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A Report on New VGOS Frequency Sequences Test Observations

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Abstract The IVS VGOS Technical Committee (IVS VTC) discussed several times on how to maximize the benefits of VGOS for geodesy and astrometry. Unused potential for improvement was identified in (a) increasing the synthesized bandwidth per VGOS observing band from 480 to 1024 MHz, and (b) distributing the four VGOS frequency bands between 3 and 14 GHz instead of only up to 10.6 GHz as is currently the case. In order to demonstrate the feasibility and possible benefits by using that potential, a series of fringe tests and test sessions were carried out in late 2024, and further tests were performed in early 2025. The results of these tests are expected to provide important input to the efforts of the IVS to anchor the observed frequency channels in the ITU Radio Regulations, so that in the future more consideration could be given to VGOS radio telescopes with regard to unwanted radio radiation. To this end, the optimum VGOS frequency configurations are sought as they are to be used in the long term. We report on the performance of these sessions and present preliminary results and recommendations for suitable frequency setups, where possible.

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1 Introduction

In recent years, VGOS operations have become routine. Consequently, previous activities of the European VGOS (EU-VGOS) collaboration (1) had been reduced to a minimum. However, after a VTC splinter meeting during the 13th International VLBI Service for Geodesy and Astrometry (IVS[1]) General Meeting in Tsukuba in March 2024, it was decided to resume work and start a series of test observations for new frequency sequences to expedite the search for an optimum broadband frequency configuration. These tests were carried out in April 2024 with the participation of

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

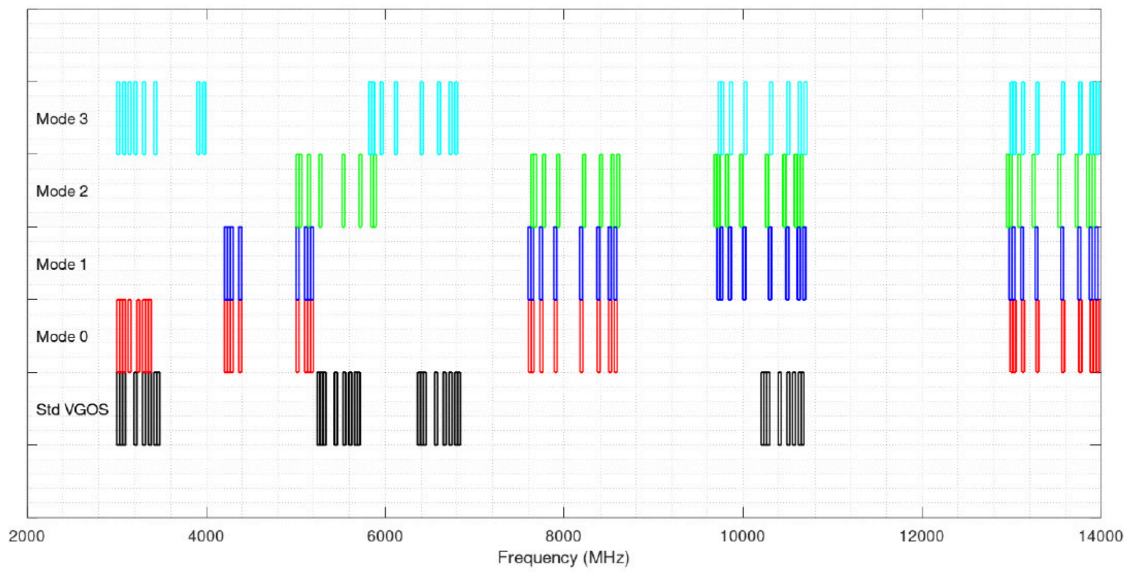

Fig. 1 The five frequency sequences, that were observed during the test sessions, are displayed starting with the standard VGOS mode on the bottom in black. The new modes (0 to 3, shown in red, blue, green, and turquoise) cover a frequency range between 3 and 14 GHz.

six European VGOS stations (NYALE13N, ONSA13NE, ONSA13SW, RAEGSMAR, WETTZ13S, RAEGYEB - hereafter referred to as Nn, Oe, Ow, Sa, Ws, Yj). A total of five different frequency setups were observed on five consecutive days, the first being the standard VGOS setup and four new versions covering frequency ranges from 3 to 14 GHz. A graphical display of the different frequency sequences is shown in Figure 1. Frequency tables of all test modes can be found in the presentation to this report (2). The sessions were correlated in Bonn.

Nn was only available on the first day due to an azimuth motor failure that occurred on the second day (and a planned maser maintenance on days 4 and 5). Since several additional problems arose during the observations, it was decided to repeat the tests in late November 2024, this time under the auspices of the IVS VGOS Technical Committee (VTC) and with participation of additional non-European stations (HARTVGS, HOBART12, KATH12M - hereafter referred to as Hv, Hb, Ke) including two sets of fringe test observations in order to fix possible issues preferably before the proper observation.

Due to a technical issue at Ws, the data for the full second test sessions were unusable. Thus, it was agreed to repeat the frequency tests while the second batch was analysed, to have a third set of measurements with possibly even more stations and data including some of the NASA stations (GGAO12M, KOKEE12M, MACGO12M - in short Gs, K2, Mg) and all AUSCOPE antennas (including YARRA12M - Yg) as well as ISHIOKA (Is) station. Table 1 gives an overview of all frequency sequence test sessions observed so far.

2 Method

One of the unused potentials for improving the VGOS frequency setup and the corresponding analytical benefits was to increase the synthesized bandwidth per observing band from 480 to 1024 MHz. Another option was to distribute the four VGOS frequency bands between 3 and 14 GHz instead of only up to 10.6 GHz as is currently the case. It was decided to include both in the frequency sequence test, knowing that not all stations were capable of handling either or both of the two options (e.g., Nn could not observe above 11 GHz, while Yj could not record a bandwidth of 1024 MHz).

The observation strategy for the first test setup (efseq0 - efseq4) was such that the observations were performed on five consecutive days, each day

Table 1 Session overview

Session name	Observing date	Observing mode	Participating stations	Duration [hrs]
efseq0	2024-04-08	VO mode	Nn, Oe, Ow, Sa, Ws, Yj	3
efseq1	2024-04-09	mode_0	Oe, Ow, Sa, Ws, Yj	3
efseq2	2024-04-10	mode_1	Oe, Ow, Sa, Ws, Yj	3
efseq3	2024-04-11	mode_2	Oe, Ow, Sa, Ws, Yj	3
efseq4	2024-04-12	mode_3	Oe, Ow, Sa, Ws, Yj	3
ft1-ft5	2024-11-12	all	(Hv,) Nn, Oe, Ow, Sa(, Ws)	-
ft1v2-ft5v2	2024-11-18	all	Hv, Nn, Oe, Ow, Sa, Ws	-
vt4330	2024-11-25	VO mode	Hb, Hv, Ke, Nn, Oe, Ow, Sa	6
vt4331	2024-11-26	mode_0	Hv, Nn, Oe, Ow, Sa	6
vt4332	2024-11-27	mode_3	Hv, Hb, Ke, Nn, Oe, Ow, Sa	6
vt4333	2024-11-28	mode_2	Hv, Hb, Ke, Nn, Oe, Ow, Sa	6
vt4334	2024-11-29	mode_1	Hv, Nn, Oe, Ow, Sa	6
ft1v3-ft5v3	2025-01-23	all	Gs, Hb, Hv, Is, K2, Ke, Mg, Nn, Oe, Ow, Sa, Ws, Yg	-
vt5034	2025-02-03	VO mode	Gs, Hb, Hv, Is, Ke, K2, Mg, Nn, Oe, Ow, Sa, Ws, Yg	6
vt5035	2025-02-04	mode_0	Gs, Hv, Is, K2, Mg, Nn, Oe, Ow, Sa, Ws	6
vt5036	2025-02-05	mode_3	Gs, Hb, Hv, Is, K2, Mg, Nn, Oe, Ow, Sa, Ws	6
vt5037	2025-02-06	mode_2	Gs, Hv, Is, K2, Ke, Mg, Nn, Oe, Ow, Sa, Ws	6
vt5038	2025-02-07	mode_1	Gs, Hv, Is, K2, Ke, Mg, Nn, Oe, Ow, Sa, Ws	6

using a different frequency setup, and the schedules corresponded to that of the first day. Thus, the analysis results could be directly compared to the standard VO setup. The scan duration was scheduled to be 60 seconds for the first hour and 30 seconds for the remaining hours. Sources were selected among two groups (cf. Table 2): group A contained often observed VGOS sources with good performance and each of them was scheduled four times if possible, group B consisted of additional often observed VGOS sources that were scheduled three times. 44 sources in total were scheduled for each session with ten sources taken from group A and 34 from group B. The schedules were prepared using VieSched++ (3).

Table 2 Source groups

Source group A	0059+581 0133+476 0202+319 0235+164 0322+222 0613+570 1751+288 1803+784 1846+322 2113+293
Source group B	0016+731 0019+058 0025+197 0109+224 0119+115 0307+380 0345+460 0415+398 0454+844 0529+483 0552+398 0602+673 0716+714 0800+618 1039+811 1053+704 1418+546 1636+473 1726+455 1746+470 1806+456 1849+670 1923+210 2000+472 2013+163 2144+092 2201+171 2214+241 2214+350 2215+150 2229+695 2309+454 2319+317 2325+093

The sessions were processed in the usual fashion, which is applied to the regular VGOS observations, with correlation in DiFX[2] version 2.5.5 and post-processing performed with HOPS[3] v3.24.

After the experience made with the execution of the first set of frequency sequence tests, it was decided to perform fringe tests for each observing mode (ft1 - ft5) well in advance to a second test series. For each mode, at least two scans were scheduled per station, all of them two minutes long with a one-minute gap in between. Moreover, since observing modes 0 and 3 seemed to be most promising, the order of the modes was changed from numerical order 0, 1, 2, 3 to modes 0, 3, 2, 1. Due to technical issues at two stations, the fringe tests were repeated one week later (ft1v2 - ft5v2).

The second set of frequency sequence tests (vt4330 - vt4334) included three southern hemisphere stations (Hv, Hb, Ke). The first hour can be seen as an extended fringe test since some stations missed the previous test or experienced technical problems. It included all stations with 90-second long scans. We especially tried to observe bright sources. Additionally, we tried to balance scans of Sa and Hb and in general tried to include the Australian stations as much as possible.

[2] DiFX - Distributed FX software correlator, (4)

[3] HOPS - Haystack Observatory Postprocessing System, https://www.haystack.mit.edu/haystack-observatory-postprocessing-system-hops/

Hours two to six were scheduled without the Australian stations. We used 30-second long scans, again trying to focus on bright sources but also balance the inclusion of Hv.
The third test series (vt5034 - vt5038) included three NASA stations (Gs, K2, Mg) and was preceded by another fringe test session (ft1v3 - ft5v3). The observing strategy was following that of the previous frequency sequence test session. The US stations were added only during the first two hours of the experiment except for K2. This way, we tried to reduce the risk of failure while also reducing the impact of station drop-out due to problems in the frequency setup.

3 Results

A more detailed description on the performance of each station can be found in (2). Here, we will merely focus on the overall results of correlation and analysis.

3.1 Summary efseq1 - efseq4

Among various problems, which arose during the first set of test sessions, the most notable issue turned out to be the original frequency selection of mode 0 violating the fourfit grid constraints. The uniform grid, that fourfit chooses, is a function of the frequency setup and should (a) not consist of more than 8192 points and (b) the total number of points should be a power of two. According to John Barrett (priv. comm.), the simplest fix would be to adjust the band LOs so that the channels all lie on frequency points such that the frequency of channel n, (f_n) is given by: $f_n = f_0 + N * (32\ \text{MHz})$ where f_0 is the first channel's frequency, and N is some integer. Hence, it was decided to shift band B up by 12 MHz (start @4216.4 MHz) and band C by 8 MHz (start @7608.4 MHz) for any follow-up observations.
Interestingly, even though Yj was only capable of recording half of the bandwidth of 1024 MHz, the post-processing chain seemed to work for all test modes. However, since it did not work for all stations, the final step of fringe-fitting was not performed and no further analysis was carried out except for efseq0 (VGOS standard mode).
Disregarding the frequency limitations at some stations, one major argument against observing up to 14 GHz was that the phase calibration tones were expected to be too weak. Hence, Frédéric Jaron tested the behaviour of the phase cal signal in the efseq sessions with particular emphasis on band D (13 to 14 GHz). His conclusions were that the power of the phase-cal signal is greatly reduced towards high frequencies as was expected. Nevertheless, the extracted phase-cal signals appear stable, also at high frequencies. Moreover, applying the phase-cal signal increases the signal-to-noise ratio of the observations. Consequently, similar studies should be performed with all international VGOS stations.

3.2 Summary Fringe Tests and vt4330 - vt4334

To help the stations get acquainted with the different frequency setups and switching between the modes, in particular if done by means of recabling, we decided to do a fringe test two weeks before the second observing session took place. The importance of such tests became quite obvious: due to numerous mishaps, it was decided to run another test one week later. One achievement was that a frequency setup error at Nn could be corrected.
The Australian stations did not participate in the fringe tests but succeeded in doing some local testing instead. In contrast, Ws only managed to join the fringe tests but missed the actual observations due to a Helium compressor failure.

- vt4330: The post-processing of the session in standard VGOS mode worked for all stations except Hb which is certainly owing to the short observing span of only the first hour. Analysis problems occurred for Hv (station had huge residuals), Hb and Ke (the observations were noisy). These stations were deselected from the routine solution.
- vt4331: Post-processing for frequency sequence mode 0 was successful for all stations and all stations were included in routine solution for analysis (with Hv observations being noisy).
- vt4332: Frequency sequence mode 3 had issues in post-processing only for stations Hb and Ke. Nevertheless all stations were included in the routine solution. One peculiarity for this session was the recording mode that the Onsala Twin Telescopes (OTTs) chose in order to avoid recabling during the different observing modes: the data were recorded in 8 datastreams with 80 channels, 16 of which being idle channels. Since HOPS is currently not able to handle more than 64 channels, the phase cals had not been treated properly in the conversion

from SWIN (correlator output) files to MkIV format and, thus, it looked as if there was not pcal present in band D for the OTTs which is, however, not the case.
- vt4333: For frequency sequence mode 2, there were problems with the proxy cable calibration extraction from the correlated data for Hb and Ke. In the analysis, it turned out that Hv had again huge residuals and was deselected from routine solution together with Hb and Ke.
- vt4334: Even though the post-processing worked for all stations with frequency sequence mode 1, Hv had again very noisy observations and the WRMS were huge (∼300 ps). Moreover, Sa showed bi- and tri-modal patterns of the residuals and ∼56 % of the potentially usable observations were deselected.

3.3 *Preliminary Results for vt5034 - vt5038*

For the third batch of frequency sequence test observations, a fringe test was appointed 11 days prior to the observing campaign which was again accompanied by various issues. For example, the NASA stations were not yet familiar with the correct frequency setup for each mode and, thus, observed all fringe tests with the standard VGOS setup so that no fringes could be expected. Due to technical issues, Ws was not able to participate and Nn had again used a wrong frequency setup which could fortunately be detected and corrected before the proper observations started. However, due to the late arrival of some of the data, the vt503X sessions had already started before the fringe test correlations could be finished.
The NASA stations are currently not capable of observing up to 14 GHz. Moreover, their bandwidth is limited to 512 instead of 1024 MHz. Nevertheless, thanks to the help of Ed Himwich, a setup could be worked out such that - depending on the mode - at least bands A and B could partly and band C could fully be covered.
In the meantime, Nn underwent an upgrade of their receiver and is now able to observe up to 14 GHz.
By the time of the EVGA meeting, the processing of the VGOS standard mode session was completed and work on modes 0 and 3 had already started, so that some preliminary results could be presented.

- vt5034: In total, 75.5% of the station data was used for the analysis where Hv showed huge residuals (the WRMS were 400ps) and Ws had a late start and then 2 hrs of non-detections, so that only 3 hrs of observations were included in the routine solution.
- vt5035: Fringes could be found for Gs and K2 and also for Nn in band D. Mg had an auto-stow problem, as a result, there was a control time-out after 30 seconds and the antenna shut down. Hence, the station cannot be included in the processing.
- vt5036: Ws erroneously observed with mode 1 instead of mode 3. Fringes could be found for K2 and Mg and also again for Nn in band D.

Some example fringe plots for vt433x and vt503x are presented in (2).

4 Conclusions and outlook

Analysis results suggest that modes 0 and 3 are the most promising ones because all stations could be included in the routine solution. But in view of the persisting issues for some of the stations, follow-up observations deem necessary. If so, several options could be considered: one could think of fringe tests only and later a 24 hours VR session for one or two modes. In case, the tests should be continued as before, fringe tests should either be scheduled earlier or data shipment needs to be performed faster. Concerning the calibration strategy, it might be sufficient to schedule less calibration scans, but for all stations at least three or preferably the double amount at the session start, middle, and end. In order to avoid further confusion with the observing modes, it might be advisable to change again the observing order, rename the modes to better reflect the non-numerical order or skip worse performing modes completely.

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