IGN Yebes Observatory Technology Development Center 2019–2020 Report

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Abstract We present the main technical developments of Yebes Observatory (IGN) in 2019 and 2020 that are related to geodetic VLBI.

1 General Information

Yebes Observatory has been a Technology Development Center of the IVS since 2015. The main areas of expertise include low noise receivers at centimeter and millimeter wavelengths, cryogenic low noise amplifiers, antennas and feeds, passive devices, cryogeny and vacuum, modules for receiver calibration, antenna control software, microwave holography for large reflector antennas, 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, which are integrated in the IVS. The first one regularly runs VGOS observations, while the second one has run 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 it is the first operational radio telescope of the four foreseen within that network (Yebes, Santa María, Gran Canaria, and Flores) [2]. Yebes Observatory also manages two GNSS receivers: one integrated in the International GNSS 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 superconducting gravimeter (OSG); the data collected by these gravimeters is sent to the International Geodynamics and Earth Tide Service (IGETS).

Additionally, the project for the construction of an SLR station (YLARA project) started in late 2020, and it is expected to be finished by early January 2023. Yebes Observatory will become a GGOS core station once YLARA starts its operation in the International Laser Ranging Service (ILRS).

Finally, we plan to install a DiFX VLBI correlator for RAEGE, which could also be part of VGOS and EU-VGOS performing distributed correlation, if such scheme is finally adopted.

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 2019 and 2020.

2 VGOS Broadband Receivers

Yebes Observatory was in charge of the full construction of three cryogenic VGOS broadband receivers, from the dewar and front-end (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. Two of these receivers are for the Ny-Ålesund Observatory of the Norwegian Map-

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ping Authority (NMA) and one for the Metsähovi Observatory of the Finish Geospatial Research Institute (FGI).

These broadband receivers are cooled using a two-stage cryostat (15 and 50 K) and operate between 2 and 14 GHz in two linear polarizations. They have a receiver noise temperature below 30 K along most of the full VGOS band.

Figure 1 shows the block diagram of one such receiver in which we can see its different modules. After the cryostat, the signal is split into two sub-bands: 2.1–5.6 GHz and 3.6–11.6 GHz following Haystack's approach to avoid the saturation of the optical fiber amplifiers from strong signals in the lower part of the band. The signals—once amplified, filtered, and transported through optical fiber links to the backends room—are directed towards two identical signal conditioning modules designed and built at Yebes. These modules split the signals from both polarizations into four frequency sub-bands ready to be injected into the DBBC3. The filtering and conditioning module for the DBBC3 does not use tunable LOs and in case that the observing bands change they can be adapted by replacing the pass band filters by new ones.

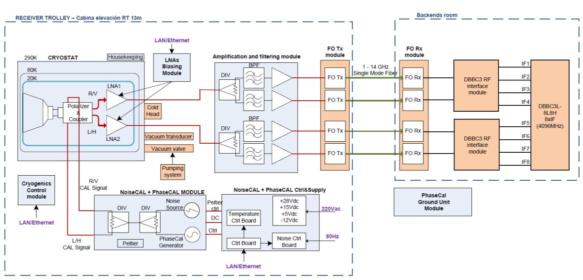

Fig. 1 Schematics of the VGOS broadband receiver for NMA and FGI.

The first NMA receiver (NMA1) was shipped in August 2019 and installed in September 2019. With respect to FGI, the VGOS receiver was shipped in October 2019 and installed in November 2019. Yebes staff was sent to each observatory to assist and provide support during the installation and commissioning of the corresponding receiver.

The receiver noise temperatures of these receivers are intercompared in Figure 2, measured in both linear polarizations along the band. It can be seen that the two receivers are almost identical with regard to noise temperature.

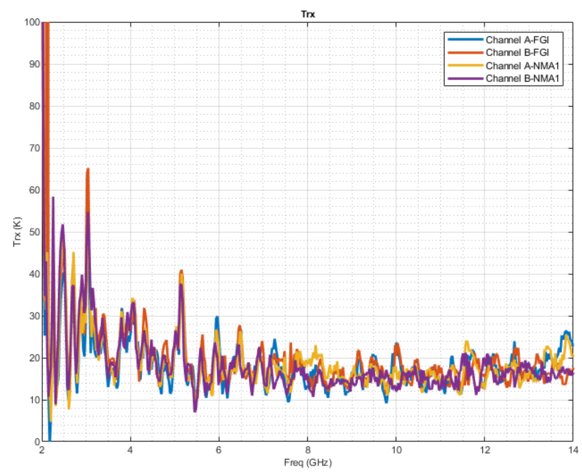

Fig. 2 Receiver noise temperatures for NMA1 and FGI.

The VGOS receivers use a cryogenics and vacuum control system which has an Ethernet connection for remote monitoring and control of both pumps (rotatory and turbomolecular), the reading of cryogenic temperature and the vacuum sensors, the control of the electrovalve, and the monitorization and control of the heat resistors and regenerators. This monitoring and control system eases the operation of the receiver from remote locations.

The second receiver for NMA (NMA2) was supposed to be intalled in 2020, but it has been delayed because it was decided to upgrade the LNAs from single-ended to balance configuration. This upgrade reduces the ripple in the receiver noise temperature curve and in the band-pass gain because balanced LNAs have much better input matching than single-ended LNAs. Additionally, 30dB directional couplers were included in the upgrade to improve the receiver noise by 3 Kelvin. It is foreseen to ship it to Ny-Ålesund in late spring 2021.

During 2020, the VGOS receiver for RAEGE Santa María station was completed. It already includes LNAs in balanced configuration, 30dB noise couplers, and a flatter envelope of the PhaseCal pulse train. Since November 2020, it is installed in the 13.2-m Yebes RAEGE VGOS radio telescope, while the Yebes VGOS receiver is being upgraded in our laboratory.

Additionally, we plan to prepare our current Up/Down converters to participate in future test observations with 1-GHz bandwidth and four R2DBEs. For this, suitable anti-aliasing filters (0.5–1.5 GHz) will be ordered.

The following upgrades are planned for the Yebes receiver during 2021:

- Revisited and improved QRFH [3]
- Balanced LNAs, to reduce the receiver noise and band-pass ripples [15]
- 30 dB noise couplers to improve receiver noise by 3 Kelvin [6]
- Updated PhaseCal AU with a flatter envelope of the pulse train
- Updated PhaseCal GU
- New post-dewar amplification unit to allow mixed mode observations (S/X and VGOS) [14]

Once the Yebes VGOS receiver is completed, the Santa María VGOS receiver will be shipped to the Azores, together with its associated backends. Then, Santa María station will join the VGOS communnity.

Finally, it has to be mentioned that, in November 2020, Yebes Observatory was contracted by HartRAO for the construction of a broadband receiver for the VGOS radiotelescope in Hartebeesthoek (South Africa). Once the receiver is finished, Yebes Observatory will have built a total of six VGOS receivers.

See [3, 4, 5, 6, 7, 8, 9, 10, 11] for more details about the VGOS receivers' development.

3 Tri-band Receiver at Santa María

The RAEGE radio telescope at Santa María is equipped with a Yebes-developed tri-band receiver, which can observe simultaneously in the bands 2.2–2.7 GHz, 7.5–9 GHz, and 28–32 GHz.

In August 2019, it suffered a failure and was shipped to Yebes for repair. It was sent back in February 2020 and was re-installed in early March 2020—just before the lockdown caused by the Covid-19 health crisis. The current receiver noise temperatures are lower than 32 K in S-band, 30 K in X-band, and 31 K in Ka-band. See [12] for details. Additionally, the Santa María station H-maser was retuned in 2020 [13].

In November 2020, the radio telescope performed joint observations of Bepi-Colombo in X/Ka together with JPL/DSN. The observations were a proof-of-concept to test if the accuracy of Doppler shift measurement can be improved by use of corrections from smaller and stiffer antennas like RAEGE VGOS ones.

During 2020, the RAEGE VGOS radio telescope underwent heavy maintenance operations, which will continue until spring 2021. It is expected to resume S/X operations by May 2021.

4 Ultra-low-noise Wide-band Amplifiers

Yebes cryogenic broadband low noise amplifiers have been extensively used in recent VGOS receivers—as well as in other VLBI observatories and even as 14-GHz-wide IF amplifiers for sub-millimeter receivers. A total of 28 amplifiers of this type were manufactured during this period, most of them already in the field.

However, an important drawback of amplifiers with such a high fractional bandwidth is the difficulty to simultaneously achieve state-of-the-art noise temperature and a good input matching, especially at the lower frequencies. This fact, combined with the poor return loss of the broadband feeds, produces ripples in the receiver noise and gain. A very advantageous solution for applications with mild power and space restrictions, as most VLBI single pixel receivers, is the use of balanced amplifiers. Yebes has excellent designs of 3 dB/90° microwave hybrids to combine with its amplifiers in a balanced configuration (see Figure 3). Since 2020, all VGOS receivers assembled in Yebes are equipped with balanced 2–14 GHz amplifiers, and some of them are being retrofitted to improved their performance.

Recent advances in this area have been driven by Yebes participation in the BRAND-EVN Radionet 4 project. The original 2-14 GHz band for VGOS was expanded to 1.5-15.5 GHz. New five-stage hybrids were developed for this band with exceptional results considering the decade fractional bandwidth. For BRAND-EVN, the balanced solution was finally preferred over the single-ended amplifier [15, 16].

An approach to further reduce the noise contribution of the hybrid in a balanced amplifier is the use of superconductors in microstrip lines. In a collaboration with Chalmers University, a prototype of a compact 4–12 GHz balanced amplifier integrating LNAs and su-

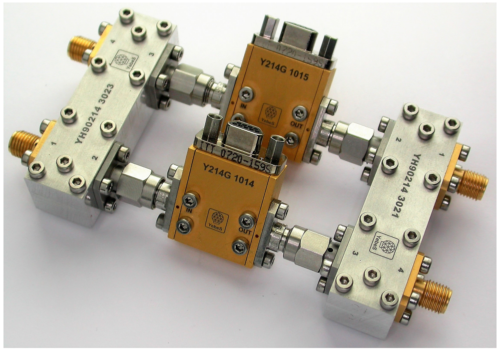

Fig. 3 Balanced Low Noise Amplifier developed in Yebes Observatory. This configuration is required for each receiver polarization channel.

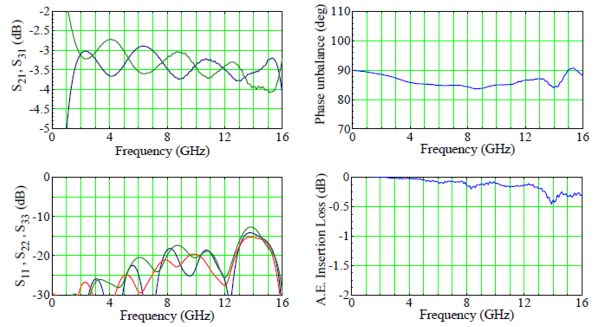

Fig. 4 Performance at 18 K of the Yebes 1.5–16 GHz cryogenic 3 dB/90° coupler for the BRAND project.

perconducting hybrids in the same block was developed, demonstrating an extremely low noise increment over the single-ended amplifier, although an operating temperature of 4 K was required [17].

5 Hardware Conversion of Linear to Circular Polarization

Most broadband receiver feeds provide dual-linear polarization. This has prevented an easy mixed-mode operation of VGOS with the legacy S/X system, which uses circular polarization. As a result, a polarization conversion is required. Two options may be considered: a hardware conversion at the front-end and a digital reconstruction of the circular polarizations at the backend.

For the implementation of the hardware option, Yebes Observatory has developed a solution based on cryogenic 3dB/90° multi-octave stripline hybrids which can be used to obtain both circular polarizations from linear polarization signals. Two designs have been manufactured: one for the 2–14 GHz band (presented in the last IVS biennial report) and another one for the 1.5–15.5 GHz band, in the frame of the BRAND-EVN Radionet 4 project. The cryogenic performance of these 2–14 GHz and 1.5–15.5 GHz broadband hybrids is very good across the whole band (see Figure 4), ensuring cross polarization below 25 dB and axial ratio below 1 dB with only a small penalty on the average noise temperature of the LNAs.

6 NoiseCal and PhaseCal Developments

All Yebes-developed VGOS receivers are equipped with a broadband noise source that can be turned ON, OFF or at 80-Hz rate under remote control. This feature is useful for amplitude calibration. The excess noise (Tcal) generated by the noise source and injected in front of the LNAs 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 regard to the Cable Delay Measurement System (CDMS), a new version was installed in the 13.2-m Yebes RAEGE VGOS radio telescope in 2020. In addition, a new 5-MHz reference cable with lower temperature dependence was installed too. This cable was laid inside an insulating plastic tube, in order to reduce thermal effects on the cable itself. This set-up has been used in VGOS observations with success.

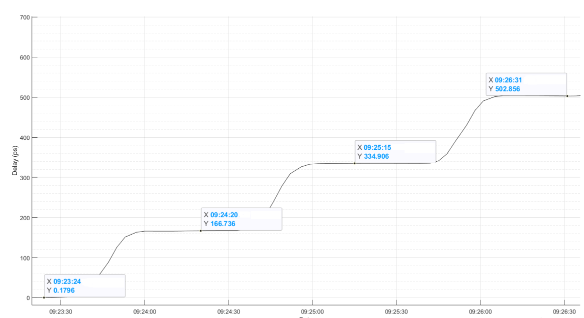

Fig. 5 CMDS test at 167-ps steps.

The system is based on a high accuracy sampling of a voltage proportional to the phase difference between the 5-MHz reference signal from the H-maser with the 5-MHz signal returned from the PhaseCal Antenna Unit, which is installed in the receiver trolley. Currently, the final version of the CDMS is under improvements for better shielded and thermal control. The goal is to provide the Yebes-developed VGOS receivers with this final version as soon as possible.

Figure 5 shows the measured delay when controlled steps of 167 ps are inserted. This test was performed in the Yebes RAEGE VGOS radiotelescope, so the whole cable run is included in the measurement, which is not the same situation as in the lab. The resolution of the system can be seen.

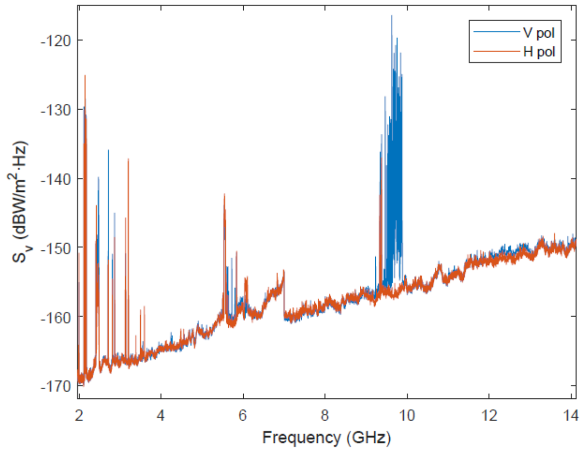

Fig. 7 Yebes RFI measurements in VGOS band at 3° elevation.

7 RFI Measurements

In 2019 and 2020, several RFI campaigns were performed with the permanent RFI measurement system (RAFITA, see Figure 6) on the roof of the lab building.

Fig. 6 Yebes RFI measurement system in the foreground and Yebes RAEGE VGOS radiotelescope in the background.

These measurements (see Figure 7) show the RFI enviroment at Yebes Observatory in the VGOS frequency range for an integrated 360° turn with the spectrum analyzer in max-hold mode. The elevation angle of the measurement was set to 3°. In additon, the RFI spectrum in the current VGOS bands A, B, C, and D were measured with better resolution and sensitivity.

In view of all these results it can be concluded that IMT, WiFi at 2.4 and 5 GHz, WiMax, fixed-service radio links, and radars at 9 GHz are the main contributors to the RFI environment.

From July to November 2020, a search for a new site of the RAEGE Gran Canaria station was carried out. RFI measurements were performed in several locations with the help of Yebes RFI portable equipment. A good candidate location was identified and the island authorities are in the process to buy the land and donate it to IGN.

Finally, the RFI shielding provided by the RAEGE radio telescope metallic servo container was evaluated, in order to check if the Santa María servo racks could be installed inside the concrete pedestal, because the container was suffering severe corrosion due to the salty environment on the island. For this purpose, the RFI environment was measured up to 4 GHz inside and outside this container when the radiotelescope was in movement. The results are shown in Figure 8. The blue trace shows the RFI generated by the servo equipment. When compared with the red trace (outside), it is clearly seen that the container is providing a good shielding. The huge RFI lines below 1 GHz are due to GMS signals. From the RFI view point, the conclusion was that it is better to keep the servo electronics inside the metallic container.

8 New Developments

In 2020, three new developments were started. The first one is a high-temperature superconducting (HTS) filter to notch the 9.4 GHz signal from radars. This design benefits from the results of the previous experi-

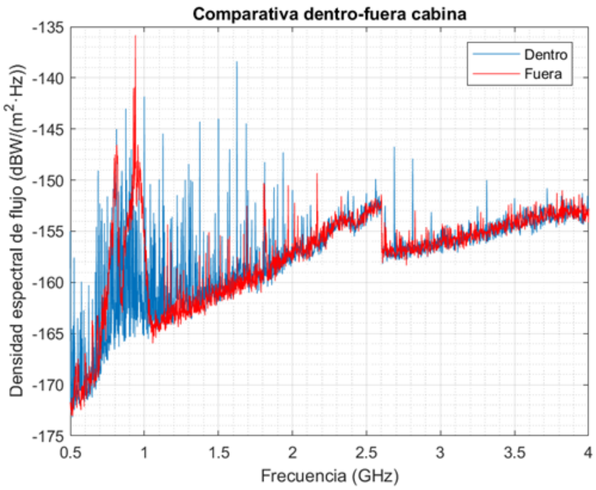

Fig. 8 RFI measurement inside (blue trace) and outside (red trace) the RAEGE servo container.

ence with the S-band HTS band-pass filter [18]. It is expected to build and test two units in 2021.

The second one is an RF-over-fiber link in the range 1–40 GHz, whose componentes were acquired. The system will be integrated and tested during 2021.

Finally, the third one is to install a DiFX VLBI correlator for RAEGE, which could also be part of VGOS and EU-VGOS performing distributed correlation, if such a scheme is adopted. We have already started with a minimal configuration to train one of the Yebes engineers and evaluate the feasiblity of this project.

Acknowledgements

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