Design and Integration of a Laser Distance Sensor for VGOS radiotelescopes

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Table of Contents

List of Figures

List of Tables

1 Introduction

The RAEGE (Red Atlántica de Estaciones Geodinámicas y Espaciales) 13.2-meter VGOS (VLBI Global Observing System) radiotelescopes operated by Yebes Observatory participate in broadband geodetic VLBI (Very Long Baseline Interferometry) observations that contribute to the realisation of the International Terrestrial Reference Frame (ITRF) at the millimetre level. Achieving this precision requires characterisation of all instrumental systematic effects, including mechanical deformations of the telescope structure that directly influence the effective phase centre position of the antenna.

A significant source of such systematics is the vertical displacement of the azimuth cabin — the rotating interface between the azimuth cabin and the concrete pedestal. This displacement results from a combination of thermal expansion and contraction of the pedestal structure, gravitational load redistribution as the telescope slews in azimuth and elevation, and long-term foundation settling. Sub-millimetre height variations can introduce path-length errors of geodetic relevance when correlated.

To characterise and correct these displacements, a high-precision laser distance monitoring system has been designed, manufactured in-house, and deployed at both RAEGE VGOS sites: Yebes (Spain) and Santa María (Azores, Portugal). The system continuously measures the vertical distance between a fixed reference point inside the pedestal and the reflective floor of the azimuth room with micrometre-level precision.

This document provides the complete technical description of the system, covering the scientific motivation, the mechanical and electronic hardware, the software, the procedures for commissioning and daily operation, and the results from the first observation campaigns.

2 System Architecture and Overview

The laser monitoring system is divided into three integrated subsystems that together form a self-contained, autonomous measurement unit:

- **Optical measurement unit:** Micro-Epsilon optoNCDT ILR laser distance sensor, mounted on a precision aluminium assembly inside the antenna concrete pedestal central bore. Emits a pulsed laser beam vertically upwards, which reflects off the azimuth room floor and returns to the sensor.
- **Mechanical mounting assembly:** Custom aluminium structure fabricated in the Yebes Observatory mechanical workshop. Aligns the sensor along the bore axis and provides stable, adjustable fixation to the bore floor.
- **Electronics controller box:** DIN-rail enclosure housing the 24 V and 5 V power supplies, the Raspberry Pi acquisition software, and an OLED status display. Requires only three external connections (230 V mains, Ethernet, sensor cable) for full plug-and-play operation.

The laser beam travels upwards through the hollow bore of the pedestal reflects off the metallic floor of the azimuth room and returns to the sensor (Figure 2.1). Due to the fact that the sensor is fixed to the static pedestal base while the azimuth room rotates with the telescope, each measurement captures the instantaneous vertical position of the ring at the current azimuth angle.

Figure 2.1: System measurement schematic.

3 Mechanical Installation

3.1 Pedestal Structure and Optical Path

The central pillar of the RAEGE/VGOS antenna pedestal contains a vertical circular bore running from the base up into the azimuth room (Figure 3.1a). In the present application this bore provides the optical path for the laser beam. External access is provided through a opening cut in the outer pedestal wall at about 50cm above ground level (Figure 3.1b).

3.2 In-House Mounting Assembly

A dedicated aluminium mounting assembly was designed and manufactured at the Yebes Observatory mechanical workshop. The design consists of a flat base plate with slotted holes for lateral fine-adjustment and a vertical upright plate to which the sensor body is attached (Figure 3.2). The

(a) Looking up from below: optoNCDT sensor pointing toward the circular bore opening leading to the azimuth room.

(b) Rectangular aperture on the pedestal outer wall. The bore and sensor mount are visible through the opening.

Figure 3.1: Pedestal aperture and internal optical path.

geometry ensures that the laser emission axis is collinear with the pedestal bore axis within the alignment tolerance required for accurate measurement.

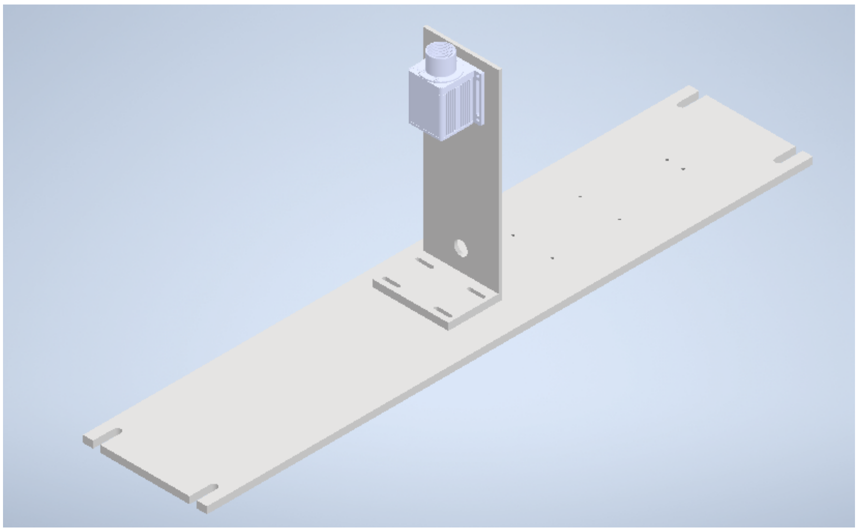

Figure 3.2: CAD model of the laser mounting assembly.

The base plate is secured to the bore floor using M6 screws. After alignment verification the screws are locked with thread-locking compound. A central hole in the upright provides a clean cable exit without mechanical stress on the sensor connector. The entire assembly is fully reversible and can be re-installed without realignment if temporarily removed for maintenance.

4 Electronics and Controller Box

4.1 Design Philosophy — Plug-and-Play Enclosure

All electronics are housed in a single DIN-rail enclosure designed for plug-and-play installation. The enclosure requires only three external connections:

- 230 V AC mains input
- RJ45 Ethernet cable for network access and remote data logging
- RS-422 serial cable from the optoNCDT sensor (via USB adapter to the Raspberry Pi)

This design minimises on-site wiring, makes the system fully self-contained, and allows the entire controller box to be swapped or moved without any rewiring of the sensor or network infrastructure. The enclosure is mounted directly on the outer face of the pedestal, adjacent to the laser aperture, and is labelled *"13M LASER CONTROLLER"* for immediate identification.

4.2 Internal Components

Components are arranged on a standard DIN rail inside the enclosure as can be seen in Figure 4.1.

Figure 4.1: Controller enclosure open.

The controller enclosure integrates several internal components responsible for power distribution, system control, and user monitoring. The mains input is protected and isolated by a Schneider Electric Acti9 iDT40T C4 (4 A) circuit breaker, which provides overload protection for the 230 V supply. Power conversion is performed by two DIN-rail power supplies: a Mean Well 24 V / 1.5 A (36 W) unit dedicated to powering the optoNCDT ILR laser sensor, and an RS PRO 5 V / 2.4 A (12 W) supply used exclusively for the Raspberry Pi. The Raspberry Pi acts as the central control unit, handling data acquisition, serial communication with the sensor, Ethernet connectivity, and hosting the system services through systemd. For local monitoring, the system includes an SSD1306 OLED display with a resolution of 128 × 64 pixels, connected via I2C (address 0x3C), which provides a live status display showing the measured distance, the sensor temperature, and the network information (IP and MAC addresses). The display is visible through a transparent sub-panel, allowing the system status to be checked without opening the enclosure.

4.3 Field Installation

The controller box is mounted on the outer pedestal wall immediately above the laser aperture. LED indicators on the power supplies (blue LED on 24 V, green LED on 5 V) provide instant visual confirmation of power status through the transparent cover (Figure 4.2a).

A laser hazard warning sign (Class 2, *PELIGRO RADIACIONES LÁSER*) is fixed to the pedestal below the controller box as required by safety regulations (Figure 4.2).

(a) Controller box with warning sing (rear part).

(b) Hazard warning sing (front part).

Figure 4.2: Final installation of the laser system.

5 Sensor Specifications

Distance measurement is carried out using a Micro-Epsilon optoNCDT ILR time-of-flight laser sensor. This device operates using a pulsed time-of-flight measurement principle and provides a measuring range from 0.05 m to 150 m, making it suitable for long-distance monitoring applications. The sensor offers a standard resolution of 0.1 mm, which can be improved to better than 0.01 mm when signal averaging is enabled, and an accuracy of ± 1 mm across the full measurement range, or better than 0.1 mm with averaging. It uses a Class 2 visible red laser (< 1 mW), which is considered eye-safe under normal reflex conditions. Communication with the control system is performed through an RS-422 serial interface operating at 115200 baud, with ASCII output transmitted via a USB adapter connected to the control computer. The device is powered by a 24 V DC supply provided by a dedicated DIN-rail power supply within the enclosure and is specified to operate in an ambient temperature range from 0 °C to +50 °C. The sensor has approximate physical dimensions of 85 × 50 × 45 mm. In the current configuration, the system performs one distance measurement every five seconds (equivalent to 12 samples per minute). In addition to distance measurements, the sensor also reports its internal device temperature, which is retrieved through the `GETTEMP` command and logged together with the measurement data.

6 Data Acquisition Software

The Raspberry Pi runs three Python 3 programs deployed in `/home/YebesObservatoryuser/laser13m/`. Each program is managed as a systemd unit (service or timer), ensuring automatic startup at boot, automatic restart on failure, and centralised log management.

6.1 `getLaserMeasures.py` — Data Acquisition and Storage

This is the core measurement program. It is triggered every 5 seconds by a systemd timer and performs a complete acquisition cycle with each execution.

Execution flow

1. Opens the serial port `/dev/ttyUSB0` at 115200 baud.
2. Sends `LASER ON` to activate the sensor.
3. Sends `GETTEMP` and reads the device temperature; retries until a valid numeric value is obtained.
4. Sends `OUTPUT RS422_ASCII` to configure the output format.
5. Sends `LASER MEASURE` to start ranging mode.
6. Reads 10 lines from the serial port and extracts the distance from the last valid response; retries if the value is non-numeric.
7. Inserts both values (temperature in °C, distance in mm) into the MySQL table `measures` via a single `INSERT INTO` statement.

6.2 `checkLaserMeasures.py` — Daily Watchdog

A monitoring program that runs once per day at 00:05 UTC. It queries the database for the timestamp of the most recent measurement and compares it with the current date. If no data has been recorded today, it sends an e-mail alert to the responsible operator, ensuring that data gaps are detected and reported within 24 hours.

6.3 showLaserScreen.py — Live OLED Display

A persistent display daemon that runs in an infinite loop. Every 10 seconds it acquires a fresh measurement from the sensor and refreshes the OLED screen with four lines of status information. It is implemented as a systemd service of Type=`simple` with `Restart=always` and `RestartSec=3`, so it recovers automatically from any transient communication error.

Data shown on display

- Line 1 (large): Distance in mm
- Line 2 (medium): Sensor temperature in °C
- Line 3 (small): IP address of the Raspberry Pi
- Line 4 (small): MAC address of the Raspberry Pi

6.4 systemd Services and Timers Summary

All units are installed in `/etc/systemd/system/` and enabled at boot. The crontab at `/home/Yebes Observatoryuser/auto/` is intentionally empty — scheduling is handled entirely by systemd.

7 Commissioning and Operation

7.1 SSH Connection to the Raspberry Pi

The Raspberry Pi is accessible via SSH from any machine on the Yebes Observatory network. The current IP address is always visible on the OLED display without needing to open a laptop.

```
# Connect via SSH (replace <IP> with the address shown on the OLED)
ssh -X -l oanuser <IP>
```

7.2 First-Time Installation (Initial Setup)

The following steps are required once when deploying a new unit or reinstalling after a system reset.

Step 1 — Copy systemd unit files

```
sudo cp $/home/oanuser/laser13m/*.service /etc/systemd/system/
sudo cp $/home/oanuser/laser13m/*.timer   /etc/systemd/system/
```

Step 2 — Reload systemd and enable all units

```
sudo systemctl daemon-reload
sudo systemctl enable --now getLaserMeasures.timer
sudo systemctl enable --now checkLaserMeasures.timer
sudo systemctl enable --now showLaserScreen.service
```

Step 3 — Install Python dependencies

```
cd /home/oanuser/laser13m
pip3 install -r requirements.txt --break-system-packages
sudo apt install python3-mysqldb  # MySQL client for Python
```

Step 4 — Serial port permissions

```
# Add oanuser to the dialout group (required once; needs re-login to take effect)
sudo usermod -aG dialout oanuser

# Log out and back in, then verify:
groups oanuser  # dialout should appear in the list
```

Step 5 — Verify OLED display (I2C)

```
# The SSD1306 should appear at address 0x3C
sudo i2cdetect -y 1
```

7.3 Daily Verification

Under normal operation no manual intervention is required. The following quick checks can be performed to confirm system health.

Check service status

```
sudo systemctl status getLaserMeasures.timer
sudo systemctl status checkLaserMeasures.timer
sudo systemctl status showLaserScreen.service
# All three should show: active (running) or active (waiting)
```

Monitor the acquisition log in real time

```
tail -f /home/oanuser/laser13m/getLaserMeasures.log
# Expected output every 5 s: Temperature: 22.1C - Distance: 7777.4mm
```

View systemd journal for a specific service

```
sudo journalctl -u showLaserScreen.service -f
sudo journalctl -u getLaserMeasures.service -n 50 --no-pager
```

7.4 Restarting Services

```
# Restart all services
sudo systemctl restart getLaserMeasures.timer checkLaserMeasures.timer showLaserScreen.service

# Stop all laser services
sudo systemctl stop getLaserMeasures.timer checkLaserMeasures.timer showLaserScreen.service

# Start them again
sudo systemctl start getLaserMeasures.timer checkLaserMeasures.timer showLaserScreen.service
```

8 YEBES Observational Results

8.1 Azimuth Sweep — Height Variation vs. Azimuth and Elevation

A dedicated measurement campaign was conducted on 1–2 September 2025. The telescope was driven in a full 360° azimuth sweep at three fixed elevation angles (EL = 25°, 45°, and 75°) with 1° azimuth steps. At each position the laser distance was recorded and the variation relative to a common reference offset was computed in micrometres.

Figure 8.1 shows the results. A structured, repeatable variation of the ring height is observed as a function of azimuth, with peak-to-peak amplitudes of approximately ±750 μm (1.5 mm total). Most significantly, the pattern is highly consistent across all three elevation angles tested. The three curves overlap closely throughout the full 360° sweep, demonstrating that the signal is dominated by an azimuth-dependent mechanical deformation of the bearing structure and is not significantly modulated by gravitational deflection associated with elevation changes.

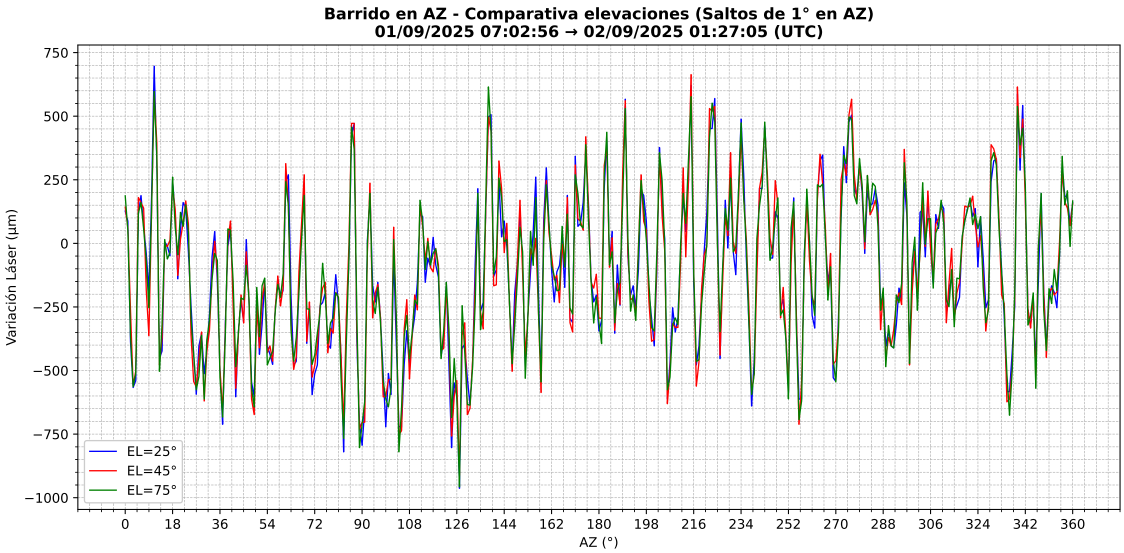

Figure 8.1: Azimuth sweep (01–02 Sep 2025): laser distance variation (μm) as a function of azimuth angle (°) for three elevation angles (EL = 25°, 45°, 75°).

The strong agreement between curves at different elevation angles suggests that the height variation is a property of the azimuth ring geometry rather than a gravitational deflection of the overall telescope structure.

8.2 Correlation with Operational VLBI Observing Sessions

Figure 8.2 presents a comparison between the dedicated azimuth sweep data and laser measurements recorded passively during two operational VGOS geodetic observing sessions (VR2401Yj and VO4045). The azimuth angle is plotted on the horizontal axis and the laser variation on the vertical axis. VLBI session data are averaged over 30-second windows to match the sparse telescope pointing cadence.

The systematic azimuth-dependent pattern observed in the dedicated sweeps is clearly reproduced in the operational session data from both experiments, confirming that the structural effect is continuously present during normal geodetic observations.

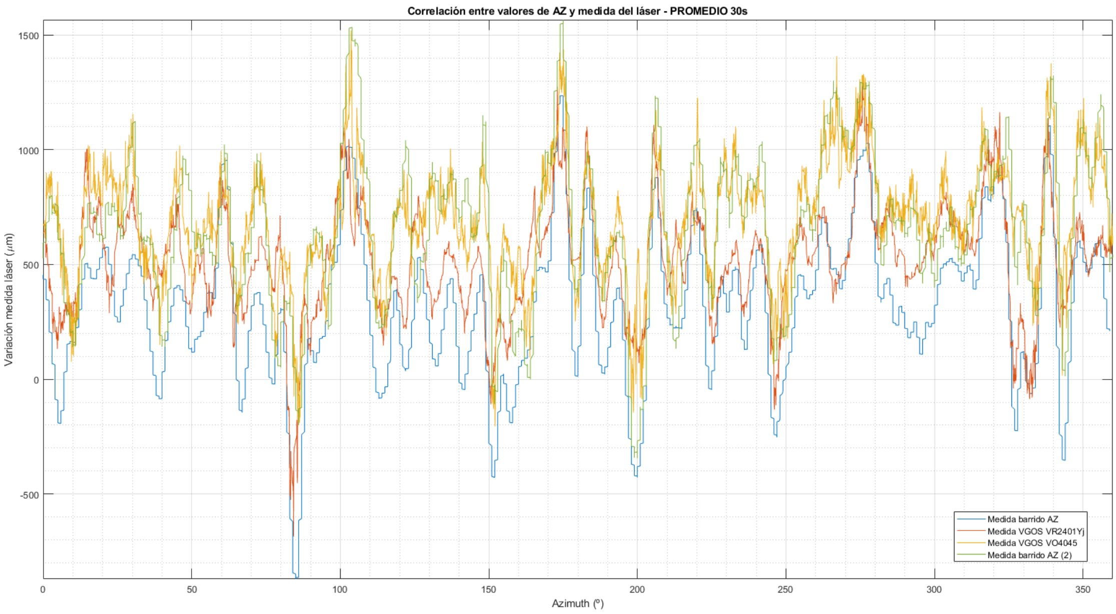

Figure 8.2: Laser variation vs. azimuth: dedicated sweeps (blue, green) compared with two VLBI sessions VR2401Yj (red) and VO4045 (yellow).

These results provide a solid empirical basis for constructing an azimuth-dependent correction model for the height of the azimuth cabin. Such a model can be incorporated into the geodetic analysis pipeline to reduce path-length errors and improve the accuracy of VLBI-derived station positions and baseline lengths.

9 Conclusions and Future Work

A compact, autonomous laser distance monitoring system has been successfully designed, manufactured in-house, installed and tested. The system runs automatically without any manual effort and keeps a complete record of everything, from the original readings to the remote database with timestamps.

Main conclusions

- The system achieves micrometre-level precision in the measurement of the vertical position of the azimuth cabin, sampling every 5 seconds continuously.
- A clear azimuth-dependent height variation with a peak-to-peak amplitude of approximately 1.5 mm is observed and is highly repeatable between independent measurements.
- The variation is essentially independent of telescope elevation angle (tested at 25°, 45°, and

75°), indicating a structural rather than gravitational origin.

- The same pattern is present during operational VLBI geodetic sessions, confirming its relevance as a systematic error source.
- The plug-and-play enclosure design (single box, three connections) enables rapid deployment and maintenance at both stations.

Future work

- **Seasonal analysis:** quantify the thermal component of the height variation by correlating laser data with ambient and structural temperature measurements over full annual cycles.
- **Correction model:** develop and validate an empirical azimuth-dependent lookup-table correction and integrate it into the VLBI geodetic analysis pipeline.
- **Cross-site comparison:** compare the Yebes and Santa María datasets to assess site-specific differences in pedestal behaviour and identify common structural signatures.
- **Extended monitoring:** continue long-term data collection to detect any trends in baseline pedestal height related to foundation settling or structural ageing.

A Bill of Materials

Table A.1: Bill of materials.

Component	Model / Description	Notes
Laser distance sensor	Micro-Epsilon optoNCDT ILR	RS-422 / ASCII; 24 V DC
Single-board computer	Raspberry Pi	Raspbian OS, Python 3
24 V DIN-rail PSU	Mean Well (36 W, 1.5 A)	Laser sensor supply
5 V DIN-rail PSU	RS PRO (12 W, 2.4 A)	Raspberry Pi supply
Circuit breaker	Schneider Acti9 iDT40T C4, 4 A	Mains protection
OLED display	SSD1306 128 × 64 px, I2C 0x3C	Status display
Enclosure	IP-rated DIN-rail box	*'13M LASER CONTROLLER'*
Mounting plate	Custom aluminium alloy	Yebes Observatory mechanical workshop
Cable adapter	RS-422 to USB serial	Sensor to Raspberry Pi

B File and Directory Structure

```
/home/Yebes Observatoryuser/
+-- laser13m/                 <- Main application directory
|   +-- getLaserMeasures.py    <- Acquisition + MySQL storage (runs every 5 s)
|   +-- checkLaserMeasures.py <- Daily watchdog + e-mail alert
|   +-- showLaserScreen.py     <- Persistent OLED display daemon
|   +-- requirements.txt       <- Python package dependencies
```

```
|   +-- getLaserMeasures.log   <- Acquisition log (stdout + stderr)
|
+-- auto/                      <- Crontab directory (intentionally empty)

/etc/systemd/system/
+-- getLaserMeasures.service   <- oneshot service (Type=oneshot, User=Yebes Observatoryuser)
+-- getLaserMeasures.timer     <- 5-second recurring timer
+-- checkLaserMeasures.service <- oneshot watchdog service
+-- checkLaserMeasures.timer   <- Daily 00:05 UTC timer (Persistent=true)
+-- showLaserScreen.service    <- Persistent display service (Restart=always)
```

C Python Dependencies

The file `requirements.txt` at `/home/Yebes Observatoryuser/laser13m/requirements.txt` lists the packages required for `showLaserScreen.py`. The packages for `getLaserMeasures.py` and `checkLaserMeasures.py` are installed at system level.

Table C.1: Python dependencies.

Package	Purpose
`pyserial`	Serial port communication with the optoNCDT sensor (all scripts)
`MySQLdb` (`python3-mysqldb`)	MySQL database access (`getLaserMeasures.py`, `checkLaserMeasures.py`) — install via `apt`
`adafruit-circuitpython-ssd1306`	OLED SSD1306 display driver (`showLaserScreen.py`)
`adafruit-blinka`	CircuitPython compatibility layer for Raspberry Pi GPIO/I2C
`adafruit-extended-bus`	Extended I2C bus support
`pillow`	Image drawing library for OLED graphics (PIL)
`board`	Raspberry Pi board pin definitions
`uuid`	MAC address retrieval