FIRST RESULTS FROM THE NEWLY MODERNIZED SAN FERNANDO LASER STATION: COMMEMORATING 45 YEARS OF SERVICE

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ABSTRACT

The San Fernando Laser station (SFEL) is a key part of Spain's space surveillance network and has recently undergone an extensive upgrade to improve satellite and space debris tracking. The improvements include an advanced alt-azimuth mount with high pointing accuracy and integrated absolute optical encoders. This upgrade includes the implementation of a complete station control software. Additionally, a new event timer with high accuracy time-stamp for Time-of-Flight measurements. At optical level, a new finder telescope that enables improved tracking of faint objects and low-reflectivity debris has been integrated. The existing Cassegrain telescope has also been upgraded and a new laser beam launcher telescope allows for precise beam adjustments in both divergence and pointing. Other auxiliary systems have been optimized to enhance the station's overall performance. These improvements allow us to consider other future and new capabilities that will strengthen SFEL's position as a reliable member of the networks in which it participates, both at the geophysical/geodetic level and in the SST field.

1 INTRODUCTION AND CONTEXT

Work in the field of space geodesy and artificial satellite tracking began at the Royal Institute and Observatory of Spanish Navy (ROA) in 1958, thanks to a collaboration agreement with the Smithsonian Institution (USA). Under this agreement, the Baker-Nunn Camera (BNC) for satellite photographic tracking became operational in San Fernando that year [1]. Since then, instrumental development at the ROA has been ongoing.

Figure 1. On the left, the original Baker-Nuun Camera installed in San Fernando, and on the right, after being transformed into the new TFRM robotic telescope.

In 1968, under an agreement between this Observatory and the *Groupe des Recherches de Geodesie Spatiale* (CNES-GRGS) of France, a primitive ruby laser was installed near the aforementioned BNC [2]. Following various agreements with CNES, the Observatory was lent a new ruby laser in 1983, which was installed in 1984 and subsequently participated in the MERIT project. In 1986, the ruby equipment was dismantled and returned to CNES. In accordance with the prior agreement, the primitive mount and part of the tracking control electronics remained at this center. In recent years, the station has been completely redesigned, from an optical, electronic, and computer standpoint, under the auspices of various scientific projects, both by the Subdirectorate General of Technology and Research of the Ministry of Defense (SDG PLATIN), the National Space Plan of the Ministry of Economy and Competitiveness (MINECO), and the General Directorate of Armaments and Material (DGAM) of the Ministry of Defense.

Figure 2. Photographs of the first-generation laser station installed at ROA by CNES, top right; the modifications to the dome for its adaptation to the laser station, bottom right and the final installation on the left in December 1979.

The Observatory's strategic location gives the station an excellent advantage: its area of action allows it to observe

Proc. 9th European Conference on Space Debris, Bonn, Germany, 1–4 April 2025, published by the ESA Space Debris Office
Editors: S. Lemmens, T. Flohrer & F. Schmitz, (http://conference.sdo.esoc.esa.int, April 2025)

satellite orbits flying over both the eastern Atlantic and the western Mediterranean, making it an important link between sensors installed in the Americas and Europe and reinforcing its role in global space surveillance.

Since 1999, the ROA has participated in various space geodesy campaigns in collaboration with the other stations of the International Laser Ranging Service (ILRS) and also with its European regional organization (EUROLAS), tracking various types of artificial satellites, such as ERS, ENVISAT, LAGEOS, and TOPEX/POSEIDON, to name just a few. With the aim of improving the performance of the Spanish contribution to the activities of the European Union Space Surveillance and Tracking (EU-SST) program, a study was conducted in 2017 on the impact of installing a more powerful laser bench than the one currently in use [3]. This new equipment was financed by EU funds and awarded by the CDTI (Spanish Institute of Technology and Communications), allowing for the tracking of a more comprehensive set of space objects, including non-collaborative objects, i.e., space debris. This laser bench, as well as the new one dedicated to collaborative object tracking within the ILRS operating framework, marked the beginning of a profound modernization of the station that prevented a critical situation that nearly led to its closure.

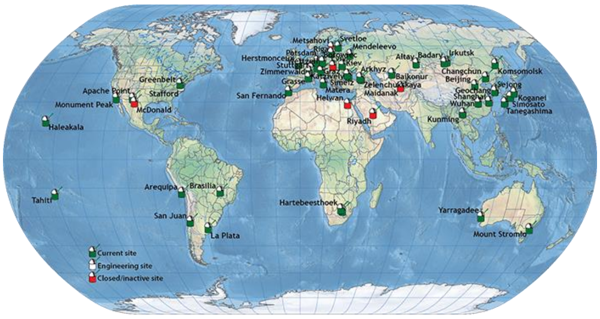

Figure 3. The distribution of stations belonging to the ILRS network.

In August 2022, the AMELAS project (Updating the Mount-Electronics of the ROA Laser Station) was approved, funded by the DGAM and awarded to AVS, a Spanish global SME recognized for its role in major science and space projects. During the first half of 2024, the main effort focused on the final integration phase of the new mount and the development of all associated subsystems. On June 25, the old mount was decommissioned and replaced with the new one prototype. The main objective of this project was to modernize the station, significantly improving its observational performance, angular resolution, and tracking capability, and decoupling the control software from the previous mount. The new mount represents a key technological advancement that has increased the efficiency of observations and improved the quality of the data obtained.

In the second half of 2024, progress was made toward the first test observations. Thanks to the rapid integration of the new system, the first successful observations took place in early August, allowing the effectiveness of the new system to be verified under real-world operating conditions. Improvement and debugging efforts continued throughout the rest of the year, contributing to further improvements in the station's performance.

As the station reached more stable operating levels, it was able to participate in a new satellite and space debris tracking campaign, led by GMV as part of the Debris Laser Tracking Network (DLTN) activity, funded by the European Space Agency (ESA S2PS1SC06) and subsequently in the EU SST - SDLR R&D on Laser Contribution (454378-2024) activity lead by DiGOS.

2 MODERNIZATION AND TECHNOLOGICAL ADVANCES

Prior to the integration of the AMELAS project, SFEL was composed of various subsystems that formed the basic infrastructure for its operation.

The control subsystem was based on a Range Gate Generator (RGG), developed by the station itself using FPGA technology; the Time-of-Flight (ToF) measurement subsystem used the Eventech A032 Event Timer, allowing for considerable measurement accuracy. The time & frequency subsystem was responsible for ensuring synchronization between the ROA's time and frequency laboratory and the station, receiving the PPS-ROA signal via a Symmetricom 8040C and a White Rabbit WR-ZEN Time Provider to ensure an accurate time reference.

However, the station had a significant weakness: the altazimuth mount, whose performance was limited in terms of accuracy and tracking capability due to the use of a pair of previously unupdated servomotors and gears. This system limited nominal accuracy to 6.5 arcseconds, but due to wear over years of operation, inaccuracies of up to 20 arcseconds could be reached. Furthermore, the pointing system lacked absolute angle encoders and accumulated errors during tracking, requiring constant return to the homing position. The low accuracy prevented efficient tracking of non-cooperative objects, especially those with low reflectivity. The software, developed in Q-Basic and compatible with MS-DOS, was highly coupled and limited the implementation of further improvements.

The telescopes also exhibited certain limitations, such as optical defects in the secondary of the Cassegrain receiving telescope or a mismatch between the mechanical pointing control of the launch telescope and the configuration of the finder telescope.

2.1 Mounting system

The cornerstone of this upgrade was the installation of a state-of-the-art altazimuth mount designed by AVS, which significantly enhances ROA's capabilities in tracking space debris by integrating advanced mechanical design, precision control systems, and robust technological innovations.

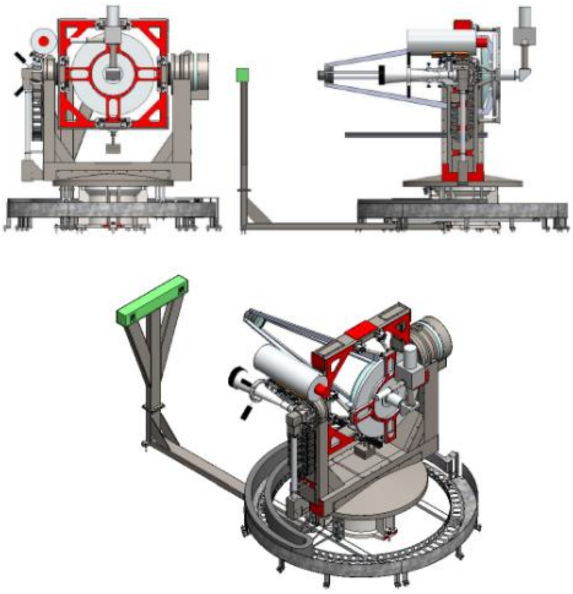

Figure 4. 3D model of the mount from the AMELAS project.

This mount has been designed to support a primary mirror telescope up to 800 mm and features a dedicated Coudé optical path for precise output laser propagation. Additionally, the mount incorporates multiple mechanized mounting areas, allowing for future station evolutions without mechanical intervention, thereby improving the station's flexibility and longevity.

The Alt-Az mount has margin for higher load-bearing capabilities, reliably supporting the telescope and essential auxiliary equipment while maintaining precise control. Extensive Factory Acceptance Tests (FAT) confirmed that the mount achieves exceptional pointing accuracy, with nominal pointing errors limited to mere arcseconds. Tracking precision has been thoroughly validated, demonstrating sustained accuracy across varying operational times and payload weights. High-performance direct-drive motors combined with optical absolute encoders support the robust fork and bearing setup, forming the backbone of the mount’s precision and stability. These components ensure minimal mechanical backlash, precise positioning, and superior reliability in sustained operational scenarios.

The system's stability and reliability have undergone rigorous validation through comprehensive vibration and stability tests, simulating diverse payload scenarios and environmental conditions. The mount is designed to function continuously, with operational requirements comfortably below the maximum capabilities of its components, thus ensuring prolonged equipment lifespan and reduced maintenance needs. Compensation systems and integrated calibration processes, such as TPoint software [4], enable its operational precision, compensating dynamically for systematic errors and environmental influences.

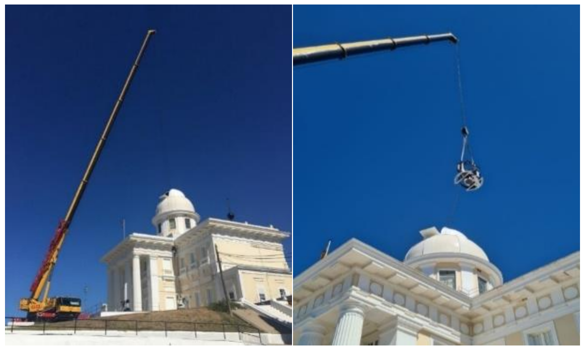

Figure 5. Photographs of the installation of the new mount, which bear similarities to those taken 40 years earlier.

Integration and compatibility are cornerstones of the mount's design philosophy. It supports future telescope modifications and accessories, and its control software and hardware seamlessly integrate with existing astronomical software and automation frameworks. The mount is optimized for remote operation.

Operational validation has been effectively demonstrated, with the mount achieving an impressively short integration timeline (from installation in July to active campaign participation by September), obtaining successful laser-ranging measurements of satellites including LAGEOS and various satellites in Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and GNSS regimes. Real-world testing and recorded observational data provide robust evidence of the mount’s practical performance capabilities.

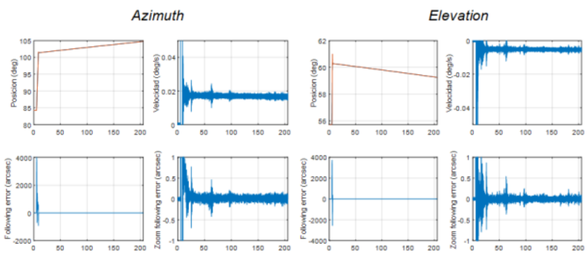

Figure 6. Azimuth and elevation graphs showing the pointing accuracy after performing transitions between tracking and movements at tracking speed in LEO.

Technologically, the Alt-Az mount distinguishes itself through unique features such as a customised control software, developed in collaboration with ROA, for meeting the specific tracking and ranging needs.

Maintenance has been streamlined for simplicity and efficiency, ensuring ease of upkeep and high availability. Built to withstand a wide range of environmental conditions, including temperature extremes and varying wind intensities, the Alt-Az mount by AVS represents a sophisticated, reliable, and future-proof solution to ROA's evolving space debris tracking requirements.

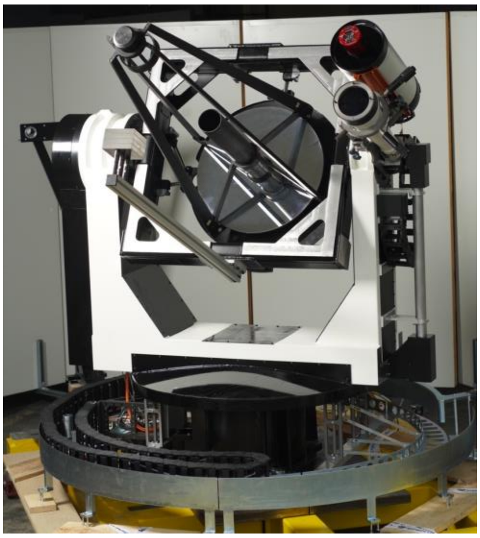

Figure 7. Final result of the AMELAS project prior to assembly at the observatory.

The calibration system, developed alongside the mount, is fixed to the common pillar to ensure its position and, therefore, the measurements taken are consistent. This configuration ensures that the calibration system operates accurately, maintaining its alignment and avoiding interference with the rest of the structure during adjustment work.

The pointing model is currently being refined using TPoint software. The pointing offsets of approximately 80 stars in elevation and azimuth are calculated relative to the catalogue. The coefficients provided by the software not only serve to correct the pointing but also provide valuable information on parameters that require optimization in iterative phases. Currently, pointing corrections are within a range of a maximum and minimum of 20 arcseconds in elevation angle, reflecting the accuracy achieved so far and underscoring the need for further parameter adjustment to improve system performance.

2.2 ToF Measurement System

The integration of the Eventech ESTT-7 event timer (ET) into the SFEL architecture has been successful at both the hardware and software levels. The transition from the ET-A032 to the new ESTT-7 has significantly simplified our setup and improved system flexibility.

To evaluate the performance improvements of the ESTT-7 compared to the A032, comparative measurements based on SLR calibration were performed, recording data simultaneously on both devices. Our calibration consists of measuring the time of flight of 1,000 laser pulses using an optical quadratic array at a known distance. The recordings obtained by both devices are shown in Fig. 8. As can be seen, a notable improvement in the dispersion of the measurements obtained by the new device is observed. The difference in the mean of both series is due to delays associated with the installation configuration of both devices Unlike the ET-A032, which was based on a traditional client-server architecture, the ESTT-7 significantly simplifies integration by offering a USB 3.2 connection and a more accessible mid-tier API. The new device has been tested in 10 Hz and kHz configurations, confirming stable performance in our environment. For the kHz tests, synthetic event data was injected into the channels.

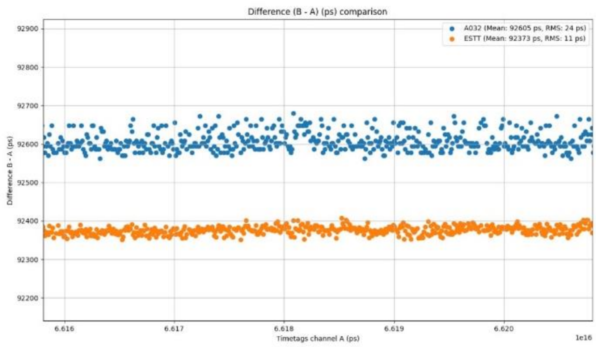

Figure 8. Comparison of accuracy and performance in the ToF measurement system using the Event Timer A032, in blue, and the ESST-7, in orange.

The system is integrated with a photodetector for each laser line, which are connected via optical fiber to an amplifier and a constant fraction discriminator. This device sends a stable signal to the ET on channel A. The same existing configuration is maintained on channel B, maintaining the connection to the detectors.

2.3 Detection system

Currently under development, the system maintains its previous configuration with the C-SPAD as the main detector. The new configuration will integrate three previously acquired detectors: an APD, a gated MCP-PMT, and the aforementioned C-SPAD. To ensure the stability of the equipment, the detectors are planned to be installed on an optical table within the laser room itself, and connected to the mount via optical fiber. This triple configuration will allow for greater versatility in different observation configurations of objects with diverse characteristics and in different observation environments. It will also require the development of control systems by station personnel to optimize operational capabilities.

2.4 Optical improvements

This section addresses the latest optical improvements implemented at the station to optimize its observation capabilities. These improvements include upgrades to the receiving, finder, and launcher telescopes, as well as advances in optomechanics and the Coudé path.

2.4.1 Receiving telescope

The SFEL receiving telescope is based on a classic Cassegrain design with a parabolic primary mirror and a hyperbolic secondary mirror. The primary mirror has an aperture of 600 mm and a focal length of 1800 mm (f/3). The secondary, with a four-magnification factor, provides a final focal length of 7200 mm (f/12). This instrument was not designed to achieve diffraction-limited images, as for the station's application, only the few photons reflected by the satellites are needed to determine the round-trip flight time. However, obtaining sharper and more precise images has improved the visibility of distant and faint objects observed at the telescope's focus, which enhances confidence in their acquisition and tracking.

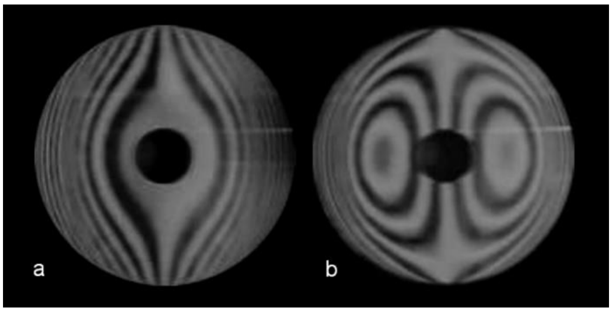

Figure 9. a) Ronchigram of the primary mirror with the Ronchi grid at the paraxial focus and b) at the marginal focus (grid frequency = 5 l/mm).

The optical quality of the instrument was assessed using the Ronchi test, both of the primary mirror alone and of the assembled and properly collimated telescope. The primary mirror was mounted on an optical bench, and the test was carried out close to its radius of curvature. The measurements of the position of the paraxial and marginal foci were as expected for an f/3 paraboloid. Although its surface is not very uniform and shows some peripheral rings, no significant discontinuities were observed, as shown in Fig. 9. However, a moderately flattened edge was visible.

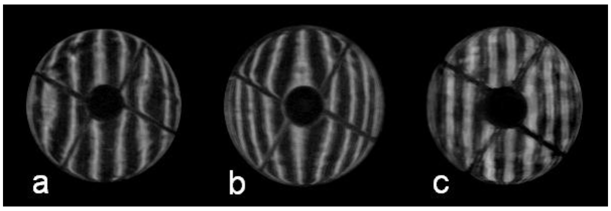

Figure 10. a) Ronchigram obtained with the original installed secondary mirror, b) after polishing it to achieve a spherical surface, and c) after correcting it to reach the required hyperboloid (grid frequency = 3.15 l/mm).

A Ronchigram with the original secondary mirror in place, obtained using a distant light source, is shown in Fig. 10.a, obtained using a distant light source. With the exception of the flattened edge of the primary mirror, the defects observed in the Ronchi pattern are mainly due to imperfections in the surface of the secondary mirror. Consequently, the decision was made to refigure this mirror in order to improve image quality. Fig. 10.b shows the Ronchigram after polishing the convex surface to a sphere, and Fig. 10.c after refiguring this to the required hyperboloid (the small distortions are due to slight atmospheric effects during testing).

2.4.2 Finder telescope

SFEL features a new high-precision finderscope, consisting of an 8-inch Celestron Rowe-Ackermann Schmidt Astrograph (RASA) telescope. Its optics, designed for advanced astronomical imaging, are compatible with astronomical CMOS cameras, offering a flat field of view free of optical aberrations such as coma, astigmatism, or chromatic aberration, making it ideal for obtaining sharp images across the entire sensor. The telescope features an ultra-stable focusing system, internal cooling, and an internal mount that allows for easy installation of a light pollution filter. This telescope is coupled with a cooled monochrome ZWO ASI 2600 MM Pro CMOS astronomical camera (Sony IMX571), with a quantum efficiency of up to 91%. The combination results in a field of view of 3.36 x 2.25 deg^2.

Figure 11. Field of view with the specified configuration of the finder telescope.

This configuration allows for the detection of small, low-reflectivity objects that move quickly relative to the station. It is especially useful for tracking space debris, which can sometimes be a real challenge due to its characteristics.

2.4.3 Launcher telescope

The new launcher telescope, manufactured and undergoing validation testing but not yet installed on the mount, is based on COTS optomechanical components and incorporates two motorized linear translation platforms (XY and Z). This configuration, designed by station personnel using the BEAM4 ray tracer, allows beam divergence to be adjusted within a range of 5 to 150 arcseconds to accommodate tracking of both collaborative objects and space debris. It also provides the ability to perform pointing corrections on the order of kilometres in the LEO along-cross track plane, that is, in the direction perpendicular to the observer's line of sight at this altitude. This capability allows for correction of possible misalignments, thereby improving the system's precision and stability during observations.

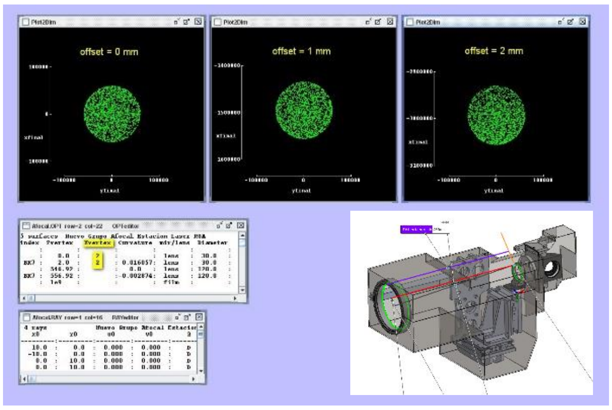

Figure 12. Design of the launcher telescope in the Beam4 tracer and 3D mechanical design.

2.4.4 Optomechanics and Coudé path

The optical configuration has been optimized, including the layout of the optomechanical components and the optical table supporting the laser benches. This improved alignment of the optical path now includes six high-reflectance dielectric mirrors (>99%) adapted to high-power lasers with a wavelength of 532 nm. The substrate material is fused silica, providing low thermal expansion, and the dielectric coating is multi-layered with damage thresholds of up to 28 J/cm^2.

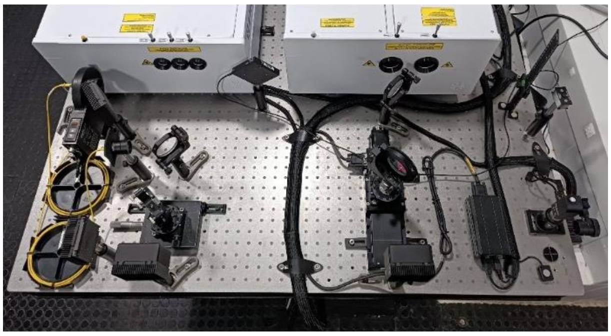

Figure 13. Optomechanics and optical configuration available at the output of the laser benches.

The optomechanical system located at the exit of the laser benches facilitates rapid configuration and allows software interchange between different devices. In addition, a new circuit has been incorporated for detecting laser pulse emission, allowing each bench to have its own independent detection subsystem.

2.5 Control software and hardware

The station's new software, developed by our own staff, is robust and designed to efficiently manage the operations performed by each station subsystem. This language enables superior and stable performance, making it ideal for handling large amounts of data and real-time tasks over long periods. Our environment is based on a Windows 11 Pro operating system with MinGW as the C++17 compiler and Qt5/6 framework for GUI interfaces, ensuring compatibility with modern development practices.

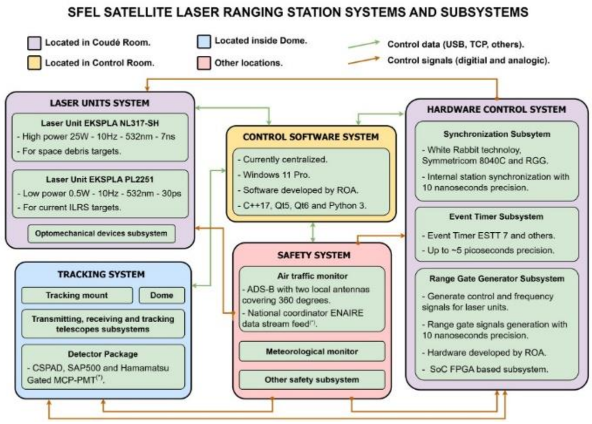

Figure 14. General diagram of the systems and subsystems of SFEL.

The control software was developed based on the station's hierarchy and structure. Currently, the control software consists of several graphical user interfaces:

- Control Interface: Centralizes the control and monitoring of all subsystems (laser benches, measurement systems, tracking mount, Range Gate Generator (RGG), among others). It manages the laser operating modes (calibration, maximum energy, tuning, etc.), and monitors their critical parameters. This interface also provides information on objects flying over the station, such as their orbit, elevation, and pass times.

- Tracking Interface: Monitors the return echoes of each measurement in real time and calculates their statistics. This allows for instant corrections during tracking, thus improving the accuracy of the results obtained.

- Filtering and Observation File Generation Interface: Allows manual and automatic filtering of tracks according to pre-selected parameters. After filtering, CRD v2.0 files are automatically generated.

- Space Object Database Interface: Organizes available objects, allowing observations to be selected and scheduled according to specific criteria.

- Prediction Generation Interface: Calculates the passage times and orbital configuration of the objects to be observed during a given period. It uses station coordinates and ephemerides provided by various providers to predict observations.
- Mount Control System: Manages the mount's motion and operating modes, making real-time corrections, and also has the ability to perform star observations to improve pointing models and ensure accurate orientation.
- Operational Safety Interface: Supervises several key subsystems to ensure the safe operation of the station. Some examples include monitoring of UPSs, including high- and low-voltage three-phase and single-phase units to ensure the station's operation during power outages; information provided by the weather station with state-of-the-art temperature, pressure, and humidity sensors (meteorological variables that intervene in tropospheric propagation models); pointing directions to avoid entering restricted areas; and monitoring aircraft in the vicinity of the station using ADS-B (Automatic Dependent Surveillance-Broadcast) technology, which allows aircraft to be detected in real time using two antennas and avoids potential interference with laser emission.

The development and integration of our own software has enabled numerous other capabilities, such as the ability to use both lasers in a single observation with minimal transition time between them, simply by adapting the optical path.

This field represents the SFEL team's core development capability, and a notable example of this is the FPGA-based Range Gate Generator (RGG). This device, based on a low-cost Intel Cyclone SoC V TSoM module, was implemented using the Linaro GCC 4.9 compiler for software and the Quartus Prime environment for hardware, using C++14 and VHDL as the primary languages.

The device controls the fire rate and gating of the lasers as well as the operation of the detectors, activating them precisely and synchronized with the emission of each laser pulse. Since the detectors are highly sensitive, activation occurs nanoseconds ahead of schedule to avoid noise and ensure accurate measurements.

The system, in operation for the past six years, has enabled gating detector resolutions of less than 10 ns working at 10 Hz fire rate.

2.6 Electronic hardware

In this area, the fundamental development is the assembly of a new control rack that facilitates access to the equipment and allows for better management of the real-time subsystems. The devices required for network management and those necessary for the station's operation, such as time and frequency signals, signal distributors, and event data recorders, among others, have been integrated. In addition, a NIM chassis has been incorporated to house the constant fraction discriminators (CFD), signal amplifiers, pulse distributors, signal converters, and the RGG, which handles critical real-time tasks.

2.7 Local tie and SRP definition

Due to the high precision achieved with SLR-type sensors, it is strictly necessary that the position from which the measurements are referenced, the Site Reference Point (SRP), achieves at least the same level of precision.

To define the coordinates of this invariant point, a topographic and geodetic task was initiated in collaboration with specialists from the Instituto Hidrográfico de la Marina (IHM), which included engineering, topographic, and geodetic methods. This non-material point, to which all observations are referenced, represents the region of uncertainty where the azimuth and elevation axes of the mount intersect.

The method for defining the invariant point consists of several successive stages, beginning with the definition of a local geodetic reference network around the mount and, in our case, inside the dome, located approximately 45 meters above the surface of the Observatory. From this network, measurements are taken on the mount while executing controlled turns, first in azimuth and then in elevation. These measurements allow us to define two circles corresponding to each rotation axis. The center of each circle represents the rotation axis, and their intersection defines the invariant point. In our solution, this point has been defined with an accuracy below than 1 mm, complying with GGOS and ILRS standards [5].

The local network connects the station's reference point with other relevant points within the Observatory, such as geodetic vertices, geodetic observation pillars, and the reference points of GNSS stations included in the International GNSS Service (IGS), SFER, and ROAG.

3 FIRST RESULTS

Since the second half of August 2024, just a few weeks after the new mount was integrated, various satellite passes in LEO, geodetic satellites in MEO such as LAGEOS-1 and LAGEOS-2, and satellites in higher constellations such as GNSS have been visualized and tracked.

Starting in September 2024, the use of laser observations was incorporated into observations, resuming routine observations and beginning to generate files. Fig. 18

shows the results obtained from the tracking of a LAGEOS-1 satellite on September 5, with a NP RMS of 33.12 ps.

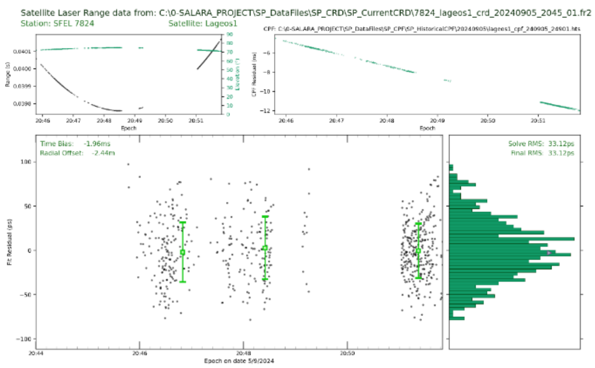

Figure 18. Results of one of the first tracks on the LAGEOS-1 satellite after the mount replacement.

To date, routine observations of different types of satellites and space debris objects have continued, refining the system and improving the results obtained. The station is currently participating in various initiatives such as the Debris Laser Tracking Network, the EU SST R&D on Laser Contribution and the results evaluation phase for exiting the ILRS quarantine.

4 FUTURE PLANS AND MEDIUM-TERM VISION

Following the current modernization, new opportunities are opening up for the development of previously unattainable projects. Four of these projects have already been approved and are awaiting funding.

Among them, the TERELAS project stands out, a new 800 mm receiving telescope that, thanks to its improved precision and reflectivity, is ideal for tracking space debris. The new mount project has already been adapted to accommodate this larger mirror in the future. KIROA, for its part, proposes the integration of a state-of-the-art laser with pulses of less than 75 picoseconds and a high frequency of up to 5 kHz, designed to simultaneously meet the standards required for ILRS tracking and space debris campaigns at SST. Meanwhile, CUPROA consists of a high-performance dome that will improve the capacity of the current one and will not limit the tracking of re-entering objects. Furthermore, the CORA project will allow the operation of the ROA sensors to be managed in a single control center. The implementation of automation technologies is also planned, such as auto-pointing systems based on astronomical camera imagery, automatic search patterns, remote control systems, security protocols, and equipment deactivation, since one of the station's current drawbacks is its limited personnel.

5 CONCLUSIONS

After 45 years of operation, the San Fernando Laser Station, under the management of the Royal Institute and Observatory of the Navy, has consolidated its expertise in SLR. Throughout this time, the station has continued operating, adapting to technological advances to remain a reliable partner within the international and national networks it collaborates with.

The ROA's constant effort to evolve has been fundamental to this adaptation. Among these advances, certain proprietary developments stand out. Furthermore, the implemented improvements have brought the station up to date and ready to tackle new challenges, such as multi-static observations, blind tracking, and daytime observations.

However, SFEL's most valuable resource continues to be its personnel, thanks to the experience gained from previous generations. This cohesive and skilled team works enthusiastically to carry out the projects they undertake.

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7 ACKNOWLEDGEMENTS

In memory of Dr. Manuel Catalán, who led the modernization of the SFEL station from its inception in 2015, and whose effort and dedication served as an example for the entire team, inspiring them to face all challenges with enthusiasm and proactivity. Rest in peace.