larger than 0.9 for all but one of the participating sites. Corresponding offsets are between 1–8 mm and root mean square differences are between 4–14 mm. Horizontal gradients from VGOS and GNSS have correlation coefficients between 0.2–0.5 for the east components and 0.4–0.7 for the north components. Corresponding offsets are sub-millimeter, and root mean square differences are on the order of 0.5–2.2 mm. The comparisons for the Onsala site of VGOS and GNSS w.r.t. microwave radiometer show correlation coefficients larger than 0.96 for the zenith total delays with offsets on the order of 7–11 mm and root mean square differences of 9–12 mm. Horizontal gradients show correlation coefficients of about 0.2 for the east components and about 0.5 for the north components. The corresponding offsets are between 0.6–1.8 mm and the root mean square differences are 0.9–1.3 mm.

Keywords VGOS • GNSS • WVR • ZTD • gradients

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1 Introduction

During the design phase of VGOS, one major restricting factor was identified to be turbulence that is affecting the signal delay in the neutral atmosphere (Nilsson and Haas, 2010). In order to address this aspect the VGOS design focuses on radio telescopes that can move fast in azimuth and elevation, so that many observations in many different local directions can be achieved (Petrachenko et al., 2009) during an experiment. This shall allow to sample the signal delay introduced by the atmosphere much better than with legacy S/X observations and thus lead to improvements for the estimated geodetic parameters. An assessment of the parameters describing the signal delay in the neutral atmosphere can be achieved by comparisons with results from independent co-located instrumentation, such as GNSS stations and ground-based microwave radiometers, often referred to as water vapor radiometers (WVR).

2 VGOS Observations

VGOS is still in its roll-out phase, and so far only eight sites routinely participate in operational VGOS sessions organized by the International VLBI Service for Geodesy and Astrometry (IVS). One of the sites, the Onsala Space Observatory (OSO), operates two VGOS stations, the Onsala twin telescopes (OTT) (Haas et al., 2019). The current VGOS operational network is a purely northern hemisphere network, see Figure 1. During 2019, 24-hour long VGOS test observations (VT) were organized by the IVS every second week. Beginning in 2020, 24-hour long VGOS operational

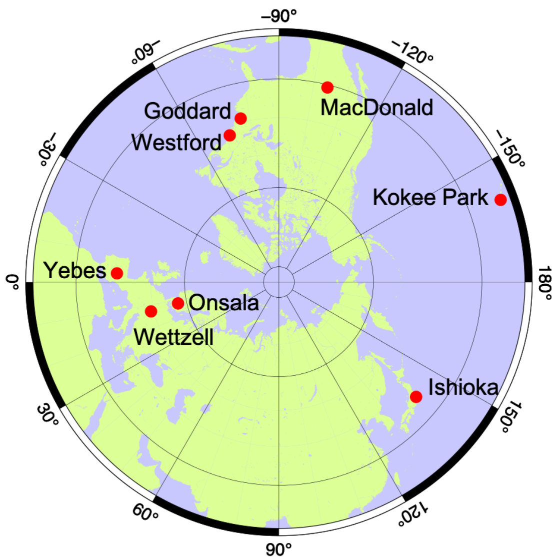

Fig. 1 The current operational VGOS network.

(VO) sessions were performed every second week. Since 2022, there is one VO session every week. The standard VGOS setup throughout 2019–2022 is to have scans of 30 s long, and the schedules are produced with the *sked* software (Gipson, 2010).

In addition to the VO series, the IVS also organizes 24-hour long so-called VGOS research-and-development (VR) sessions to investigate various aspects of the VGOS system, such as different frequency setups, different radio source catalogs, or shorter scan lengths. Such a VR session is of interest in this study.

3 The VGOS R&D Session VR2101

The VGOS R&D session VR2101 was observed on 29/30 July 2021 and involved seven VGOS stations at six sites: GGAO12M (Goddard, US), KOKEE12M (Kokee Park, US), MACGO12M (MacDonald, US), ONSA13SW (Onsala, SE), ONSA13NE (Onsala, SE), WESTFORD (Westford, US), and WETTZ13S (Wettzell, DE). All sites are equipped with co-located GNSS stations, often several ones, and at least OSO operates a WVR. As an example, Figure 2 presents the co-located instrumentation at OSO.

The VR2101 schedule was prepared with the software *VieSched++* (Schartner and Böhm, 2019) and re-

Fig. 2 Co-located instrumentation at the Onsala Space Observatory: The Onsala twin telescopes (left); ONSA and ONS1, two of the GNSS stations (middle); the microwave radiometer (right).

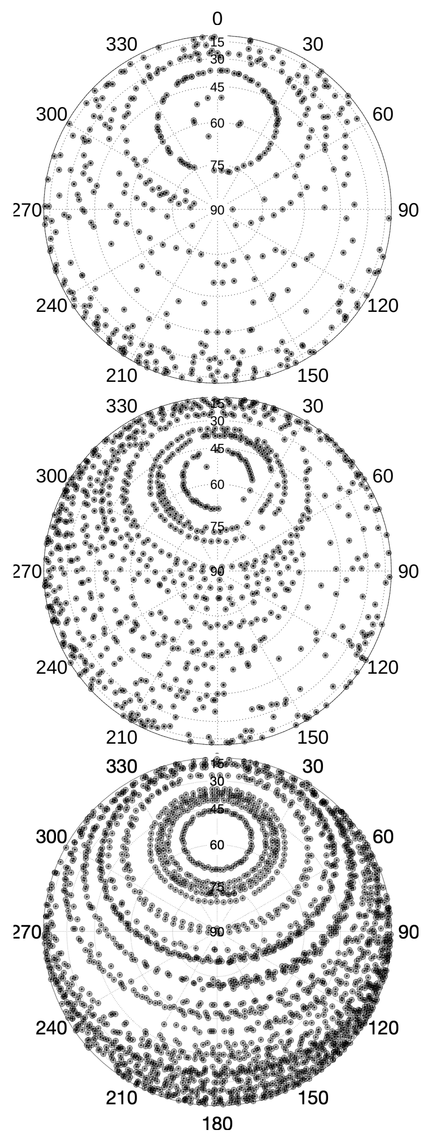

Fig. 3 Local sky coverage at the Onsala Space Observatory for R11101 (top), VO1203 (middle), and VR2101 (bottom).

sulted in 3,397 scans with a total of 23,040 observations. The goal of the session was to observe with short scan length in order to achieve as many observations as possible in different directions so that the local sky at the participating stations could be sampled densely.

To provide some insight into the sky coverage aspect, we can compare the sky coverage at OSO obtained for VR2101 to a standard R1 session and an operational VO session. OSO regularly contributes to R1 sessions with its 20-m diameter telescope ONSALA60. The legacy S/X session R11101 was observed in August 2021 involving seven stations and had 1,638 total scans with an average scan length of 75 s. During this session ONSALA60 participated in 436 scans. The session VO1203, observed in July 2021, involved seven VGOS stations. The total number of scans was 1,265 with an average scan length of 30 s. During this session, each of the OTT participated in 856 scans, i.e., two times more than during a standard R1 session. The session VR2101 involved seven VGOS stations and had in total 3,397 scans with an average scan length of 11 s. Each of the OTT participated in 2,436 scans, i.e., three times more than during a standard VO session. Figure 3 illustrates the distribution of observations in these different sessions.

4 Data Analysis

We analyzed the VGOS database of VR2101 with the *ASCOT* software (Artz et al., 2016) using a least-squares analysis. The analysis strategy followed the recommendations for the IVS ITRF2020 analysis (Gipson, 2020). A minimum elevation cutoff of 5° was used and the VMF3 mapping functions (Landskron and Böhm, 2018) were applied. Zenith hydrostatic delays (ZHD) were modeled using the locally observed pressure as recorded in the VLBI logfiles. Zenith wet delays (ZWD) corrections and horizontal gradients (GRAD) were estimated with a 5-minute temporal resolution using loose constraints. Zenith total delays (ZTD) were calculated by adding the a priori ZHD and estimated ZWD.

Data recorded with the co-located GNSS stations at all sites (except Westford where no GNSS data were available) were analyzed with the GipsyX software (Bertiger et al., 2020). The analysis used multi-GNSS data with the precise point positioning (PPP) approach (Zumberge et al., 1997). A minimum elevation cutoff of 7° was used and the VMF3 mapping functions (Landskron and Böhm, 2018) were applied. ZHD were modeled using standard pressure values, while ZWD corrections and GRAD were estimated with a 5-minute temporal resolution using loose constraints. Again, ZTD were calculated by adding the a priori ZHD and estimated ZWD.

The data of the WVR at OSO were analyzed with an in-house software. A sky-mapping analysis with an elevation cutoff of 25° was performed using unconstrained least-squares analysis (Elgered et al., 2019). ZWD and GRAD parameters were estimated with a 5-minute temporal resolution.

The WVR is not sensitive to the hydrostatic delay, i.e., the derived parameters are pure ZWD and wet horizontal gradients. There are various ways to compare WVR-derived atmospheric parameters to those derived from VLBI and GNSS. For this study we chose to compare ZTD and total horizontal gradients. To do so, we added ZHD based on the locally recorded pressure data at Onsala to the ZWD from the WVR analysis and added VMF3-referred horizontal hydrostatic gradients (VMF data server, 2022) based on ERA-Interim numerical weather model data to the WVR-derived gradients.

For comparsion purposes, we referred all ZTD values to the same reference height, which we chose to be the GNSS reference point at each station. We applied corresponding height corrections (Rothacher et al., 2011), since the reference points of the different techniques are usually at different heights, see Figure 4. For the GRAD parameters, no further corrections were needed, except the one described above for the WVR.

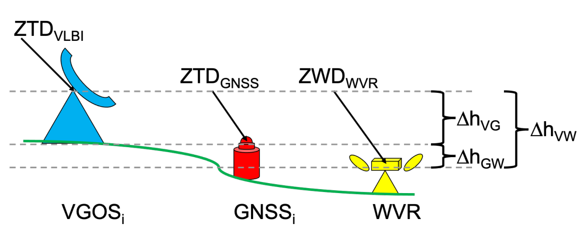

Fig. 4 Sketch showing a co-location site with three different instruments and the heights of their respective reference points. In order to meaningfully compare atmospheric parameters, corresponding height corrections need to be applied.

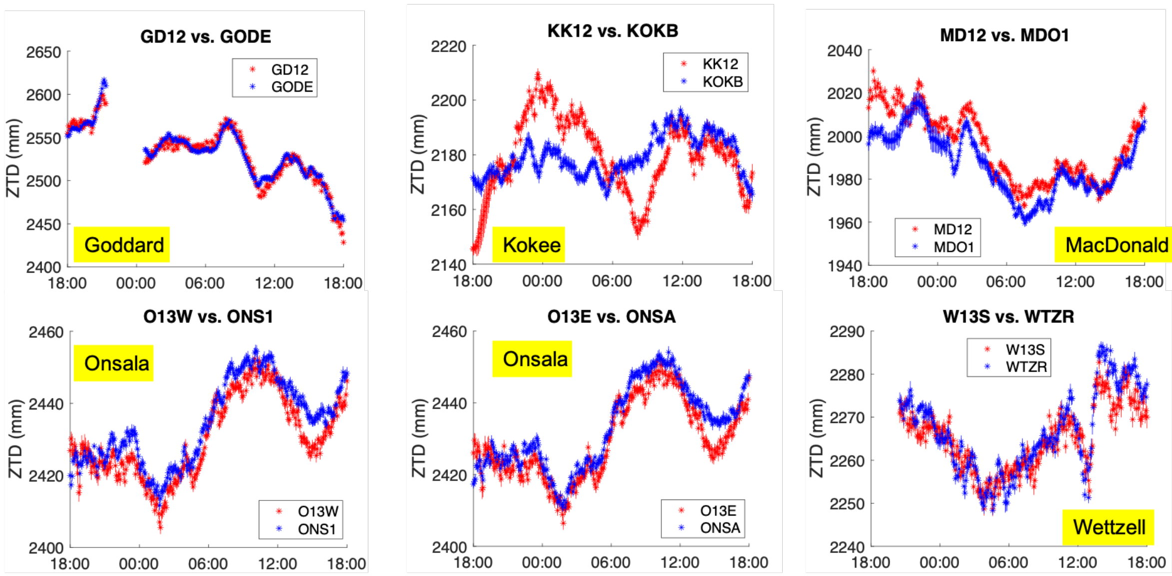

Fig. 5 Time series of ZTD with a 5-minute temporal resolution from VGOS (red) and GNSS (blue), respectively, for the six sites participating in VR2101 that had both techniques operating.

5 Results

Figure 5 presents comparisons for all six sites participating in VR2101 where both VGOS and GNSS data were available. ZTD from VGOS and GNSS are shown in red and blue, respectively. For most sites the red and blue curves show a high degree correlation with similarity even for short-term signatures. The exception is Kokee Park, where the GNSS results show less variability than the VGOS results. Statistical information on correlation coefficients, biases and weighted root-mean-scatter are provided in Table 1 for both ZTD and GRAD. Table 2 focuses on ZTD and GRAD derived from the co-located equipment at OSO including both twin telescopes (O13E, O13W), two GNSS stations (ONSA, ONS1), and the WVR.

While the correlation coefficients for ZTD are all larger than 0.91 (except for Kokee Park), the correlations for the gradient components are smaller and do not exceed 0.71. The correlation coefficients are generally smaller for the east than for the north gradients, which is unusual and contradicts previous studies, e.g., Ning and Elgered (2021). Furthermore, the presence of gradients varies significantly with time, and a 24-hour-long experiment is not a representative data set in order to draw general conclusions.

Table 1 Comparison of VGOS and GNSS: ZTD, east (GRE) and north (GRN) gradient components: ρ – correlation coefficient, δ – offset VGOS-GNSS (mm), $\Re$ – RMS difference (mm).

	ZTD			GRE			GRN		
Station	ρ	δ	$\Re$	ρ	δ	$\Re$	ρ	δ	$\Re$
GGAO12M	0.97	−0.8	7.5	0.54	0.0	1.2	0.62	0.7	1.6
KOKEE12M	0.33	0.2	13.4	0.32	−0.1	1.7	0.40	0.7	2.2
MACGO12M	0.93	7.7	9.6	0.25	0.0	1.1	0.37	−0.2	1.2
ONSA13NE	0.96	−3.2	4.6	0.20	−0.2	0.6	0.63	0.0	0.5
ONSA13SW	0.96	−2.6	4.1	0.22	−0.1	0.6	0.59	0.0	0.5
WETTZ13S	0.91	−1.6	4.5	0.45	0.1	0.6	0.71	−0.1	0.7

Table 2 Comparison of ZTD, east (GRE) and north (GRN) gradient components at the Onsala Space Observatory, from both OTT (O13W, O13E), two GNSS stations (ONSA, ONS1), as well as the microwave radiometer (WVR): ρ – correlation coefficient, δ – offset (mm), $\Re$ – RMS difference (mm).

	ZTD			GRE			GRN		
Stations	ρ	δ	$\Re$	ρ	δ	$\Re$	ρ	δ	$\Re$
O13E - O13W	0.99	−0.6	0.9	0.94	−0.0	0.2	0.96	0.0	0.2
ONSA - ONS1	0.99	−1.9	2.6	0.70	0.0	0.4	0.70	0.0	0.5
O13E - ONSA	0.96	−3.2	4.6	0.20	−0.2	0.6	0.63	0.0	0.5
O13E - ONS1	0.95	−4.5	5.8	0.22	−0.2	0.6	0.66	0.0	0.6
O13W - ONSA	0.96	−2.6	4.1	0.22	−0.1	0.6	0.60	0.0	0.5
O13W - ONS1	0.95	−4.0	5.3	0.11	−0.1	0.6	0.63	0.0	0.6
O13E - WVR	0.96	−11.1	12.2	0.26	−0.1	1.1	0.51	−0.1	0.7
O13W - WVR	0.96	−10.5	11.6	0.29	−0.8	1.1	0.50	−0.1	0.6
ONSA - WVR	0.97	−7.5	8.8	0.21	−0.6	1.0	0.47	−0.1	0.7
ONS1 - WVR	0.96	−5.6	7.4	0.16	−0.6	1.1	0.53	−0.1	0.7

6 Conclusions and Outlook

To our knowledge, for the first time, parameters describing the signal delay in the neutral atmosphere derived from the independent co-located techniques VLBI, GNSS, and WVR could be compared with an identical temporal resolution of 5 min. This high temporal resolution for VLBI was possible thanks to VR2101, with a large number of scans. High correlations, above 0.9, are achieved for the ZTD. The correlations for the horizontal gradients are lower and do not exceed 0.5 and 0.7 for the east and north components, respectively. Offsets and RMS differences are in the sub-millimeter to millimeter range. Further VGOS R&D sessions (VR sessions) are needed to understand the level of disagreement and its reasons.

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