Alternative Frequency Setups for VGOS

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Abstract In the search for an appropriate frequency setup for VGOS observations, arguments from three different perspectives are discussed: (1) radio regulation, (2) smart selection of the frequency sequence using the Golomb ruler, and (3) consistency requirements for the ICRF.

Keywords VGOS, frequency setup

1 Introduction

During decades, legacy geodetic VLBI observations with dualband S/X receivers have been made using the same frequency configuration. The advantage is a consistent time series of radio sources for the ICRF as well as consistent time series of station positions for the ITRF. There is no need to question it. The VGOS observation system introduces broadband receivers extending the frequency range from the S/X-bands to the range of 2–14 GHz, the number of observation channels from 14 to 32, and the bandwidth of each channel from 16 to 32 MHz. This opens up the question of: **Where to put the VGOS observation channels?** For the attempt to answer we consider three perspectives:

1. an allocated or available spectrum,
2. optimizing the precision analyzing with the group delay resolution function,
3. consistency with the ICRF.

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2 Allocated or Available Spectrum

The ITU Radio Regulations allocate spectral bands to PRIMARY and secondary services. Bands are allocated for up to six different services in the VGOS range of 2–14 GHz (Figure 1). There are no "not-allocated" bands for VGOS exclusively available.

In Figure 1 the orange-red rectangles mark allocations to MOBILE telecommunication while the green fields are related to FIXED broadcast services, both of which are a major threat for radio quietness at radio telescope sites. The allocated bandwidths for the Radio Astronomy Service (RAS) are marked with red and sum up to 250.9 MHz (Table 1). The minimum accumulated bandwidth requirement of VGOS is 1,024 MHz instead. VGOS has to tolerate any other active service according to the radio regulations and receives a certain protection only in bands assigned to the Radio Astronomy Service (RAS).

Another strategy to achieve protection for the observation bands of VGOS would be for the IVS to come up with a fixed frequency setup of 32 channels, which should be then protected by footnotes in the radio regulations. A fixed frequency setup would be adequate for the long-term time series for the ICRF and UT1 but would give away the possibility of escaping in a flexible manner from increasing RFI. Emissions from outside of the VGOS channel bands might still interfere and be detrimental to the VGOS observations, though.

As a matter of fact VGOS is a *global* network, but radio regulations are introduced by *national* authorities, although mostly according to the agreements reached by the World Radio Conferences. The introduction of 5G in the 3.6 GHz bands shows different allocations between nations. This makes it even harder to maintain a common VGOS frequency setup for the

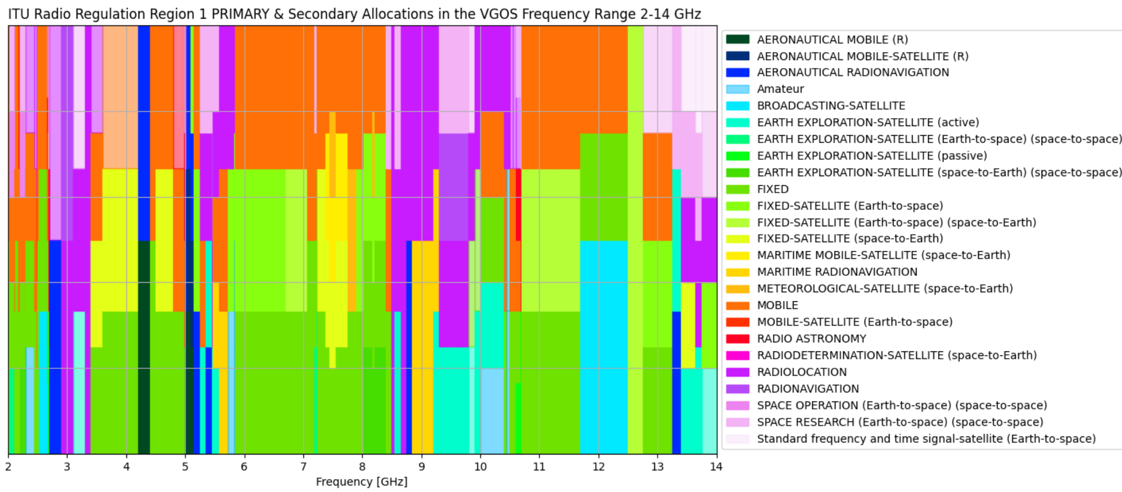

Fig. 1 Frequency allocation in the range of 2–14 GHz in ITU Region 1 (Europe-Africa). (There exist only small differences with respect to Regions 2 and 3.) Free frequency bands for VGOS are not available.

global VGOS network as we encounter different RFI situations among the VGOS countries.

This situation suggests for ideal VGOS sites to be located in a radio-quiet-zone (RQZ) or at least in a coordination zone in which conflicts of interest can be regulated by the authorities.

Table 1 Spectral bands in the VGOS range of 2–14 GHz allocated to the Radio Astronomy Service with different levels of protection. VGOS requires at least 1,024 MHz of bandwidth to reach its goals. [ITU-R Radio Regulations]

Frequency [MHz]	Bandwidth	Allocation, Footnote
2655 – 2670	15	secondary, No. 5.149, 5.208B
2670 – 2690	20	secondary, No. 5.149, 5.208B
2690 – 2700	10	PRIMARY, No. 5.340, 5.413, 5.20B
3260 – 3270	7	No. 5.149
3332 – 3339	7	No. 5.149
3345.8 – 3352.5	6.7	No. 5.149
4825 – 4835	10	secondary, No. 5.149
4950 – 4990	40	secondary, No. 5.149
4990 – 5000	10	PRIMARY, No. 5.149, 5.402, 5.443B
6650.0 – 6675.2	25.2	No. 5.149, 5.458A
10600 – 10680	80	PRIMARY, No. 5.149
10680 – 10700	20	PRIMARY, No. 5.340
total:	**250.9**	**RAS bandwidth in 2-14 GHz**

3 Optimizing the Precision Analyzing with the Group Delay Resolution Function

The VGOS concept was developed in order to overcome limitations in the time resolution of the S/X measurements and to improve the radio telescope infrastructure by a network of more homogeneous instruments (Table 2). One leverage for increasing the accuracy is to increase the observation bandwidth. This includes observing a wider spectrum and observations up to Ku-band (up to 14 GHz). Observing with 32 channels (instead of 14) with 32 MHz bandwidth (instead of 16) promises much more information per time unit, and hence the duration of scans can be shortened. More observations per time interval enable a denser atmosphere sampling. The higher temporal resolution resolves frequency dependent source positions (source structure).

Table 2 Time resolution is inversely proportional to the observed bandwidth.

	spanned bandwidth	**resolution**
full potential VGOS	2.0 ... 14.0 GHz = 12.0 GHz	83 ps
VGOS-480, VGOS-992	3.0 ... 10.7 GHz = 7.7 GHz	130 ps
legacy X-band	8.213 ... 8.933 GHz = 0.720 GHz	1388 ps

Table 3 lists the known (legacy S/X from R1 sessions, VGOS-480 as a benchmark setup, and VGOS-992) and some alternative frequency setups (G8-1-2, G22+10, and G22) which were developed by [1].

Table 3 Three known and three alternative frequency setups for geodetic VLBI. The legacy S/X setup is typical for the R1 sessions. VGOS-480 is the VGOS benchmark setup. and VGOS-992 covers a wider bandwidth for each block of eight channels compared to VGOS-480. The alternative setup G8-1-2 contains the application of the Golomb ruler of the order 8 for the spacing where the two upper channels are downshifted to match the available block bandwidth of 992 MHz (to be comparable with VGOS-992) but extended to Ku-band. G22 uses the Golomb ruler of the order 22 using only 22 channels, with G22+10 adding ten channels to G22 in a least redundant way in order to make use of the hardware available.

leg. S/X	VGOS-480	VGOS-992	G8-1-2	G22+10	G22
2225.99	3000.4	3000.4	3000.4	2576.4	2576.4
2245.99	3032.4	3032.4	3032.4	2608.4	2608.4
2265.99	3064.4	3064.4	3128.4	2864.4	2864.4
2295.99	3192.4	3288.4	3288.4	3024.4	3024.4
2345.99	3288.4	3576.4	3480.4	3632.4	
2365.99	3352.4	3768.4	3704.4	3952.4	3952.4
	3416.4	3896.4	3896.4	4176.4	
	3448.4	3960.4	3960.4	4496.4	
8212.99	5240.4	5240.4	5304.4	4816.4	4816.4
8252.99	5272.4	5272.4	5336.4	5968.4	5968.4
8352.99	5304.4	5368.4	5432.4	6480.4	6480.4
8512.99	5432.4	5528.4	5592.4	6544.4	6544.4
8732.99	5528.4	5816.4	5784.4	6672.4	6672.4
8852.99	5592.4	6008.4	6008.4	7664.4	7664.4
8912.99	5656.4	6136.4	6200.4	8304.4	8304.4
8932.99	5688.4	6200.4	6264.4	8592.4	
	6360.4	6360.4	7864.4	8912.4	
	6392.4	6392.4	7896.4	8976.4	
	6424.4	6488.4	7992.4	9104.4	9104.4
	6552.4	6648.4	8152.4	9392.4	
	6648.4	6936.4	8344.4	9712.4	9712.4
	6712.4	7128.4	8568.4	10672.4	10672.4
	6776.4	7256.4	8760.4	10992.4	10992.4
	6808.4	7320.4	8824.4	11216.4	11216.4
	10200.4	10200.4	12888.4	11632.4	
	10232.4	10232.4	12920.4	11888.4	11888.4
	10264.4	10328.4	13016.4	12656.4	
	10392.4	10488.4	13176.4	13136.4	13136.4
	10488.4	10776.4	13368.4	13488.4	13488.4
	10552.4	10968.4	13592.4	13712.4	
	10616.4	11096.4	13784.4	13872.4	13872.4
	10648.4	11160.4	13484.4	13968.4	13968.4

The comparison of the cross power spectrum of VGOS-480 vs. VGOS-992 shows that a wider block bandwidth results in a better side peak suppression. When the spanned bandwidth is extended to Ku-band (G8-1-2) a further improvement can be reached (Figure 2). The enhancement of the block bandwidth from 480 MHz (left) to 992 MHz (right) reduces the number of high side peaks. It shows that the selection of the frequency sequence has an impact on the easiness of determining correctly the main peak in the correlation process.

This analysis shows that the high performance of VGOS can be optimized further by smart frequency selection. It seems that the best performance can be achieved by applying the Golomb ruler to the frequency sequences. In this comparison the sequence G22 performs best in terms of minimum main peak width, and G22+10 performs best in side peak suppression (Figure 3). Both differ marginally but are significantly better than VGOS-480 or VGOS-992, both not using Ku-band (Figure 4)! G22 allows saving of resources, as with fewer channels/less data, an equivalent result can be achieved. In summary, the VGOS accuracy can be improved by an adequate frequency selection. Optimization trials are worth the effort before a new sequence will be frozen for decades in order to provide consistency over time!

4 Consistency with ICRF

We know that ICRF reference sources are mostly Active Galactic Nuclei (AGN) and expose some frequency dependencies of their cores plus a time variable position. With the increased resolution from VGOS, this source structure is an issue to be resolved in the analysis. This reveals the question: To which radio frequency do the ICRF sources refer?

The ICRF3 publication reads: *"The new frame, referred to as ICRF3, is based on nearly 40 years of data acquired by very long baseline interferometry at the standard geodetic and astrometric radio frequencies (8.4 and 2.3 GHz), supplemented with data collected at higher radio frequencies (24 GHz and dual-frequency 32 and 8.4 GHz) over the past 15 years."* [A&A 644, A159 (2020)] This implies that the group delay is referred to that frequency of "8.4 GHz". No statement could be found about how the data is linked to that specific radio frequency. Hence it seems to be just a label. Note that the average X-band frequency of the R1 observation sequence as listed in Table 3 is 8.60349 GHz, instead of 8.4 GHz! It appears that, due to non-resolved

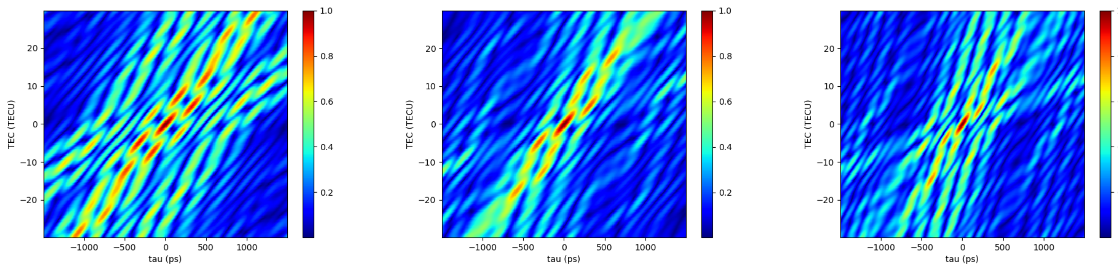

Fig. 2 Cross power spectrum of VGOS-480 (left) vs. VGOS-992 (middle) vs. G8-1-2 (right). The color code shows the level of correlation (0..1) between group delay (TAU) and total electron content units (TECU) of a given frequency sequence. In this bird perspective the red spots mark correlation peaks. The searched for main peak is centered.
VGOS-992 vs. VGOS480: Wider block bandwidth results in better side peak suppression (fewer red spots).
G8-1-2 vs. VGOS-992: Inclusion of the Ku-band increases time resolution and reduces the main correlation peak width.

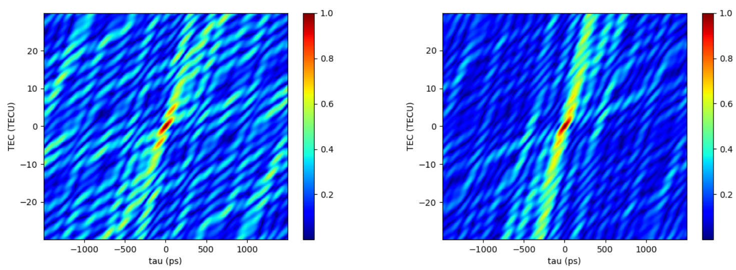

Fig. 3 Cross power spectrum of G22 (left) vs. G22+10 (right). The rigorous application of the Golomb ruler of the order 22 covering the frequency range from 2.5 to 14 GHz achieves with only 22 channels an even better result than G8-1-2. Adding ten more observation channels with a least redundant approach in the linear combinations among the channel frequencies reduces side peaks further but does not change much the overall performance.

sources in the legacy S/X data bases, the subject of a precise *reference frequency* had not been an issue.

This triggers a number of new questions:

1. What is the ICRF "reference frequency" in a VGOS sequence?
2. Do we introduce four source positions for each frequency block group delay (e.g., VGOS-480/992, G8-1-2)?
3. Or do we use one super group delay combined from the four block group delays?
4. Do we use only one group delay over a wider spectrum using the average frequency as reference (e.g., G22/+10)?
5. Do we need to select frequencies with respect to maintaining consistency with the former ICRF?

Figure 5 shows the distribution of the discussed observation channels (Table 1) with their center frequency of all channels. The closest center frequency to "8.4 GHz" is the G22+10 sequence.

5 Conclusions

Three perspectives on the frequency selection for VGOS can be summarized:

1. All radio bands are allocated, mostly to active services which potentially interfere with intended VGOS observations. Radio Quiet Zones (RQZ) for VGOS sites are desirable, and at least coordination zones should be established.
2. Currently used VGOS sequences can be improved by alternative sequences making use of the Golomb ruler. Reduction from 32 to 22 channels is then possible and would save resources.
3. The future VGOS sequence will define a new CRF as source structure is resolved. The adequate frequency selection could preserve consistency with legacy ICRFs.

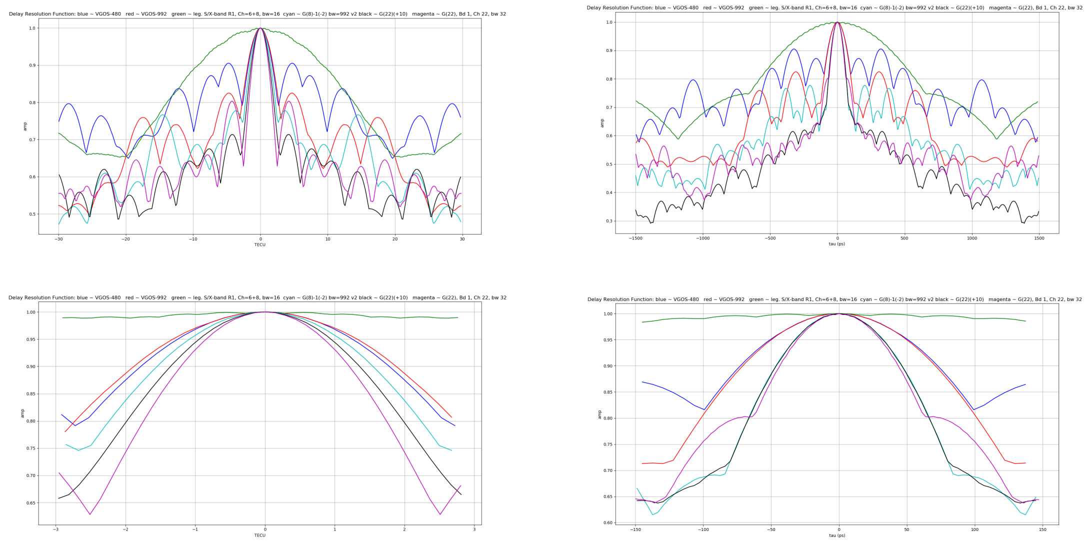

Fig. 4 Superposition plots of the cross power spectrum of the presented frequency sequences as side views to the power spectrum, along TECU (left) and TAU (right). The main peak is 10x amplified in the lower figures. The best performance is shown by G22 (magenta) and G22+10 (black).

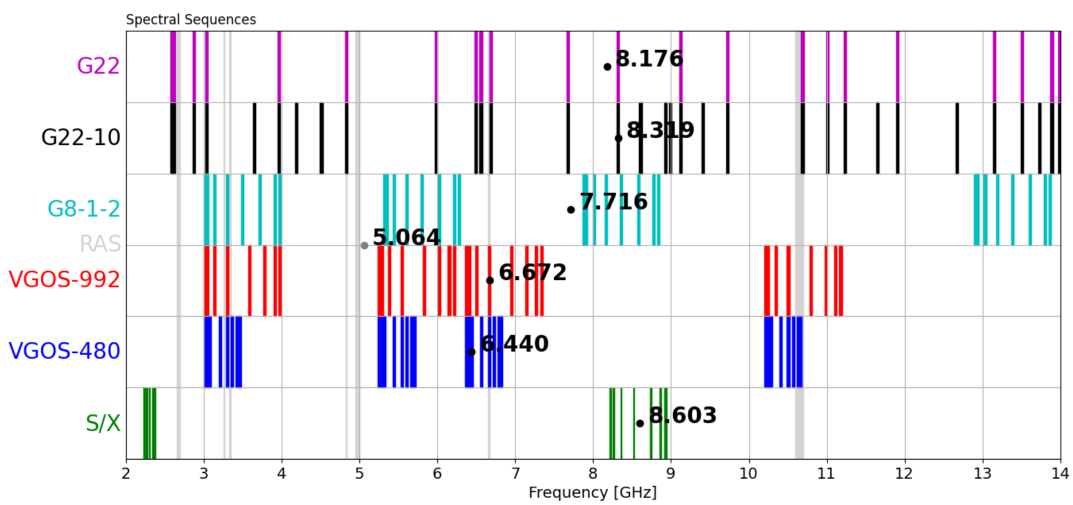

Fig. 5 Channel distribution in the range of 2–14 GHz with their respective center frequencies for different frequency sequences. The selection of channels may be of importance for consistency of the ICRF when it is to be tied to the legacy observations. (RAS bands of Table 1 are in grey.)

Acknowledgements

The plots in Figures 2, 3, and 4 were created with the delfun1.py script from Bill Petrachenko.

References

1. H. Hase, "On the Frequency Selection for Geodetic VLBI", unpublished paper for IVS-VTC, July 8, 2021.