IGN Yebes Observatory Technology Development Center 2021–2022 Report

J. A. López-Pérez, C. Albo-Castaño, R. Amils-Samalot, L. Barbas-Calvo, M. Bautista-Durán, F. J. Beltrán-Martínez, M. Díez-González, J. D. Gallego-Puyol, P. García-Carreño, A. García-Castellano, A. García-Marín, O. García-Pérez, G. Gómez-Molina, J. González-García, I. López-Fernández, I. Malo-Gómez, E. Martínez-Sánchez, M. Patino-Esteban, D. Regajo-Rodríguez, J. C. Rodríguez-Pérez, F. Tercero-Martínez, B. Vaquero-Jiménez, P. de Vicente, J. A. López-Fernández

Abstract The main technical developments of the Yebes Observatory (IGN, Spain) in 2021 and 2022 related to geodetic VLBI are introduced.

1 General Information

Yebes Observatory has been a Technological Development Center of the IVS since 2015. The main areas of expertise include low-noise cryogenic receivers at centimeter and millimeter wavelengths, cryogenic low-noise amplifiers, antennas and feeds, passive devices (i.e., filters, OMTs, septums, microwave hybrids, and couplers), cryogeny and vacuum, modules for receiver calibration, antenna control software, microwave holography for large reflector antennas' surface characterization, RFI detection and measurements, and topographic measurements for the local-tie.

Yebes Observatory operates two radio telescopes, 13.2 m and 40 m in diameter, respectively, that are integrated into the IVS (see Figure 1). The first one runs regular VGOS observations, and the second one has been running legacy IVS observations since 2008. The details are explained in the corresponding station report [1].

The 13.2-m radio telescope belongs to the RAEGE (Red Atlántica de Estaciones Geodinámicas y Espaciales) and is the first operative radio telescope of the four foreseen within that network (Yebes, Santa Maria, Gran Canaria, and Flores) [2]. Yebes Observatory also manages two GNSS receivers: one integrated into the International GPS Service (IGS) and a second one in the Spanish national GNSS network (Red Geodésica Nacional de Estaciones de Referencia GNSS, ERGNSS). It also runs an absolute gravimeter (FG5) and a relative superconductor gravimeter (OSG); the data collected by these gravimeters is sent to the International Geodynamics and Earth Tide Service (IGETS).

Fig. 1 General view of Yebes Observatory.

Santa Maria was the second operative RAEGE station. A detailed description can be found in [3].

Additionally, the project for the construction of an SLR station (YLARA project) started in late 2020, and it is expected to be finished by mid-2023. A detailed description of the YLARA status can be found in [4]. Yebes Observatory will become a GGOS core station once YLARA starts its operation within the International Laser Ranging Service (ILRS).

Finally, we are installing a DifX VLBI correlator for RAEGE, which could also be part of VGOS and EU-VGOS performing distributed correlation, if this idea is realized.

Yebes Observatory, IGN

IGN Yebes Observatory Technology Development Center

IVS 2021+2022 Biennial Report

These activities are performed by a staff of engineers, astronomers, and technicians, with the help of the instrumentation located in the laboratories and workshops.

In the following sections we describe the most relevant technical activities performed during 2021 and 2022.

2 VGOS Broadband Receivers

During the period to report, Yebes Observatory has upgraded the VGOS receiver for the RAEGE Yebes 13.2-m radio telescope. These upgrades are detailed in [5]. The measured average receiver noise temperature is 11.5 K in the 3–14 GHz range (see Figure 2). The upgraded receiver was installed in June 2022.

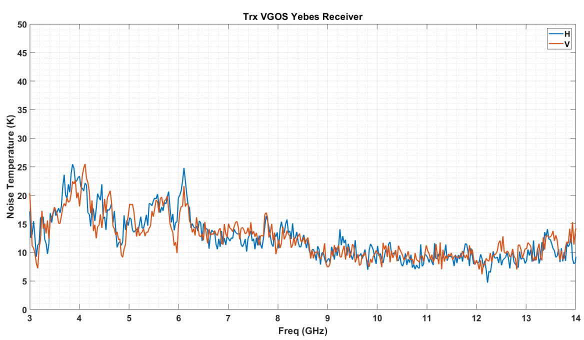

Fig. 2 RAEGE Yebes VGOS receiver noise temperature.

Additionally, Yebes Observatory also upgraded the Santa Maria VGOS receiver, previously installed in the Yebes RAEGE radio telescope until the upgrade of the Yebes VGOS receiver. The measured average receiver noise temperature is 12.5 K in the 3–14 GHz range (see Figure 3). After the upgrade in the lab, the receiver was shipped to Santa Maria in August 2022 and installed in October 2022. This receiver replaced a tri-band S/X/Ka one, mainly used for S/X legacy observations. Fringes were detected with the Santa Maria VGOS receiver on November 29 with the 12-m GGAO and 13.2-m RAEGE Yebes radio telescopes.

Concerning VGOS receiver developments for other institutions, the second VGOS receiver for the Norwegian Mapping Authority (NMA) was delivered in 2021 to Ny-Ålesund (Svalbard), and a team from Yebes assisted NMA during the installation.

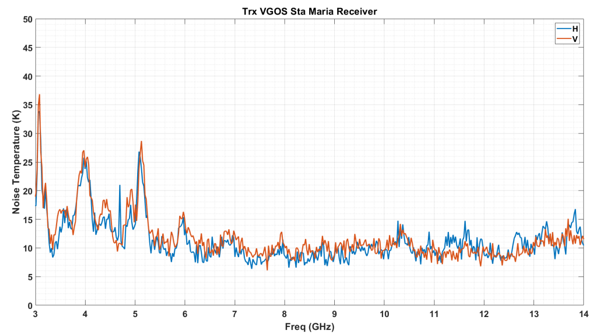

Fig. 3 RAEGE Santa Maria VGOS receiver noise temperature.

In parallel, Yebes Observatory was commissioned to build three complete new cryogenic VGOS broadband receivers, from the dewar and frontend (QRFH and LNAs) to the room temperature signal chain up to the input of the backends, including the PhaseCal and NoiseCal modules, the Cryogenics and Vacuum Control Unit, and the receiver control software.

These receivers will be delivered to the Hartebeesthoek VGOS station in South Africa, the Matera VGOS station in Italy, and the next Songkhla VGOS station in Thailand (NARIT). Only the frontend will be provided to the NARIT VGOS receiver, according to the scope of supply.

Upon the delivery of these receivers, Yebes Observatory will have built eight receivers for the VGOS community. This number will increase to ten after the completion of the RAEGE Gran Canaria and Flores stations within the next few years.

See [6] and [7] for related VGOS developments.

3 Low-noise Wideband Amplifiers

Throughout this reporting period, a significant number of 2–14 GHz cryogenic balanced amplifiers were prepared and characterized for their use in VGOS receivers. Some of them, such as the ones planned for NMA 2, are upgrades of single-ended amplifiers that require only two LNAs and four hybrid couplers, while others (Matera, HartRAO, NARIT) need four amplifiers and four hybrids each to cover both polarizations.

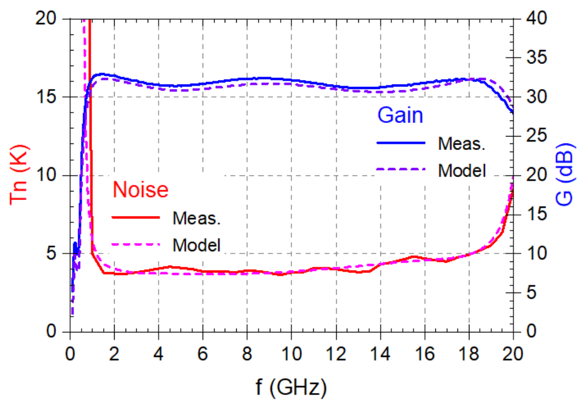

Fig. 4 Measured and modeled gain and noise temperature of the 2–18 GHz LNA at 6 K ambient temperature.

In the last five years, Yebes has been developing a new generation of state-of-the-art InP transistors with superb noise performance in collaboration with Diramics[1]. The availability of these devices has motivated a redesign of the 2–14 GHz cryogenic LNA used in VGOS balanced amplifiers. This redesign encompasses two main changes: first, the adaptations in the matching networks needed to incorporate one of the new transistors into the first stage of the amplifier, and secondly, a general optimization of the design needed to exploit the advantages of a balanced configuration (the input and output return loss of the balanced LNAs are set by the excellent reflection of the hybrid couplers and are no longer a requirement of the single LNAs). Consequently, noise temperature improves significantly (around 33%), having higher gain and being a factor of two flatter, despite power dissipation being reduced by one third. The results of this enhanced amplifier version will be published soon. So far only RAEGE stations (Yebes and Santa Maria) have been equipped with balanced units of this new type. A total of eight amplifiers and hybrid couplers were manufactured to assemble four balanced amplifiers for the two polarizations of both receivers.

These optimized transistors have also facilitated another development based on the 2–14 GHz amplifier: a new LNA with an expanded ultra-wideband 2–18 GHz range and a 4 K noise temperature [8]. Figure 4 illustrates the noise and gain performance of this amplifier. To improve the input matching with the antenna, a balanced architecture is recommended in direct amplification receivers. The required 3 dB 90° 2–18 GHz hybrid has not been designed yet but could be produced by scaling the existing one developed by our group for the BRAND receiver (1.5–15.5 GHz).

[1] Diramics AG, Switzerland (https://diramics.com)

4 Cryogenic Directional Couplers

VLBI receivers include calibration subsystems that inject amplitude and phase calibration signals in the frontend by means of a directional coupler. It is usually placed after the feed horn to take into account the maximum number of receiver components in the calibration.

In VGOS receivers, the directional coupler is placed before the LNA at cryogenic temperature, reducing the impact on the noise temperature from its dissipative losses. There are commercial off-the-shelf devices available, but they are not specially conceived to survive thermal cycles from ambient to cryogenic temperature. Some of them were measured at Yebes, showing degradation of their cryogenic performance ([9], [10]) and a potential risk of failure due to the thermal stress on the connector contact. For these reasons, we developed a 30 dB cryogenic directional coupler specially suited for cryogenic operation, improving the performance and reliability of commercial units. It works in the 2–14 GHz frequency band, although its best performance was in the 3–14 GHz range because of the high level of RFI present in the lower part of the VGOS band.

The materials and mechanical construction were carefully selected following the stripline structure in [11]. The result is a very compact, reliable, and low thermal mass device, able to withstand extreme thermal cycling. The coupling and reflection characteristics show a very low temperature dependence. Their main characteristics are the following: coupling of 29.2 dB ± 1 dB with a return loss better than 20 dB in the direct path ports, plus an average effective insertion loss lower than 0.1 dB and directivity higher than 16 dB [12].

Eight units were built to meet the needs of the Yebes, Santa Maria, HartRAO, and Matera VGOS receivers. One unit is shown in Figure 5.

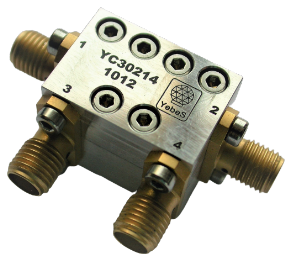

Fig. 5 30 dB cryogenic directional coupler.

5 NoiseCal and PhaseCal Developments

All Yebes-developed VGOS receivers are equipped with a broadband noise source that can be turned ON or OFF or to an 80 Hz rate under remote control. This feature is useful for amplitude calibration. The excess noise (Tcal) generated by the noise source is injected in front of the LNAs and is carefully measured in the laboratory and reported.

Concerning the PhaseCal Antenna Unit, the envelope of the pulse train was equalized to have a flatter spectrum with the help of a COTS unit. Details are given in [5].

With regard to the Cable Delay Measurement System (CDMS), a new version was developed, and the results were published in [13].

To measure the accuracy of the system, a Narda manual phase shifter was used. It allows the manual insertion of known phase offsets in the 5 MHz signal path, from 0º to 180º at 1 GHz, which corresponds to offsets from 0º to 0.9º at 5 MHz (0.9º at 5 MHz equals 500 ps). Therefore, it is possible to introduce very precise and known delays into the system to verify that they are detected and measured correctly.

Figure 6 shows the measured delay for 10 ps steps (two-way). It can be seen that these changes are easily detected. However, it must be taken into account that the changes are made manually, using the shifter's wheel, and the wheel settings can be affected by a little slack or play.

The noise of the system provides a value of the measurement error introduced by the system itself. This error is the ultimate accuracy that the system can reach in the absence of the effects on the cable to be measured. It was measured inside the Yebes gravimeter room, where the temperature has a gradient of $\pm$

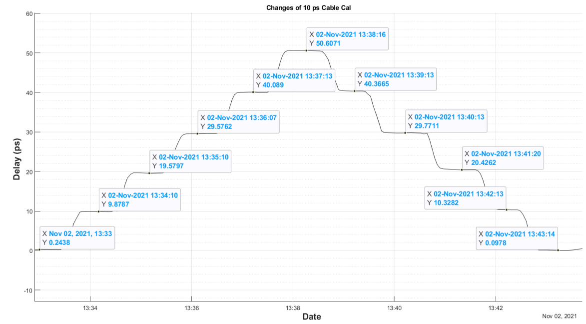

Fig. 6 CDMS response to 10 ps delay steps.

1° only, with a 1 m cable for the connections between units.

The RMS noise computed in one hour is below 0.1 ps. It is shown in Figure 7.

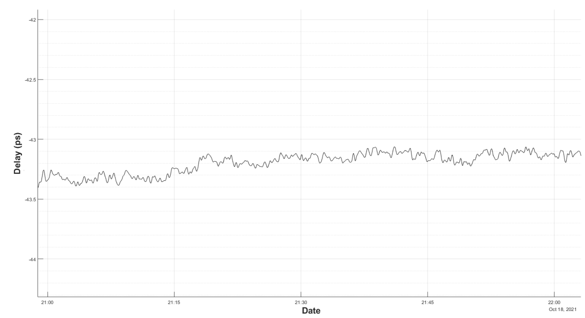

Fig. 7 CDMS noise during one hour.

6 RFI Measurements

During the period of 2021–2022, several works related to RFI were carried out in Yebes Observatory. These encompass hardware development for RFI systems, RFI monitoring system campaigns, and software development related to RFI.

Concerning the hardware, some additional modules of filtering and amplification were developed at Yebes Observatory to improve the sensitivity of the RFI system in order to evaluate some specific RFI signals (i.e., Starlink and the second harmonic from IMT800).

In relation to RFI monitoring campaigns / measurements, we tried to detect RFI from Starlink satellites by using the RFI permanent system (RAFITA), installed at the rooftop of the labs building and with the VGOS radio telescope. Both measurements showed some Starlink channels over Yebes Observatory. The difficulty is to prove if these signals come through the main beam or side-lobes. The goal of the measurements is to obtain the flux at the input of both antennas. Calibrated measurements were obtained with RAFITA only.

Additionally, RFI measurements were performed at 3 GHz from pulsed RFI signals that were received during the pointing scans in VGOS A-band with the RAEGE radio telescope.

Monitoring campaigns with RAFITA covered the VGOS frequency range, across the whole sky over five hours. The data is stored and later post-processed to create 3D maps with the total RFI power at specific frequency ranges (see Figure 8).

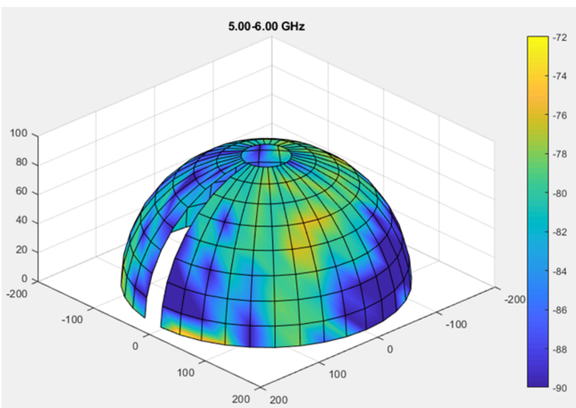

Fig. 8 3D map of RFI power in the range 5–6 GHz.

Finally, regarding RFI software development related to the monitoring campaigns with RAFITA, some software in MATLAB was developed to calibrate the data and to integrate the RFI power and plot the RFI-3D maps.

7 VLBI Correlator

Yebes Observatory is installing a DIFX VLBI correlator for RAEGE, which could also be part of VGOS and EU-VGOS performing distributed correlation (see [1] for further details).

For the past two years, a small prototype of correlator with 28 computing cores was used to get training with the processing pipeline. As a result of this stage, it could be used to confirm the first interferometric fringes between the new Ny-Ålesund VGOS antenna and RAEGYEB, as well as the baseline RAEGSMAR and RAEGYEB. Currently, it is on duty to correlate the VGOS Intensive sessions run by GGAO, RAEGYEB, and RAEGSMAR.

In 2023, a significant upgrade of the hardware is expected to allow the processing of VGOS-type experiments with more baselines. The specifications for the new HPC consist of up to 128 computing cores and 1 PB of storage space.

8 New Developments

After the installation of the VGOS receiver at the RAEGE Santa Maria station, a strong radio signal was detected near 3 GHz. This signal was so strong that the receiver was saturated and intermodulated at the LNA stage. Therefore, observations were not possible. As a quick temporal solution, it was decided to install COTS high-pass filters (4–16 GHz) at the input of the LNAs at the cost of losing the VGOS A-band. Detailed information on the performance of these commercial filters is available in [14]. This is a temporary solution while a high-temperature superconducting notch filter is developed. Its design started in November 2022, and it will be ready for installation by June 2023 if the characterization in the lab is successful. This filter will allow observing in the VGOS A-band.

Additionally, HTS filters were designed to notch the SLR radar signals around 9.4 GHz in the Matera and HartRAO VGOS receivers. Similarly, these filters will be assembled in 2023 prior to their characterization in the laboratory.

Acknowledgments

Special thanks are given to all Yebes and Santa Maria staff for their valuable contributions to the technological developments and radio telescopes' operations.

References

1. J. González et al.: "Yebes Observatory Report". In IVS 2021+2022 Biennial Report, this volume, edited by K. A. Armstrong, D. Behrend, and K. D. Baver. 2023.
2. José A. López-Pérez, João S. Ferreira, Javier González-García, Carlos Albo-Castaño, Abel García-Castellano, P. de Vicente-Abad, José A. López-Fernández, Francisco W. Macedo, Luís R. Santos, Sara Pavão: "The current status of RAEGE". 25th EVGA meeting. March 15-18, 2021.
3. João S. Ferreira, Abel García-Castellano, José A. López-Pérez, Mariana Moreira, Diogo Avelar, Valente Cuambe, Francisco Wallenstein, Javier González-García, Carlos Albo-Castaño: "RAEGE Santa Maria: Station Overview". IVS 2022 General Meeting Proceedings, pp. 42-46, edited by Kyla L. Armstrong, Dirk Behrend, and Karen D. Baver. NASA/CP-20220018789. 2023.
4. Beatriz Vaquero, José A. López-Pérez, José C. Rodríguez, Adolfo García-Marín, Elena Martínez, Carlos Albo-Castaño, Laura Barbas, José A. López-Fernández, Pablo de Vicente: "Yebes Laser Ranging Station (YLARA), development status 2022". 22nd ILRS workshop, Guadalajara, Spain.
5. José A. López-Pérez, F. Tercero-Martínez, J. D. Gallego-Puyol, I. López-Fernández, C. Albo-Castaño, I. Malo-Gómez, M. Díez-González, M. Patino-Esteban, P. García-Carreño, O. García-Pérez, J. González-García, G. Gómez-Molina, M. Bautista-Durán, R. Amils-Samalot, A. Rivera-Lavado: "Description of RAEGE Yebes VGOS receiver upgrades". IVS 2022 General Meeting Proceedings, pp. 47-51, edited by Kyla L. Armstrong, Dirk Behrend, and Karen D. Baver. NASA/CP-20220018789. 2023.
6. D. Regajo, O. García-Pérez, F. Tercero: "QRFH antenna for (YQR-03-003)". CDT Technical Report 2021-14.
7. G. Gomez-Molina, O. García-Pérez, J. M. Serna-Puente, F. Tercero: "New Designs in VGOS frontends in Yebes Observatory". 25th EVGA meeting. March 15-18, 2021.
8. I. López-Fernández, J. D. Gallego, C. Díez, I. Malo, R. I. Amils, R. Flückiger, D. Marti: "2 – 18 GHz Ultra-wideband Cryogenic Amplifier with 4 K Noise Temperature". Proceedings of the 32nd International Symposium on Space Terahertz Technology. 2022.
9. I. Malo, J. D. Gallego, J. González, I. López-Fernández, C. Díez, R. Amils: "New 30 dB coupler for the injection of the calibration signal to the 2 – 14 GHz wideband VGOS receiver". CDT Technical Report 2019-16.
10. I. Malo, J. D. Gallego, I. López-Fernández, C. Díez, R. Amils: "Krytar 30 dB coupler for the injection of the calibration signal to the 2 – 14 GHz wideband VGOS receiver". CDT Technical Report 2020-16.
11. I. Malo, J. D. Gallego, C. Diez, López-Fernández, C. Briso: "Cryogenic hybrid coupler for ultra low noise Radio Astronomy balanced amplifiers". IEEE Transactions On Microwave Theory And Techniques, vol. 57, no. 12. December 2009.
12. I. Malo, J. D. Gallego, M. Diez, López-Fernández, R. Amils, R. García, G. Martínez: "Yebes 30 dB cryogenic directional coupler for the injection of the calibration signal to the 2 – 14 GHz wideband VGOS receiver". CDT Technical Report 2022-15.
13. Pablo García-Carreño, Javier González-García, María Patino-Esteban, Francisco J. Beltrán-Martínez, Marta Bautista-Durán, Pablo Luis López-Espí, José A. López-Pérez: "New Cable Delay Measurement System for VGOS Stations". Sensors 22, no. 6: 2308. https://doi.org/10.3390/s22062308
14. I. Malo, J. D. Gallego, I. López, M. Diez, R. Amils, A. García, R. García, G. Martínez: "Cryogenic Measurement of two LTCC Commercial Filters for Interferences Reduction in Radio Astronomy Receivers". CDT Technical Report 2022-14.