The VGOS High Road: From Inception and Prototyping to Operations to Maturation and Beyond

D. Behrend, C. Ruszczyk, P. Elosegui, A. Neidhardt

Abstract Legacy S/X has been the production system of the IVS since the inception of the service. VGOS was declared operational in 2020 after a visionary journey that involved designing, prototyping, and demonstrating the feasibility of the new observing system to generate high-quality geodetic products. And a fledgling VGOS network of between 8 and 10 stations has been contributing to IVS products operationally ever since. That VGOS network had further increased by the end of 2022 to 12 stations, and counting. Currently, the VGOS observing program encompasses the 24-hour VGOS-OPS and VGOS-RD session series; further, a weekdaily VGOS Intensive series has been established (with other VGOS Intensives being set up). In addition to the network, VGOS correlation capabilities have also expanded to try to keep pace with the increased VGOS correlation load, morphing into a multi-center distributed correlator. In this paper, we provide a status overview of the infrastructure realization efforts of the VGOS station network and the correlation centers as well as plans for a bright VGOS future.

Keywords VGOS, infrastructure, correlator

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1 Introduction

When the IVS was established in 1999, the VLBI production system was—and had been for almost two decades—the legacy S/X system. In the early 2000s, studies were started that looked into the creation of a next-generation VLBI system using smaller, faster antennas and a wide bandwidth. This was the start of a journey to design, prototype, and demonstrate the VLBI Global Observing System (VGOS).

Following an extended development period, the new system was declared operational in 2020. High-quality geodetic and astrometric results were obtained from VGOS data and started to contibute to IVS products (including to ITRF2020). The fledgling VGOS network was limited in size (8 to 10 stations) and geographic distribution (northern hemisphere) but continued to grow, reaching some 12 stations by mid-2023. The network growth is expected to continue in the next few years (in particular in the southern hemisphere) and will help to improve overall data quality.

The larger network as well as the anticipated increase in observing cadence necessitated an expansion of the VGOS correlation capabilities. The correlator network saw an expansion from initially one to now seven centers to handle the correlation load (one 24-hour VGOS session per week or fortnight plus 5 to 10 1-hour VGOS Intensive sessions on various baselines). In the following, we give an overview of the infrastructure realization efforts of the VGOS station network and the correlation centers. We summarize the history of VGOS using some of the milestones and making reference to essential publications. Finally, we point out some of the system's current limitations (e.g., data transfer rates, storage capacities) and provide an outlook on a bright VGOS future.

2 VGOS: Some History

In the early 2000s, the IVS Directing Board recognized that the VLBI equipment of the legacy S/X system, developed in the 1970s and 1980s, was approaching the end of its lifetime and formed a working group to formulate a vision for a next-generation VLBI system. Over the time period from September 2003 to September 2005 IVS Working Group 3 on VLBI2010 examined current and future requirements for VLBI geodetic systems and summarized its findings in a final report (see Figure 1). This vision paper forms the basis for the subsequent developments.

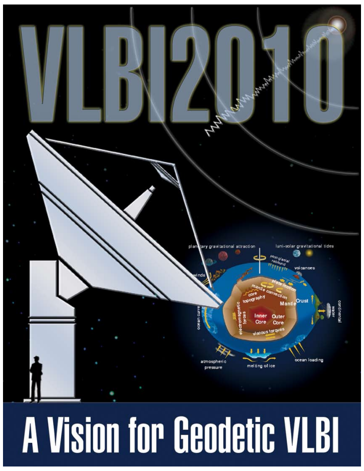

Fig. 1 *Vision document:* Final Report of IVS Working Group 3 on VLBI2010 “A Vision for Geodetic VLBI” (Niell et al., 2005).

To encourage the implementation of the recommendations of WG3, among other things, the Board then established the VGOS Technical Committee (VTC; formerly known as VLBI2010 Committee, V2C) in September 2005. As a committee the VTC is a permanent body in the IVS (unlike the temporary WG3). The primary function of the VTC is to promote and guide research into the improvement of the “technique” of geodetic VLBI. The committee saw as the most urgent issue the need to define the specifications for the VGOS antenna and accomplished this task with the publication of a progress report in 2009 (see Figure 2) which focused on the design aspects of the VGOS system. The VTC continues to work on improving the VLBI technique to this day.

With the specifications defined, it was possible to start work on prototyping a VGOS system. Two proof-of-concept broadband signal chain systems were developed and installed at antennas in Westford and Goddard. The baseline was used between 2014 and 2017 to demonstrate the feasibility of VGOS. In addition to the developments on the station side, also new correlation and analysis procedures for the four-band, dual-linear-polarization data had to be created. A summary of the successful demonstration of the VGOS technique was eventually published in 2018 (see Figure 3).

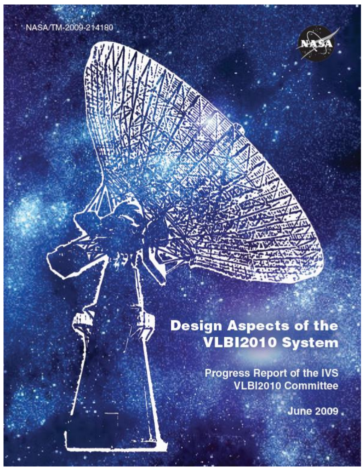

Fig. 2 *Definition of specifications:* Progress Report of the VGOS Technical Committee (VTC, formerly VLBI2010 Committee) “Design Aspects of the VLBI2010 System” (Petrachenko et al., 2009).

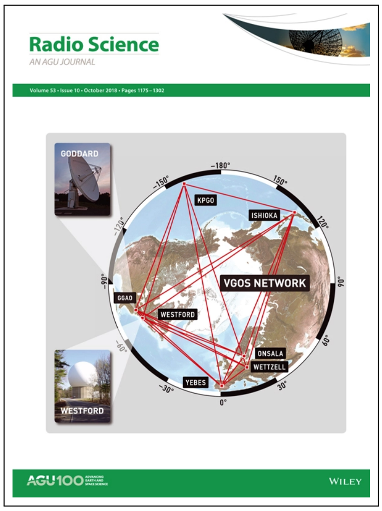

Fig. 3 *Demonstration of VGOS technique:* technical report in Radio Science (Niell et al., 2018).

3 Status and Growth of the VGOS Station Network

As of mid-2023, the VGOS observing network consists of 12 stations (see Figure 4). The addition of three further stations to this network is imminent. The network will further grow in 2024 and 2025 to about 25 stations. Recent milestones and the state of individual VGOS station projects are summarized in Table 1. Additional growth with a smaller number of stations is anticipated towards the end of this decade.

Table 1 Individual VGOS station projects with recent milestones and projected broadband readiness.

Station	Recent milestone	VGOS broadband
GGAO	VGOS-OPS, VGOS-RD	ready
Westford	VGOS-OPS, VGOS-RD	ready
Wettzell (Ws)	VGOS-OPS, VGOS-RD	ready
Yebes (Yj)	VGOS-OPS, VGOS-RD	ready
Ishioka	VGOS-OPS, VGOS-RD	ready
Kokee Park (K2)	VGOS-OPS, VGOS-RD	ready
Onsala (Oe, Ow)	VGOS-OPS, VGOS-RD	ready
McDonald	VGOS-OPS, VGOS-RD	ready
Hobart	VGOS-OPS, VGOS-RD	ready
Katherine	VGOS-OPS, VGOS-RD	ready
Ny-Ålesund (Nn)	VGOS-OPS, VGOS-RD	ready
Santa Maria	VGOS-RD	imminent
Sheshan	VGOS tagalong	imminent
Yarragadee	S/X observing	imminent
Wettzell (Wn)	VGOS fringe tests	2024
Ny-Ålesund (Ns)	S/X observing	2024
HartRAO	signal chain work	2024
Metsähovi	signal chain work	2024
Matera	RT built	2024
Chiang Mai	site preparation	2024
Songkhla	site selected	end 2024
Gran Canaria	RT stored, land purchase	2025
Fortaleza	RT and signal chain built	2025
Flores	RT design, RFI surveys	2025
Kanpur	proposal	2025
Badary	fixed broadband system	2017 [S/X/Ka]
Zelenchukskaya	fixed broadband system	2017 [S/X/Ka]
Svetloe	fixed broadband system	2019 [S/X/Ka]
Tahiti	site selected, RFI survey	beyond 2027

Beyond the projects listed, there are also efforts underway in other parts of the world. This includes undertakings in India (for three stations), Malaysia, and Indonesia. Please do let the authors know of any other projects that may be in the discussion stage.

In general, the observing network reaches levels of a mature buildout, but there remain gaps in Africa, South America, and Antarctica—that is, there is a level of scarcity in the southern hemisphere overall.

4 VGOS Correlation Capabilities

The VGOS correlation capabilities have evolved from a single correlator (until 2019) to a network of (up to seven) distributed correlators that can process VGOS sessions operationally (see Figure 5).

TSUK has processed VGOS Intensive data but does not have sufficient resources yet to handle 24-hour sessions. UTAS handles AUS mixed-mode sessions. Other correlation centers (e.g., at Yebes) may evolve over time to full-blown VGOS correlators. The correlator group regularly meets to have knowledge exchange and to refine the VGOS processing chain.

5 VGOS Observing: Current Limitations

Cadence of VGOS-OPS sessions. In 2022 and early 2023, the turnaround time for 24-hour VGOS sessions (end of observing to vgosDB creation) was 2+ months. With 4–5 correlators processing 24-hour sessions, a turnaround time of 30 days or better is needed to avoid a backlog of sessions. The last few VGOS-OPS sessions of 2023 were closer to this target time.

Data storage. Both stations and correlators need sufficient storage capacity for Level-0 data (raw station data). Several have upgraded their capacities recently. A subset of the correlators can handle physically shipped Mark 6 modules, while some only support e-transfers.

e-transfer rates. For transferring Level-0 data electronically, sufficiently large data transfer rates are needed. For stations sustained rates of 5–10 Gbps are sufficient, whereas correlators need multiples of these rates (20 Gbps or better for one 24-hour session per week; 140 Gbps at full VGOS maturity when observing continuously and assuming a monolithic correlator).

Hardware availability. Several hardware parts—such as masers, digitizers, and feed system components (e.g., LNAs)—are produced by small companies with small production series. Some parts have become unavailable (“unobtainium”), while other parts have high costs or long purchase order lead times associ-

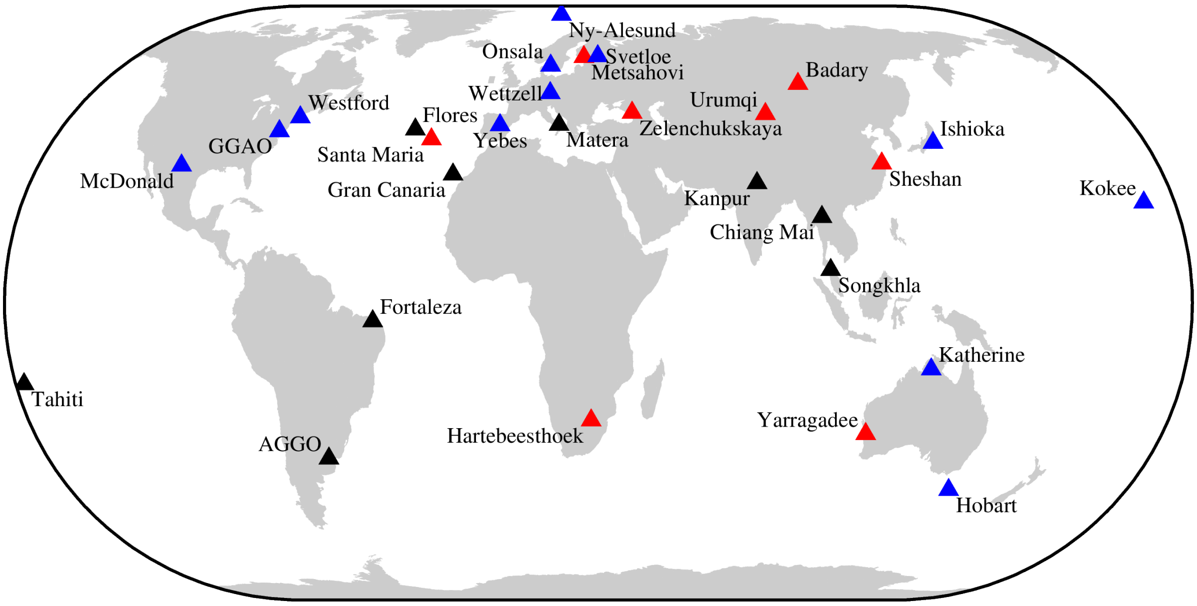

Fig. 4 Geographic distribution of the operational VGOS antennas (▲), built antennas with signal chain work in progress (▲), and VGOS projects in the planning stage (▲).

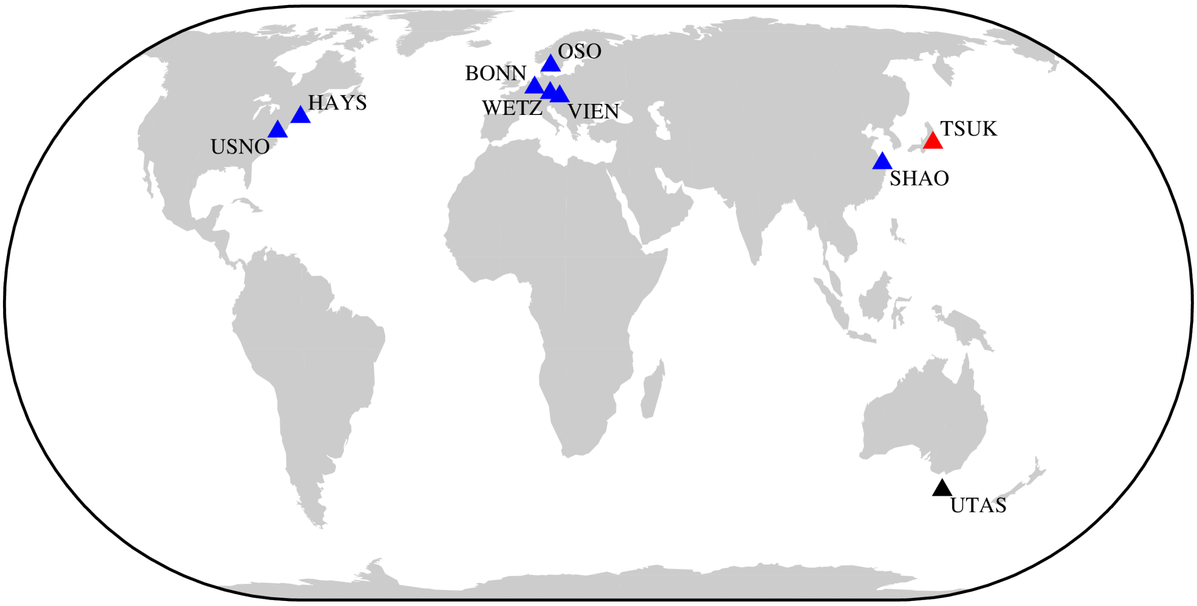

Fig. 5 Geographic distribution of the operational VGOS correlators (▲), correlators under verification (▲), and future correlation centers (▲).

ated with them. An inherent risk is a slowdown in the signal chain buildout or difficulties in maintaining the existing ones.

RFI impact. Both ground-based and space-borne radio emissions from active services can impact the station operations. Unwanted frequencies at one (or several) of the VGOS bands can cause radio frequency interference with possible loss of data or the need to install tailor-made notch filters into the signal chain. The latter situation was the case, for instance, for the VGOS antennas at Ishioka and Santa Maria.

6 Conclusions and Outlook

In 2022, the VGOS observing program encompassed about 265 Intensive (1-hour) sessions and 50 (24-hour) sessions. However, data transport and storage as well as correlator time are the main resources that limit the current program. It is expected that data transfer rates both at the stations and correlators will be improved over time resulting in an increased cadence of observing sessions. This needs to go hand in hand with enhancements of storage capacity.

There is still work to be done to be able to transition from the legacy S/X system to the VGOS system as the production workhorse of the IVS. Having two systems in parallel, of course, also means that they compete for resources. It is however essential that the nascent VGOS time series are rigorously integrated with the existing S/X time series so that the long-lasting S/X series can be carried forward by VGOS without real lapse. The tie of the S/X and VGOS systems can be accomplished by mixed-mode sessions as well as local tie sessions at sites with co-located legacy S/X and VGOS stations.

With a VGOS network of 25+ stations in the mid-2020s and the possibility of having 9–10 VGOS correlation centers processing operational VGOS sessions, we see the makings of the VGOS system reaching maturity. The VGOS Intensive series VGOS-INT-A furnishes dUT1 results by a factor of two better than the equivalent legacy S/X series. The IERS Rapid Service/Prediction Center has started to use the results operationally. Further VGOS Intensives are in the process of being validated. In short, the process has begun to phase in VGOS as a production tool.

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