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“PROPOSAL FOR NEW VGOS FREQUENCY TESTS”

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Rationale

The global geodetic VLBI network is a unique sensor for providing precise positioning of Earth in the universe and for monitoring Earth rotation. It provides essential data for geodetic reference frames and the difference between the ephemeris time scale and the atomic time scale.

The VLBI Global Observing System (VGOS) had been designed to address the needs in global geodesy for precise reference frames for this century. The requirement of globally 1mm accuracy for positioning and rate determinations down to 0.1 mm/year was only possible by setting up the VGOS infrastructure. Meanwhile several VGOS radio telescope sites have been built and provide data.

The VGOS system design introduced broadband receivers capable of observing radiosources in the range of 2-14 GHz. The resolution of the VLBI delay measurement is inverse of the spanned bandwidth. First VGOS observations used a configuration from 3.0 to 10.7 GHz. The full potential to observe frequencies above 10.7 GHz has not yet been exploited.

Goals and objectives of testing new VGOS frequency configurations

- Arrange for a series of test observations using new frequency setups
- Expanding the observed bandwidth from 3.0-10.7 to 3.0-14 GHz
- Expanding the sub-band bandwidth (A, B, C, D) from 480 MHz to 1 GHz
- Awareness of existing technical limitations at stations with respect to the VGOS-specifications
- Preparation at stations to become VGOS compliant
- Training of staff at stations and correlators with new setups
- Identify shortcomings in the VGOS processing chain
- Analysis of unwanted electro-magnetic emissions in new observation channels or adjacent bands
- Prepare a decision on the (new) VGOS standard observation mode, whose observation channels should be used in spectrum management for future protection initiatives

- Analysis of concerning geodetic products and evaluate improvements and advantages/disadvantages over the 3.0-10.7 GHz configuration
- Orientation for new VGOS radio telescope projects how to specify future broadband feeds and receivers

Motivation of the tests.

Regular VGOS observations (VO's) are currently conducted in four sub-bands ranging from 3 GHz to 14 GHz, each with 480 MHz:

- Sub-band A: 3000.4 – 3480.4 MHz
- Sub-band B: 5240.4 - 5720.4 MHz
- Sub-band C: 6360.4 – 6840.4 MHz
- Sub-band D: 10200.4 – 10680.4 MHz

The lower frequency limit of 3 GHz was chosen to mitigate the impact of ubiquitous radio frequency interference (RFI) below this threshold, originally specified as 2 – 14 GHz for VGOS. The upper limit of 10.68 GHz is constrained by the limited frequency performance of certain QRFH receivers and the use of satellite downlinks in 10.7-12.7 GHz.

It is well-known that maximizing bandwidth reduces delay uncertainty, enhancing geodetic accuracy. Given the constraints of unwanted electromagnetic emissions and receiver performance, the current frequency selection is a practical compromise. However, newer receivers, especially those deployed in European VGOS stations, now support operations up to 14 GHz with improved performance. This opens the possibility of testing theory in practice by expanding the frequency range to further reduce delay uncertainty and improve geodetic data quality.

Furthermore, new radio communication services are being allocated (or are under consideration for allocation) within the VGOS 2 – 14 GHz range. These services pose a risk of interference, potentially degrading receiver performance or even rendering radio telescopes inoperable. To safeguard VGOS operations, proposed frequency plans should avoid existing and anticipated radio service allocations.

International organizations emphasize the need of geodetic observations which then also requests their protection:

- UN Resolution 69/266 urges member states to enhance the global geodetic reference frame through national and intergovernmental cooperation. It must be recognized that the VLBI Global Observing System (VGOS) is essential for reference frames and hence a direct response to this call.
- IAU Resolution B1 (2021) and IUGG Resolution 1 (2023) advocate for the protection of geodetic radio astronomy from radio frequency interference. These resolutions encourage collaboration among astronomers, geodesists, and related scientists to proactively safeguard space geodesy.

To preserve the accuracy and reliability of VGOS observations, regulatory measures should protect VGOS sites from disruptive radio services (5G, mega-constellations, HIPS, …). The CRAF-VGOS group is actively engaging with the national administrations and the ITU-R to ensure VGOS specifications and operational needs are recognized.

Key milestones in this effort include:

- ITU-R Report RA.2507-0 *Technical and operational characteristics of the existing and planned Geodetic Very Long Baseline Interferometry* – Successfully published, detailing VGOS technical and operational characteristics.
- ITU-R Recommendation on geodetic VLBI – Currently in progress, targeted for completion by March 2025 under WP7D.
- WRC-27 Proposal – Following the recommendation, a joint proposal will be prepared for inclusion as an Agenda Item at the World Radiocommunication Conference (WRC-27). If approved, a four-year study cycle will analyze the coexistence of VGOS with other radio services, culminating in an ITU-R decision at WRC-31 regarding VGOS frequency allocations.

Given all these objectives, the proposed tests are essential for defining an optimal frequency plan that aligns with VGOS requirements. The results will prepare a decision of the IVS on their future observation channels for the purpose of spectrum management. They also will directly contribute to the ITU-R Recommendation and subsequent regulatory studies, ensuring long-term operational stability and geodetic precision for VGOS.

These were the underlying reasons for the performance of these tests, as discussed in the VTC splinter meeting during the last IVS-GM in Japan.

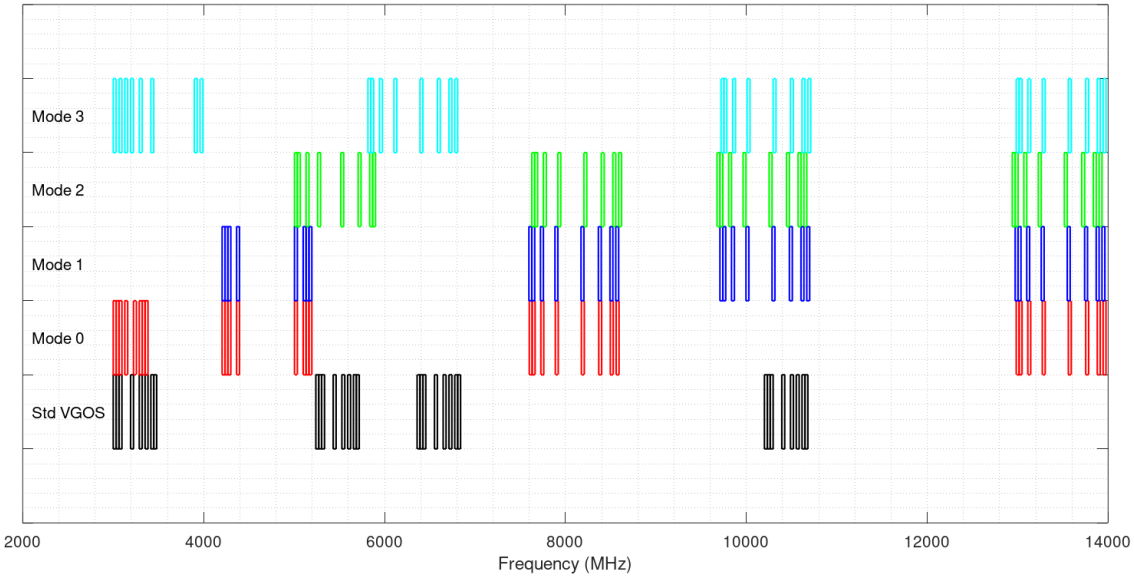
New frequency plans.

Four different frequency plans (Mode 0 to Mode 3) were prepared by J. A. López-Pérez following these constraints:

- Avoid existing and anticipated radio service allocations
- When possible, each sub-band will span to about 1 GHz, instead of 480 MHz
- Respect the Golomb ruler (as much as possible) so that no two pairs of channels are the same distance apart.
- Extend the spanned bandwidth up to 14 GHz.

The new frequency plans were revised by Bill Petrachenko and John Barret to assess any potential issue with Fourfit. The current plans are free from Fourfit constraints.

The following figure shows the channels for each mode, together with the channels for the current VGOS set-up. The 5G and mega-constellation frequencies have been avoided.



Annex I collects all the channel frequencies for each proposed observing mode.

According to the analysis from Hayo Hase (From Delay to Millimeter, 2024-05-31), Mode 0 and Mode 3 are the ones that provide more improvement in delay uncertainty (27% and 25%, respectively) with respect to the VGOS standard plan. See the table below from his document (mode 00 is the current Std.-VGOS frequency plan).

$$\sigma_\tau = \frac{2.65}{2\,\pi * RMS_{bandwidth}[GHz] * SNR}[ns]$$

SNR		20	30	40	
	$RMS_{bandwidth}$ [GHz]	Delay uncertainty σ_τ [ps]			improvement [%]
mode 00	2.9288	7.2	4.8	**3.6**	reference
mode 0 2024 04 09	4.0208	5.2	**3.5**	**2.6**	27.2%
mode 1 2024 04 10	3.2562	6.5	4.3	**3.2**	10.1%
mode 2 2024 04 11	2.9844	7.1	4.7	**3.5**	1.9%
mode 3 2024 04 12	3.8988	5.4	**3.6**	**2.7**	24.9%
		blue = target 3-4 ps reached			
		purple = better than proposed target			

Procedures

IVS is using its infrastructure on a volunteer basis. VGOS stations are invited to contribute telescope and preparation time for the tests.

New tests are announced in function of the previous achieved experiences and results.

All tests are under the guidance of the chair of the IVS-VTC, Jose Antonio Lopez Perez, with the support from VTC members.

Schedules and source catalogue

- The schedules were prepared by Matthias Schartner, and the source catalogue was agreed between Matthias Schartner and Frederic Jaron.
- Cynthia Thomas updates the master schedule to include all these tests.

Correlation and post-processing:

- The correlation is performed at the Bonn correlator. This task is led by Simone Bernhart and Yoon Kyung Choi, with support from Frederic Jaron for post-processing.

Data analysis:

- Esther Azcue and Mariana Moreira from IGN VLBI Analysis Group.
- Onsala group will perform analysis too
- Arthur Neill offered to analyze the data, as well.
- This analysis is required to compare the quality of the products. It was missing in the tests from April, due to the identified issues, but it should be done with the data from batches 2 and 3.

References:

UN GA Resolution 69/266: A global geodetic reference frame for sustainable development, 2015 https://ggim.un.org/documents/a_res_69_266_e.pdf

IAU GA Resolution B1 in support of the protection of geodetic radio astronomy against radio frequency interference, 2021
https://www.iau.org/static/archives/announcements/pdf/ann21040a.pdf

IUGG GA Resolution 1: Improving protection of Geodetic Observatories from Active Radio Services, 2023 https://iugg.org/wp-content/uploads/2023/09/2023_IUGG-GA-Resolutions.pdf

Hase, H.: From delay to millimeter, (unpublished note), 2024

Annex I: Table with channel frequencies for the tests

	EFSEQ0_VGOS_standard		EFSEQ1-Mode_0		EFSEQ2-Mode_1		EFSEQ3-Mode_2		EFSEQ4-Mode_3	
	fstart (MHz)	fstop (MHz)	fstart (MHz)	fstop (MHz)	fstart (MHz)	fstop (MHz)	fstart (MHz)	fstop (MHz)	fstart (MHz)	fstop (MHz)
Band A	3448,4	3480,4	3352,4	3384,4	5164,4	5196,4	5868,4	5900,4	3960,4	3992,4
	3416,4	3448,4	3320,4	3352,4	5132,4	5164,4	5836,4	5868,4	3896,4	3928,4
	3352,4	3384,4	3288,4	3320,4	5100,4	5132,4	5708,4	5740,4	3416,4	3448,4
	3288,4	3320,4	3224,4	3256,4	5004,4	5036,4	5516,4	5548,4	3288,4	3320,4
	3192,4	3224,4	3128,4	3160,4	4364,4	4396,4	5260,4	5292,4	3192,4	3224,4
	3064,4	3096,4	3064,4	3096,4	4268,4	4300,4	5132,4	5164,4	3128,4	3160,4
	3032,4	3064,4	3032,4	3064,4	4236,4	4268,4	5036,4	5068,4	3064,4	3096,4
	3000,4	3032,4	3000,4	3032,4	4204,4	4236,4	5004,4	5036,4	3000,4	3032,4
Band B	5688,4	5720,4	5176,4	5208,4	8556,4	8588,4	8588,4	8620,4	6776,4	6808,4
	5656,4	5688,4	5144,4	5176,4	8492,4	8524,4	8524,4	8556,4	6712,4	6744,4
	5592,4	5624,4	5112,4	5144,4	8364,4	8396,4	8396,4	8428,4	6584,4	6616,4
	5528,4	5560,4	5016,4	5048,4	8172,4	8204,4	8204,4	8236,4	6392,4	6424,4
	5432,4	5464,4	4376,4	4408,4	7884,4	7916,4	7916,4	7948,4	6104,4	6136,4
	5304,4	5336,4	4280,4	4312,4	7724,4	7756,4	7756,4	7788,4	5944,4	5976,4
	5272,4	5304,4	4248,4	4280,4	7628,4	7660,4	7660,4	7692,4	5848,4	5880,4
	5240,4	5272,4	4216,4	4248,4	7596,4	7628,4	7628,4	7660,4	5816,4	5848,4
Band C	6808,4	6840,4	8568,4	8600,4	10668,4	10700,4	10636,4	10668,4	10680,4	10712,4
	6776,4	6808,4	8504,4	8536,4	10604,4	10636,4	10572,4	10604,4	10616,4	10648,4
	6712,4	6744,4	8376,4	8408,4	10476,4	10508,4	10444,4	10476,4	10488,4	10520,4
	6648,4	6680,4	8184,4	8216,4	10284,4	10316,4	10252,4	10284,4	10296,4	10328,4
	6552,4	6584,4	7896,4	7928,4	9996,4	10028,4	9964,4	9996,4	10008,4	10040,4
	6424,4	6456,4	7736,4	7768,4	9836,4	9868,4	9804,4	9836,4	9848,4	9880,4
	6392,4	6424,4	7640,4	7672,4	9740,4	9772,4	9708,4	9740,4	9752,4	9784,4
	6360,4	6392,4	7608,4	7640,4	9708,4	9740,4	9676,4	9708,4	9720,4	9752,4
Band D	10648,4	10680,4	13944,4	13976,4	13932,4	13964,4	13900,4	13932,4	13944,4	13976,4
	10616,4	10648,4	13880,4	13912,4	13868,4	13900,4	13836,4	13868,4	13880,4	13912,4
	10552,4	10584,4	13752,4	13784,4	13740,4	13772,4	13708,4	13740,4	13752,4	13784,4
	10488,4	10520,4	13560,4	13592,4	13548,4	13580,4	13516,4	13548,4	13560,4	13592,4
	10392,4	10424,4	13272,4	13304,4	13260,4	13292,4	13228,4	13260,4	13272,4	13304,4
	10264,4	10296,4	13112,4	13144,4	13100,4	13132,4	13068,4	13100,4	13112,4	13144,4
	10232,4	10264,4	13016,4	13048,4	13004,4	13036,4	12972,4	13004,4	13016,4	13048,4
	10200,4	10232,4	12984,4	13016,4	12972,4	13004,4	12940,4	12972,4	12984,4	13016,4

STATUS OF NEW VGOS FREQUENCY TESTS

2025.02.11

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After the IVS-GM 2024 in Tsukuba, Japan, a first fringe test was carried out from April 08-12, 2024. Based on that experience a second test was conducted on November 25-29,2024. A further test with different scan length was scheduled for February 3-7, 2025.

The status and short results are given below.

Test log

Three batches of tests have been performed so far.

1. Test – Fringe test

Table 1 shows the information about the first batch.

Date	Session	Freq. plan	Duration	Stations	Comments
2024-04-08	EFSEQ0	Std. VGOS	3 h	Nn Oe Ow Sa Ws Yj ~~Wn~~	-
2024-04-09	EFSEQ1	Mode 0	3 h	Nn Oe Ow Sa Ws Yj ~~Wn~~	-
2024-04-10	EFSEQ2	Mode 1	3 h	Nn Oe Ow Sa Ws Yj ~~Wn~~	-
2024-04-11	EFSEQ3	Mode 2	3 h	Nn Oe Ow Sa Ws Yj ~~Wn~~	-
2024-04-12	EFSEQ4	Mode 3	3 h	Nn Oe Ow Sa Ws Yj ~~Wn~~	-

Table 1: First batch of new frequency tests.

The main issues during the first batch of tests were presented by Simone Bernhart during the VTC telecon from 2024.06.06:

- Yj only recorded 512 MHz bandwidth, due to backend constraints, so there are 4 missing channels per sub-band
- Sa was observing with nearby radar ON, but the effect is mitigated by HTS filters
- Ws had a polarization swap and issues with one LNA
- Oe/Ow had problems in the range 3.2 -6.8 GHz and a late start in EFSEQ0
- Nn was not operational for EFSEQ1 to EFSEQ4 due to maser maintenance.
- Mode 0 suffered a bug in the computation of channel frequencies leading to Fourfit issues. It has been solved since then. It is not present in the remaining batches.

Some suggestions were made for the following batch of tests:

- Solve the Fourfit constraints, as mentioned above.
- Include additional calibration scans with longer integration time (from 60 s to 90 s scan every hour)
- Increase observing time from 3 h to 6 h to get more scans/data.

2. Test – VGOS –mode trial

The status of the second batch of tests at the time of this document is summarized in Table 2. Yj was not available due to a breakage of the azimuth cable-wrap, and Ws suffered helium compressor problems.

Date	Session	Freq. plan	Duration	Stations	Comments
2024-11-25	VT4330	Std. VGOS	6 h	Hb Hv Ke Nn Oe Ow Sa ~~Ws~~ ~~Yj~~	Processing session
2024-11-26	VT4331	Mode 0	6 h	Hv Nn Oe Ow Sa ~~Ws~~ ~~Yj~~	Waiting on media
2024-11-27	VT4332	Mode 3	6 h	Hb Hv Ke Nn Oe Ow Sa ~~Ws~~ ~~Yj~~	Waiting on media
2024-11-28	VT4333	Mode 2	6 h	Hb Hv Ke Nn Oe Ow Sa ~~Ws~~ ~~Yj~~	Waiting on media
2024-11-29	VT4334	Mode 1	6 h	Hv Nn Oe Ow Sa ~~Ws~~ ~~Yj~~	Waiting on media

Table 2: Second batch of new frequency tests.

A previous fringe test was performed on Nov. 12th, 2024, according to the following schedule. The given scan duration is approximate, but not larger than 4-6 minutes for each mode. Gaps of about 1.5 h are included for backend rewiring and reconfiguration between scans.

UT Time	Freq. Plan
8:00	Mode VGOS standard
8:02	
9:30	Mode 0
9:32	
11:00	Mode 3
11:02	
12:30	Mode 2
12:32	
14:00	Mode 1
14:02	

The status of the third batch of tests at the time of this document is summarized in Table 3. The same previous fringe tests were performed on Jan 23rd.

Date	Session	Freq. plan	Duration	Stations	Comments
2025-02-03	VT5034	Std. VGOS	6 h	Gs Hb Hv Is K2 Ke Mg Nn Oe Ow Sa Ws Yg	Waiting on media
2025-02-04	VT5035	Mode 0	6 h	Gs Hv Is K2 Ke Mg Nn Oe Ow Sa Ws	Waiting on media
2025-02-05	VT5036	Mode 3	6 h	Gs Hb Hv Is K2 Mg Nn Oe Ow Sa Ws	Waiting on media
2025-02-06	VT5037	Mode 2	6 h	Gs Hv Is K2 Ke Mg Nn Oe Ow Sa Ws	Waiting on media
2025-02-07	VT5038	Mode 1	6 h	Gs Hv Is K2 Ke Mg Nn Oe Ow Sa Ws	Waiting on media

Table 3: Third batch of new frequency tests.

During the preparation of the third batch, some issues appeared with the "$PROCS" for NASA stations. As these stations can't cover the 13 GHz band, they purposed RDBE-D to cover the upper frequencies of Band C for those modes with channels in the 13-14 GHz range. Of the possible choices, this increases the spanned bandwidth slightly.

Final remarks:

- Simone Bernhart volunteered to lead a presentation about the results of these tests in the next EVGA meeting, to be held in Matera (6-10 April 2025).