Understanding the CubeSat faint object population with 2-meter class telescope observations

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ABSTRACT

Context: The exponential growth in the number of CubeSats and very faint objects (VFOs) in orbit presents significant challenges for space traffic management and astronomical observations.
Aims: This research aims to evaluate the feasibility of using 2-meter class telescopes for Space Surveillance and Tracking (SST) of CubeSats and VFOs.
Methods: Observations were conducted using the Calar Alto (CAHA) 2.2m telescope and the 2m Liverpool Telescope (LT). For planning and pointings, ***Senplanner*** was used. Data reduction and astrometric analysis were performed using ***Gendared***, and orbit determination was conducted with ***Sstod*** COTS.
Results: The results demonstrate the capability of 2-meter class telescopes to detect and track CubeSats and VFOs. For instance, the LT showed residuals in right ascension ranging from -0.8 to 0.6 millidegrees, indicating high accuracy. The CAHA demonstrated reliable detection with residuals in right ascension from -2.2 to 3.1 millidegrees, showcasing the potential for improving SST with these telescopes.
Conclusions: The study underscores the importance of larger telescopes in space traffic management, highlighting the need for long-term monitoring and consistent calibration. Future strategies should focus on improving observation techniques and expanding the network of large telescopes for comprehensive space surveillance.

Context: El creixement exponencial en el nombre de CubeSats i objectes molt febles (VFOs) en òrbita presenta desafiaments significatius per a la gestió del trànsit espacial i les observacions astronòmiques.
Objectius: Aquesta recerca té com a objectiu avaluar la viabilitat d'utilitzar telescopis de classe de 2 metres per a la Vigilància i Seguiment de l'Espai (SST) de CubeSats i VFOs.
Mètodes: Les observacions es van dur a terme utilitzant el telescopi de 2,2 m de Calar Alto (CAHA) i el Telescopi Liverpool (LT) de 2m. Per a la planificació i les orientacions es va utilitzar ***Senplanner***. La reducció de dades i l'anàlisi astromètrica es van realitzar amb ***Gendared***, i la determinació d'òrbita es va dur a terme amb ***Sstod*** COTS.
Resultats: Els resultats demostren la capacitat dels telescopis de classe de 2 metres per detectar i seguir CubeSats i VFOs. Per exemple, el LT va mostrar residus en ascensió recta que oscil·laven entre -0,8 i 0,6 mil·ligraus, indicant una alta precisió. El CAHA va demostrar una detecció fiable amb residus en ascensió recta des de -2,2 fins a 3,1 mil·ligraus, mostrant el potencial per millorar la SST amb aquests telescopis.
Conclusions: L'estudi subratlla la importància dels telescopis més grans en la gestió del trànsit espacial, destacant la necessitat de monitoratge a llarg termini i calibratge consistent. Les estratègies futures haurien de centrar-se a millorar les tècniques d'observació i expandir la xarxa de telescopis grans per a una vigilància espacial completa.

Key words. Astronomy and astrophysics – Position astronomy – Telescopes – Satellites

1. Introduction

The number of satellites in orbit has grown exponentially in recent years, driven by the increasing deployment of CubeSats and the presence of other very faint objects (VFOs). These satellites play a critical role in communication, navigation, Earth observation, and various scientific applications. However, their proliferation raises significant concerns about their impact on astronomical observations and space traffic management (ESA 2024; IAU CPS 2023; UNOOSA 2023; EUSST 2023; ESA 2023). Understanding and mitigating these impacts is essential to preserve the quality of astronomical data and ensure safe and sustainable use of space.

The high orbital altitudes of geosynchronous (GEO) and medium Earth orbit (MEO) satellites shield them from atmospheric dragging, allowing them to remain in orbit for thousands of years after their operational lifetimes. This longevity, coupled with their increasing numbers and faint magnitudes, complicates efforts to track and manage these objects effectively. Consequently, there is a growing need to employ larger telescopes for space traffic management, capable of detecting and characterizing these smaller and fainter objects. The primary objective of this document is to evaluate the feasibility of using 2-meter class telescopes for Space Surveillance and Tracking (SST) of CubeSats and other VFOs. Specific goals include:

– Develop and implement an observation plan using ***Senplanner*** to effectively track artificial satellites.

– Conduct observations with the Calar Alto (CAHA) 2.2m telescope and the 2m Liverpool Telescope (LT), and perform astrometric reductions using ***Gendared***.
– Use orbit determination tools to accurately calculate the orbits of VFOs.
– Assess the impact of CubeSats and VFOs on astronomical observations.

This research is a collaborative effort between the University of Barcelona and the GMV enterprise, leveraging the capabilities of the LT and the CAHA telescope to follow fast bodies and determine their orbits. The study aims to enhance our understanding of the CubeSat and VFO population, thereby contributing to improved space traffic management and preservation of the quality of astronomical observation.

This document is structured as follows:

– **Fundamentals (Sec. 2):** Discusses the essential concepts of CubeSats, VFOs, orbital regimes, space traffic management, and the impact of these objects on astronomy and sky quality.
– **Tools (Sec. 3):** Explains the software used for observation planning and data analysis.
– **Observations (Sec. 4):** Details the observation strategies, planning, and execution processes using 2-meter class telescopes.
– **Data Analysis (Sec. 5):** Describes the methods for data reduction, object detection, and analysis of collected data, including astrometric reductions and orbit determination.
– **Results and Discussion (Sec. 6):** Evaluates the effectiveness of 2-meter class telescopes in tracking and characterizing VFOs, and discusses the implications for space traffic management.
– **Conclusion (Sec. 7):** Summarizes the findings and suggests directions for future work.
– **Acknowledgements (Sec. 8)**

2. Fundamentals

CubeSats (Fig. 1) are a class of nanosatellites defined by their standardized cube-shaped form factor. Each unit, or "U," measures 10x10x10 cm and typically weighs about 1.33 kg. These small satellites have revolutionized access to space due to their cost-effectiveness and versatility, enabling a wide range of scientific, educational, and commercial applications. VFOs encompass a broader category, including small, dim satellites and space debris, that are challenging to be detected and tracked in orbit due to their low reflectivity and small size.

CubeSats are deployed in various orbital regimes, primarily Low Earth Orbit (LEO), but increasingly in higher orbits such as MEO and GEO. Their rapid deployment rate and increasing numbers contribute significantly to the growing population of VFOs, raising concerns about collision risks and space debris proliferation.

2.1. Orbital regimes

Satellites operate in distinct orbital regimes, each with unique characteristics (ESA 2024):

– **LEO**: Extends up to 2,000 km above Earth. This region is densely populated with satellites due to its cheaper accessibility, including the majority of CubeSats. It experiences significant atmospheric dragging, leading to shorter orbital lifetimes.

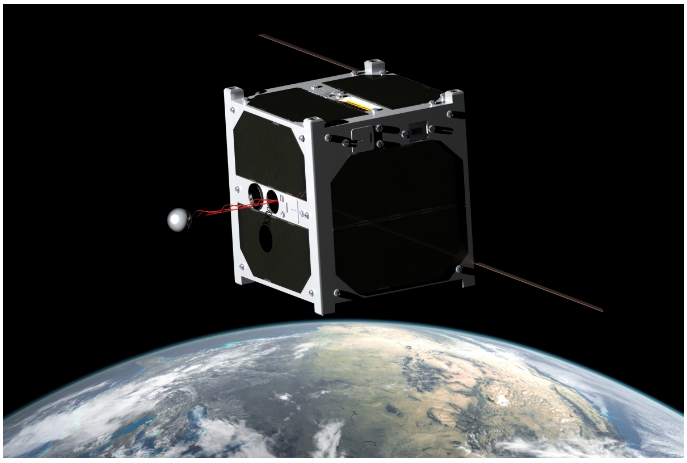

Fig. 1. Image illustrating the modular design of CubeSats. Each CubeSat unit measures 10 cm x 10 cm x 10 cm, and can be used individually or stacked together in various configurations, depending on mission requirements. This modularity allows for versatile deployment options and scalability in satellite missions.

– **MEO**: Ranges from 2,000 km to approximately 31,570 km. This regime is primarily occupied by navigation satellites such as the Galileo, GPS, and GLONASS constellations.
– **GEO**: Located in a distance from the center of the Earth spanning from 35,586 km to 35,986 km. Satellites located at GEO match Earth's rotation and appear stationary relative to the surface. This orbit is critical for communication and weather satellites, but is also increasingly crowded.

2.2. Tracking modes

There are several methods for optical tracking of satellites, this section focuses on the two most commonly used techniques:

– **Sidereal tracking:** involves setting the telescope to move at the same rate of the Earth rotation, effectively keeping the stars stationary in the field of view (FoV) while the satellites, space debris and solar system objects create streaks due to their relative motion.
– **Non-sidereal tracking:** involves adjusting the telescope's tracking rate to match the apparent motion of a satellite or the object to be observed, keeping the object stationary in the FoV. The telescope tracking system is programmed to follow the predicted motion of the satellite based on its orbital parameters. The satellite appears as a point-like object, while the stars form trails.

2.3. Space Traffic Management

Space Traffic Management (STM) encompasses the procedures and technologies required to track, predict, and mitigate the risks associated with space objects. An effective STM ensures the safe and sustainable use of space by preventing collisions, managing satellite constellations, and mitigating space debris. The key components of STM include (EUSST (2023)):

– **Catalog Maintenance:** Maintaining an up-to-date catalog of all active satellites, defunct objects, and debris.
– **Collision Avoidance:** Predicting potential collisions and issuing avoidance maneuvers to prevent in-orbit collisions.

- **Debris Mitigation:** Implementing measures to reduce the generation of new debris, such as post-mission disposal and active debris removal.
- **Reentry Management:** Monitoring and managing the reentry of space objects to minimize the risk to people and properties on Earth. This includes predicting the reentry path and timing of defunct satellites and large debris and ensuring that controlled reentries are conducted safely.

2.4. Impact on astronomy and sky quality

The increasing number of satellites and space debris significantly impacts astronomical observations and sky quality. International collaboration and regulation are essential to mitigate the adverse effects of these ever-increasing artificial objects in orbit. One major issue is light pollution, where reflected sunlight from satellites and debris creates bright streaks in astronomical images. This light intrusion complicates data analysis and significantly reduces the quality of astronomical observations, making it more challenging to study faint celestial objects.

The brightness of current satellites varies as a function of nighttime, often peaking during twilight hours when the Sun's rays still reach higher altitudes, making satellites particularly visible. This problem is more pronounced shortly after sunset and before sunrise when the sky is still dark, but satellites remain illuminated by the Sun.

In order to minimize the light pollution effect, several strategies could be explored, such as deploying satellites with darker coatings to reduce reflectivity, designing satellite constellations with fewer, more strategically placed satellites, and developing ground-based software algorithms to filter out satellite trails from astronomical data.

Furthermore, satellites, especially those used for communication, emit radio frequency interference (RFI) (e.g. Di Vruno et al. 2023). This interference disrupts radio astronomical observations, also during daylight, by masking or distorting the faint radio signals from cosmic sources.

Another critical concern is orbital crowding. The growing number of objects at LEO increases the likelihood of collisions between satellites and debris. Such collisions generate even more debris, creating a cascade effect known as the Kessler Syndrome (Kessler,Donald J. and Cour-Palais 1978). This escalating debris further exacerbates the problem, making it more difficult to track the small objects, avoid collisions and posing a significant threat to both manned and unmanned space missions. Adding to the complexity, the intentional destruction of satellites in orbit by anti-satellite missiles (ASAT) during military tests significantly worsens the space debris issue. The resulting fragments from these events can persist in orbit for extended durations, posing enduring risks to space operations.

These challenges collectively hinder the ability of astronomers to maintain clear and precise observations of the night sky, affecting both optical and radio astronomy. The increased light pollution, RFI, and orbital debris make it increasingly difficult to conduct high-quality astronomical research and could potentially lead to gaps in our understanding of the Universe.

2.5. Current telescopes for satellite tracking

Modern satellite tracking primarily utilizes optical telescopes and radar systems, which are essential for maintaining space situational awareness and monitoring the increasing number of satellites and debris in Earth's orbit. Telescopes with diameters around 1 meter are standard for these tasks due to their lower pressure to perform astronomical observations on them and their lower cost. For instance, the Ground-based Electro-Optical Deep Space Surveillance (GEODSS) system in the U.S. uses 1-meter primary mirrors to achieve high-resolution optical observations. Similarly, the European Space Agency's (ESA) Optical Ground Station (OGS) in Tenerife, Spain, employs a 1-meter diameter telescope for tracking space debris and conducting laser communication experiments. Additionally, the Montsec Observatory (Fabra-ROA Montsec) in Catalonia, Spain, plays a significant role in satellite and debris surveillance, contributing to the global effort of space situational awareness with its advanced optical systems. These telescopes are designed to detect, identify, and track objects at LEO, MEO and GEO with high precision. Additionally, the European Union Space Surveillance and Tracking (EUSST) network, includes a network of sensors such as radars, telescopes, and laser ranging stations contributed by member states, providing essential data for collision avoidance through global distribution and enhanced detection capabilities.
Furthermore, radar systems play a complementary role to optical telescopes in satellite tracking. These systems are advantageous for their ability to operate under various weather conditions and provide continuous monitoring, particularly effective for tracking objects at LEO.

2.6. Limitations and need for larger telescopes

As explained in previous section, optical telescopes with diameters around 1 meter, alongside radar systems are used to monitor and track space objects. While these systems are capable of tracking a substantial number of objects, they face several critical limitations that underscore the necessity for larger telescopes.
The primary limitation of current optical telescopes is their restricted resolution and sensitivity, which decreases with the square of the distance (d^2). This makes it challenging to detect debris smaller than 10 centimeters in diameter. Despite their relatively small size, these debris fragments pose significant collision risks to operational satellites. The inability to detect and track such small debris can have serious implications for satellite safety and longevity.
The high collision risk associated with smaller debris fragments is largely due to their high velocities, often exceeding 7-8 km/s. At these speeds, even minuscule fragments have significant kinetic energy. For instance, a 1-gram piece of debris traveling at 8 km/s ($\sim$ 29000 km/h) has a kinetic energy equivalent to that of a 1-kilogram object traveling at 800 m/s ($\sim$ 2900 km/h). This high kinetic energy can result in substantial damage to operational satellites, potentially causing further fragmentation and leading to the Kessler Syndrome mentioned above.
The enhanced detection of faint debris is critical for assessing collision risks and improving the mitigation strategies for active GEO satellites, underscoring the necessity of using larger telescopes for comprehensive space debris monitoring (Blake et al. 2020). Radar systems, although excellent for

detecting objects in LEO, suffer from decreased resolution at higher altitudes, complicating the tracking of objects in more distant orbits. The limitation for radars is power. It goes as distance to the fourth power (d^4), making detection of distant objects almost impossible.

In order to enhance the detection and tracking capabilities for smaller debris, the implementation of larger telescopes is essential. Larger telescopes can offer improved resolution and sensitivity, enabling the detection of smaller objects at greater distances. The FoV of 1-meter telescopes is small, limiting the sky area that can be monitored at any given time. This constraint imposes deploying more telescopes to achieve broader coverage, increasing costs and operational complexity. Alternatively, wide field of view telescopes, such as the Fabra-ROA Montsec telescope and ESA's Flyeye, can be used to monitor larger areas of the sky more efficiently, reducing the need for multiple telescopes and simplifying operations.

Furthermore, the increasing number of small satellites and space debris exacerbates the tracking challenge. Smaller telescopes struggle to keep up with the growing number of faint objects, leading to potential gaps in monitoring and coverage.

To address these issues, there is a clear need for larger telescopes. Telescopes with diameters of 2 meters or more offer significantly better resolution and sensitivity, allowing for the detection of smaller debris beyond the capabilities of 1-meter class telescopes. Improved resolution enables accurate identification and tracking of objects, reducing collision risks and supporting more effective space traffic management.

This increased sensitivity is essential for comprehensive space situational awareness, reducing the likelihood of missing smaller or fast-moving objects. As human activities extend beyond LEO to GEO orbits and deep space, larger telescopes become indispensable. They can effectively track objects at greater distances with the required resolution and sensitivity, supporting missions and operations in these distant regions.

The development and deployment of larger telescopes are essential to overcoming the current limitations of satellite tracking systems. These advancements will enhance our ability to detect, track, and manage the growing population of satellites and debris, ensuring the long-term sustainability and safety of space operations.

However using 2-meter class telescopes for satellite tracking presents specific challenges that need to be addressed compared to 1-meter class telescopes. One of the primary challenges associated with 2-meter class telescopes is their higher cost. These larger telescopes are more expensive to build, operate, and maintain than their 1-meter counterparts. Additionally, time allocation for satellite tracking might be more competitive because 2-meter class telescopes are in high demand for various advanced astronomical studies. Another significant challenge is the narrower FoV of 2-meter class telescopes. This means they can cover less sky area at a time. This limitation can be a drawback for comprehensive space surveillance, which requires monitoring large sections of the sky to detect and track numerous objects. The operational demands of 2-meter class telescopes are higher due to their complexity. These telescopes require more sophisticated operational planning and management, including handling larger data volumes and more intricate calibration and maintenance processes.

In conclusion, while current optical telescopes and radar systems provide a foundational capability for satellite tracking, their limitations in detecting small debris require the development and deployment of larger telescopes. These advanced systems will play a vital role in safeguarding operational satellites and maintaining the integrity of space activities among the growing challenges posed by space debris.

2.7. Review of Previous Feasibility Studies

Several feasibility studies have evaluated the use of larger telescopes for SST:

- The Population of Optically Faint GEO Debris (2016): The article (Seitzer et al. 2016) investigates optically faint debris in GEO orbit using the 6.5-meter Magellan 'Walter Baade' telescope at Las Campanas Observatory in Chile. This telescope enabled the detection of debris objects fainter than $R = 19$ mag, typically smaller than 10 cm, due to its superior light-gathering capabilities. The study highlighted the presence of rapidly tumbling debris with variable brightness, detectable only with high-resolution optical instruments. These findings are crucial for understanding the GEO debris environment and improving space situational awareness. Compared to smaller 1-meter class telescopes, the Magellan telescope's greater sensitivity and resolution allowed for the identification of a significantly larger population of smaller, fainter debris, enhancing our ability to monitor and mitigate potential collisions in GEO (Seitzer et al. 2016).
- DebrisWatch I (2020): The study employs the 2.54 m Isaac Newton Telescope to conduct an extensive survey of faint debris at geosynchronous altitudes (Blake et al. 2020). By probing to the 21st visual magnitude, the researchers identified 129 orbital tracks indicative of GEO-like motion, uncovering a bimodal brightness distribution that includes numerous faint, rapidly tumbling objects. This survey demonstrates a superior detection capability compared to 1 m class telescopes, as it achieves greater sensitivity and resolution, allowing for the identification of smaller debris (aprox. 10 cm) and providing more detailed photometric data.
- An automated system to discover and track unknown GEO objects using ground-based Optical Telescopes (2022): focused on the integration of optical and radar data from large telescopes, showing significant improvements in orbit determination accuracy for GEO objects. This study presented a fully automated system to discover and track unknown objects in GEO orbits using the LT optical telescope. The system utilizes advanced tracking algorithms designed for non-linear problems, providing more accurate state estimations with robust uncertainty representations. This integration allowed for enhanced situational awareness and more precise orbit determination for both known and unknown space objects (Zhou et al. 2022).

These studies underscore the critical role of larger telescopes in advancing SST capabilities. They improve the detection, tracking, and characterization of CubeSats and VFOs, thereby enhancing overall STM. The findings highlight the need to investigate the feasibility of using larger astronomical telescopes for this purpose to ensure the sustainability and safety of space operations. However, while these studies have significantly advanced our understanding of the GEO debris environment, they fall short in several critical areas that are essential for comprehensive Space Situational Awareness (SSA). Notably, they lack detailed astrometric measurements, which are crucial for accurate orbit determination. Precise astrometry is necessary to predict future positions and potential collision risks of space debris, but the studies primarily focused on detection and characterization, without providing the positional accuracy required for robust orbit predictions. Additionally, none of the referenced studies have conducted residual analysis, which involves comparing observed positions with those predicted by orbital models. The absence of residual analysis means that the current understanding of the errors and uncertainties in orbit predictions remains incomplete, which could compromise the effectiveness of collision avoidance strategies and mitigation efforts.

3. Tools used for observation planning, data reduction and sensor calibration

Accurate and efficient observation planning, data reduction, and sensor calibration are significant components in the field of SST. These processes are essential for maintaining a comprehensive and up-to-date catalogue of space objects. To achieve this, a suite of advanced software tools is employed, each designed to address specific aspects of the workflow. This section provides a detailed overview of the key software tools used in the observation campaigns conducted in this study. These tools include ***Senplanner*** for observation planning, ***Gendared*** for data reduction, and ***Sstod*** for orbit determination and sensor calibration.

The integration of these specialized software tools ensures a cohesive and streamlined process for SST operations. The combined functionalities of them not only enhance the reliability and accuracy of SST operations but also ensure that observational data is effectively utilized to maintain a robust and dynamic catalogue of space objects.

*3.1. **Senplanner** for scheduling observations*

The observation plans for both, the CAHA and LT telescopes, were prepared using the GMV ***Senplanner*** software (GMV 2024c). ***Senplanner*** is an advanced software platform for a task schedule for an integrated network of SST sensors, encompassing radar systems, laser ranging devices, and optical telescopes. Its core functionality is to sustain an object catalogue through the analytical evaluation of observation opportunities and surveillance strategies. ***Senplanner*** facilitates the automated generation and submission of requisite inputs for SST sensor observation campaigns, using precise orbital data for object tracking and survey strategy formulation. The software's technical capabilities include visibility computation algorithms, tracking plan generation protocols, optical survey strategy optimization techniques, and real-time sensor monitoring and diagnostics.

Senplanner relies on various datasets and files to perform its functions effectively. Essential files include Earth Orientation Parameters (EOPs), which provide data related to the Earth's rotation and orientation, and information on Leap Seconds, which is crucial for maintaining timekeeping accuracy. Additionally, data from the Regional Geodetic and Astronomical System (RSGAS) relevant to the observation site is required, along with the Two-Line Element (TLE) Catalogue that provides orbital data for satellite tracking. The output visibility schedule is shown in Figure 4.

*3.2. **Gendared** for data reduction*

The main framework used for this analysis was ***Gendared*** (Generic Data Reduction Framework), which is tailored for the operational reduction of image data acquired from ground-based space surveillance optical telescopes (GMV 2024a). ***Gendared*** processes raw images to produce astrometric and photometric data of detected objects, ensuring accurate and reliable results.

The image reduction in ***Gendared*** involves a series of steps organized into configurable pipelines tailored for different observational campaigns and telescopes. Each pipeline consists of sequential or parallel processing steps based on their dependencies, including preparation of the dataset environment, calibration of images, background subtraction, astrometric calibration, object detection, and photometric calibration.

The input data for ***Gendared*** includes raw images from optical telescopes, such as science frames and calibration frames. The output consists of reduced images with detected objects marked, detailed object information organized into tracklets, and comprehensive reports, including astrometric solutions.

*3.3. **Sstod** for orbit determination and sensor calibration*

The second phase of data analysis included detailed orbit determination and sensor calibration, which were performed using ***Sstod*** COTS software (GMV 2024b). This software is designed to support core functionalities such as orbit determination and sensor calibration. COTS processes data from various types of sensors, including optical telescopes, radars, and laser ranging stations, to maintain a comprehensive catalog of space objects and their orbits. The software's robust capabilities enable the accurate calibration of sensors and the precise determination of orbital parameters for detected objects. This process includes the correlation of measurements and the computation of orbital trajectories, ensuring high precision and reliability in tracking space debris and satellites.

The CCSDS Tracking Data Message (TDM) (CCSDS 2017) provides input data for the ***Sstod*** COTS system, using astrometric positions derived from the ***Gendared*** software. This data includes position angles measured as right ascension and declination within the EME2000 reference frame, sequentially recorded with time tags referenced to the reception time. The data section captures the object's changing position in the sky with precise angular measurements at multiple timestamps, corresponding to the number of astrometric measurements obtained within the specified interval. Combined with the telescope site coordinates, ***Sstod*** COTS uses this information to compute the orbital parameters for the identified VFOs.

4. Observations

Observations are fundamental to this study for several reasons. Firstly, they provide the raw data needed to accurately determine the orbits of satellites. By tracking these objects over time, it is possible to collect precise positional information, which is essential for calculating their orbits and predicting their future positions. This data is crucial for maintaining an up-to-date catalog of space objects, ensuring that accurate tracking is possible for collision avoidance and overall space traffic management.

Additionally, the primary aim of this study is to evaluate the effectiveness of using 2-meter class telescopes for SST. Observations conducted with the CAHA and the LT provide the necessary data to assess the capability of these telescopes to detect, track, and characterize CubeSats and VFOs. By analyzing the observational data, we can determine how well these telescopes perform in tracking these small and faint objects, which is critical for SSA.

Moreover, observations allow for testing and validation of the methodologies and software tools used for tracking and data reduction. By applying these techniques to real observational data, we can assess their accuracy and reliability. This validation is essential for improving SST practices and ensuring that the tools and methods used are robust and effective.

4.1. Calar Alto (CAHA) Observations

Calar Alto Observatory, located at the Sierra de Los Filabres in Almería, Spain, is jointly operated by the Junta de Andalucía and the Institute of Astrophysics of Andalucia (CSIC). The 2.2-meter Ritchey-Chrétien telescope is a key tool for a variety of astronomical studies due to its excellent imaging capabilities. The 2.2m telescope at CAHA is equipped with the Calar Alto Faint Object Spectrograph (CAFOS), a versatile instrument capable of imaging and spectroscopic observations. CAFOS offers a 16 arcmin FoV, making it ideal for various observational programs, including those targeting satellites and other celestial objects. For Galileo satellites, which have an apparent motion of about 0.5 deg/min, they would take roughly 32 seconds to cross the full FoV.

The observation was made as part of an organized trip by the master courses at the University of Barcelona (Master in Astrophysics, Particle Physics and Cosmology), sharing telescope time with other students. Initially, approximately two hours were scheduled for this program in service mode. However, the observations were conducted during the second twilight of both nights, giving a total time of observation around 1 hour (half of our initial expectations).

4.1.1. Observation Strategies

In order to cover any possible changes during the observing time, we prepared an extended list of candidates. The initial objective of the observing nights at CAHA was to observe seven objects: three Galileo satellites for calibration, one bright GEO object, one medium brightness GEO object, one very faint GEO object, and one MEO object. However, this was not possible due to the limited observation time. Consequently, we could finally observe four Galileo satellites (see Table 1) to calibrate the time stability of the telescope. These satellites were chosen based on their visibility and strategic importance for calibration purposes.

While preparing the plan of the observation, we noted that the default readout time of 110 seconds of CAFOS detector with the full frame was excessively long for our purposes. To mitigate this, the FoV was reduced to 1024x1024 pixels (providing a FoV of 9 arcmin), thereby decreasing the readout time to 35 seconds.

The observation strategy involved pointing the telescope directly at the selected satellites and employing sidereal tracking mode. This mode ensures the telescope tracks the stars, resulting in images where stars appear as point-like sources while the satellites manifest as streaks due to their relative motion (see Fig. 7).

To ensure accurate astrometric calibration, we must ensure to identify a minimum of five stars within the 9 arcminute FoV. This was achieved by using the *Gaia* catalogue (Gaia Collaboration et al. 2023j), accessed via the *astroquery* tool. The *Gaia* catalogue provides precise positional data for stars, which is critical for approximate the amount of stars in the FoV. We used the declination corresponding to GEO ring, considering it a representative sample of the entire sky, allowing us to simplify the analysis while preserving the general relevance of the findings. We could confirm the presence of at least five stars within the FoV. The results, see Fig. 2, demonstrate the efficacy of this approach for all positions, with the minimum value of 7 stars and maximum value of 1973 stars in the field.

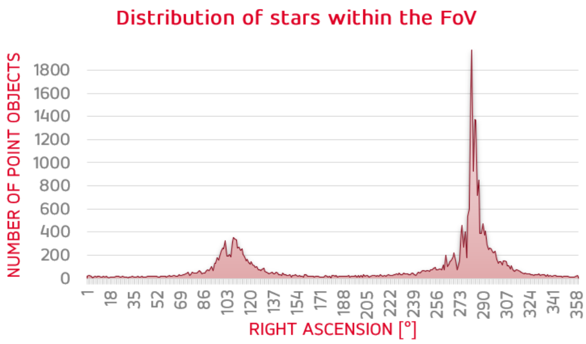

Fig. 2. Minimum and maximum star counts in 9 arcminute FoV using *Gaia* catalogue data.

To optimize observation parameters and prevent issues such as star trailing and saturation, we developed an algorithm to determine the maximum exposure times for the CAFOS instrument at different altitudes above the Earth's surface. The first step in the code involves calculating the effective FoV. Using predefined constants for topocentric and geocentric adjustments, the algorithm calculates exposure times for both zenith and horizon observations. These constants account for the positional changes of stars as observed from different points on the Earth's surface. To visualize the instrument performance across different heights, the algorithm plots the calculated exposure times for zenith and horizon positions. These plots provide valuable insights into how the instrument's exposure capabilities vary with altitude (Fig. 3).

Based on this analysis, we chose an exposure time of 3 seconds for the MEO objects. This exposure time was selected to ensure high-quality data collection while minimizing the risks of star trailing and saturation.

Only bias frames were taken for the observation because they are crucial for capturing and subtracting electronic noise, ensuring accurate data calibration. Dark and flat frames were not required due to the negligible impact of pixel sensitivity variations and thermal noise on the short exposure time. Dark frames have 0.062 counts in the 3 second exposures. Flat frames, even important for photometric studies, have a negligible impact in SST astrometry.

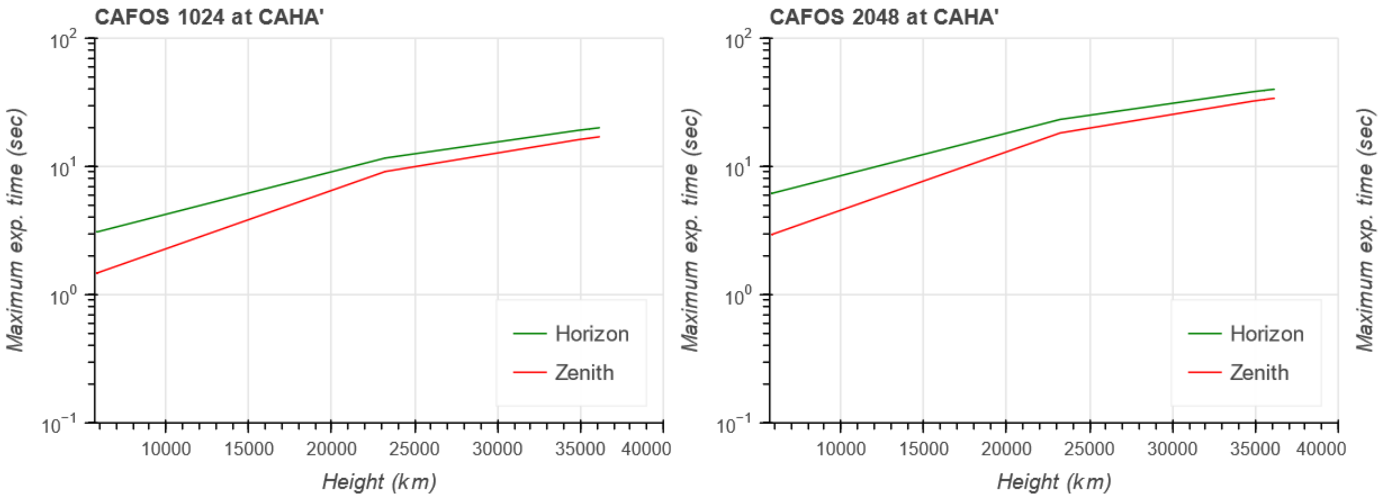

Fig. 3. Maximum exposure time diagrams for the CAFOS Instrument at various altitudes for CAFOS with 9 arcmin FoV and CAFOS with 16 arcmin FoV: This diagram illustrates the maximum exposure times required for CAFOS instrument at varying heights, with data plotted for both zenith (red) and horizon (green) positions. The logarithmic scale of the y-axis highlights the significant differences in exposure times, facilitating a comprehensive comparison across the two FoV and their observational conditions.

4.1.2. Observation Timeframe, Planning and Execution

The CAHA observation was performed from April 12 to April 14, 2024, with selection of observation windows with solar elevations between -18 and -15 degrees. The decision to schedule the observation during twilight was strategic, as satellites are naturally more visible during these periods, thereby optimizing the efficacy of the observational study and also allowing other observers to use darker hours during the night for their purposes.

The plan for satellites best visibilities was made with ***Senplanner*** with configuration for the CAHA site, ensuring the precise location of the telescope, was conducted in full calibration mode. This involved generating satellite coordinates at 1-minute intervals for accurate tracking and observation. Based on the output from ***Senplanner***, the best-fitting visible satellites within the given timeframes were selected, with pointing set for every 1-minute interval. Figure 4 shows the output from the Senplanner software for the CAHA site configuration.

The observation procedure with the CAHA 2.2m telescope involved several steps to ensure accurate and efficient data collection:

– Begin observations with sidereal tracking mode, pointing the telescope at the Galileo satellites.
– Capture images with an optimized exposure time to ensure sufficient signal-to-noise ratio while avoiding saturation.
– Monitor the data acquisition process to ensure data quality and make adjustments as needed.
– Create a macro procedure, which will execute commands for all given objects.

In the context of this observational campaign, the resulting data includes detailed information about the satellites, encompassing their orbit, physical dimensions, the total number of images captured, and the subset of images that contain at least five visible stars. This comprehensive data is systematically presented in Table 1.

Name	COSPAR	Nr img	Nr 5*
GSAT0211	2016-030A	6	6
GSAT0212	2016-069B	9	9
GSAT0216	2017-079B	7	6
GSAT0217	2017-079C	36	24
	Sum:	58	45

Table 1. List of Galileo satellites used for CAHA observation, including the number of images captured and the count of images featuring at least five stars. All chosen satellites are of dimensions $1.2 \times 2.53 \times 1.1$. The last row includes the sum of all images in the table.

4.2. Liverpool Telescope Observations

The Liverpool Telescope (LT), located at the Roque de los Muchachos Observatory on the island of La Palma in the Canary Islands, Spain, is operated by the Astrophysics Research Institute of Liverpool John Moores University. The LT is a fully robotic 2-meter Ritchey-Chrétien telescope, renowned for its rapid response capabilities and automated operation, making it a vital instrument for time-sensitive astronomical observations.

The LT is equipped with the Rapid Imaging Search for Exoplanets (RISE) instrument, which is specifically designed for high time-resolution imaging. RISE is capable of capturing images with an exposure time as short as 1 second, making it ideal for studying rapidly changing astronomical phenomena, such as exoplanet transits and satellite observations. This high-speed imaging capability allows astronomers to obtain precise light curves and detailed data, contributing significantly to the study of transient events and dynamic celestial objects.

It is important to note that while there have been previous studies using the LT, such as (Zhou et al. 2022), these studies primarily focused on photometry rather than astrometry or residuals. Therefore, our study presents a significantly broader scope, extending beyond the limitations of prior research.

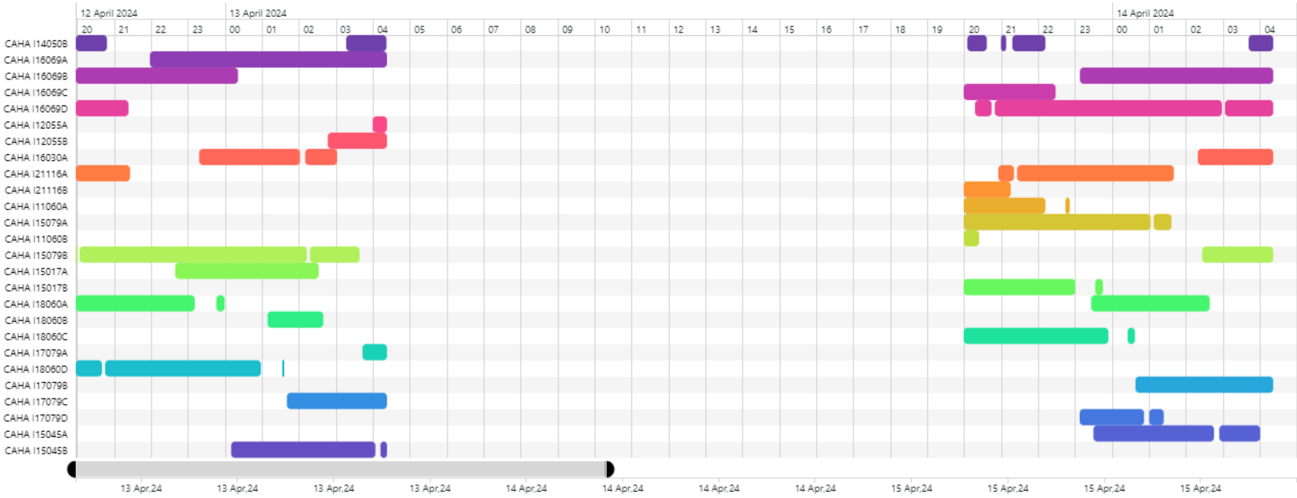

Fig. 4. Observation plans for the CAHA 2.2m telescope, generated using the ***Senplanner*** software, showcasing its advanced capabilities in visibility computation, tracking plan generation, and real-time sensor monitoring for optimal SST sensor network coordination

4.2.1. Observation time request on LT

For the project presented in this document, 5 hours of observational time were requested under the Reactive Time program. The Reactive Time program provides rapid access to the LT for urgent or unforeseen astronomical events, allowing observations to be conducted outside the usual semester-based rounds. The proposal's resolution was given within a week, demonstrating the feasibility and efficiency of this type of observation for our purposes.

4.2.2. Observation Strategies

The process for the LT observation was similar to that used for the CAHA telescope, with initial planning using a 1024x1024 pixel detector, resulting in a FoV of 9.2 x 9.2 arcminutes. For the LT observations, object tracking was employed, resulting in the satellites appearing as point-like sources while the stars showed as streaks (see Fig. 8). The four Galileo satellites and one CubeSat in GEO selected for observation are detailed in Table 2.

Similar to the CAHA telescope preparation, the observation plan for the LT involved detailed scheduling and calibration. The goal was to ensure precise positional tracking and accurate calibration data. The setup ensured efficient and effective use of the telescope's capabilities, providing high-quality data for the satellites being observed.

4.2.3. Observation Timeframe, Planning and Executions

Five hours were allocated from the end of April to September. The estimation for the requested five hours of observation time was based on a detailed analysis of the satellite inventory and the specific requirements for each type of satellite. The observational campaign included five Galileo satellites for calibration, nine MEO satellites, and nine GEO satellites, ranging from bright satellites to VFOs.

To maximize efficiency, observations were scheduled during twilight periods when the solar elevation was between -15 and -18 degrees, based on optimal twilight conditions. At the end, the hours could be allocated at any time, with observations executed while the telescope was not used for other observations. This strategy maximized the efficiency of the allocated time for observations, as it used all available astronomical nights and twilights. The observations time could not be fully used due to the strict deadline associated with this master's thesis. The maintenance work on the LT, which rendered it unavailable for over a month, significantly impacted the observation schedule, resulting in only 1 hour of observations being conducted.

For the LT, ***Senplanner*** was also used to plan the observations, employing 1-minute interval pointing. This data was then introduced into the Phase2 LT software, which is described below. This approach ensures precise tracking and optimal use of the telescope's capabilities for observing the selected satellites.

The observation process with the LT encompasses several critical stages. Initially, precise target coordinates and details are input, followed by configuring the instrument settings, including exposure times, filters, and readout modes. Subsequently, observation windows are scheduled based on visibility constraints, and detailed observation blocks are created. After obtaining approval from the LT operations team, the observations were conducted, and the resulting data were made available for download from the LT archive.

In alignment with the observational procedures used with the CAHA telescope, the campaign yielded the data on the satellites. The dataset is presented in Table 2.

Name	COSPAR	Dimensions [m]x[m]x[m]	Nr img	Nr 5*
GSAT0104	2012-055B	1.1x2.6x1.1	50	14
GSAT0211	2016-030A	1.2x2.5x1.1	25	20
GSAT0216	2017-079B	1.2x2.5x1.1	25	24
GSAT0217	2017-079C	1.2x2.5x1.1	50	50
ASCENT	2021-118E	0.2x0.3x0.2	25	14

Table 2. List of satellites used for LT observation, including the dimensions, the number of images captured and the count of images featuring at least five stars.

5. Data Analysis

The data analysis of astronomical images begins with the creation of bias frames to capture the electronic noise inherent to the CCD detector, dark frames, which are created to account for thermal noise in the CCD detector and lastly, flat field frames generated to correct for variations in pixel sensitivity and vignetting across the CCD detector. In all cases, frames are averaged to produce a master frame. Once the master calibration frames are generated, they are applied sequentially to the raw science images: the master bias frame is subtracted first to remove electronic noise, followed by the subtraction of the master dark frame to eliminate thermal noise, and finally, the resulting image is divided by the master flat frame to correct for pixel sensitivity variations and vignetting. This meticulous sequence of calibration steps ensures that the corrected science images accurately reflect the observed astronomical phenomena, free from systematic errors.

The next in data reduction process is astrometric calibration, which aims to align observed positions with known star catalogs to determine accurate coordinates. The process begins with the identification of reference stars within the image that have well-known positions listed in astrometric catalogs such as *Gaia* DR3 (Gaia Collaboration et al. 2023j) or UCAC4 (UCAC4 2012). Next, image distortion correction is performed to account for optical distortions inherent to the telescope and imaging system by applying a distortion model derived from calibration frames, ensuring accurate positions of objects in the image. Initial coordinate matching follows, where the pixel coordinates of detected objects are matched to sky coordinates from the reference catalog based on initial estimates of the telescope's pointing direction and scale. Then, the astrometric transformation parameters are computed, including rotation, scaling, and translation needed to convert pixel coordinates to sky coordinates accurately. This transformation is often modeled using a polynomial or more complex function depending on the optical system. The transformation parameters are iteratively refined by minimizing the residuals between the observed positions of reference stars and their catalog positions, employing robust fitting techniques to mitigate outliers or erroneous matches. Finally, the refined transformation is applied to all detected objects in the image to obtain their accurate celestial coordinates, with the final astrometric solution. Accurate astrometric calibration ensures the reliability of positional data, facilitating precise orbit determination and further astrophysical analyses.

To accurately identify and distinguish between different types of celestial objects, an object detection procedure should be exercised. The process begins with background subtraction, where the background light and noise in the images are estimated and removed to enhance the visibility of potential objects, isolating them from the sky background and mitigating the effects of light pollution and artifacts. Following this, thresholding is applied to the images, setting an intensity threshold above which pixel values are considered part of an object. This threshold level is carefully chosen to minimize false detections while ensuring that faint objects are detected. Once potential objects are identified, object segmentation is performed to isolate individual objects by grouping contiguous pixels that meet the threshold criteria into distinct entities, delineating the boundaries of each detected object using segmentation algorithms.

Then, the detected objects undergo classification based on their shape, size, and motion characteristics. Template matching techniques are often employed to differentiate between various types of objects, such as stars, galaxies, and VFOs. This classification is essential for further analysis, such as orbit determination and photometric calibration. Finally, the detected and classified objects are subjected to verification and validation, involving cross-referencing with known catalogs to confirm their identities and positions. Figure 5 summarizes data reduction and analysis workflow.

Data analysis was conducted using a combination of software tools for astrometric reduction, object detection, and orbit determination explained in Section 3.

The ***Gendared*** framework configurations for the CAHA and LT telescopes exhibit distinct differences tailored to their specific observational modes. For the CAHA telescope has been used a survey configuration mode, which is observational mode where stars appear as point-like objects and target objects are streak-shaped (see Fig.7), and relied solely on bias frames for calibration, which corrects for electronic noise but not for thermal noise or pixel sensitivity variations. In contrast, the LT telescope operated in a tracking configuration, where the stars appear as streak-shaped and the target objects are point-like (see Fig.8). The LT calibration process was more comprehensive, incorporating fully calibrated frames.

5.1. Examples of Astrometric Reductions and Detected Objects

Below are several examples of astrometric reductions and detected objects by ***Gendared***. All figures were generated using specific software configurations and analyses for this research. The detections shown in these examples include a CubeSat in GEO observed from LT and Galileo in MEO observed from CAHA and LT.

- **CubeSat** (ASCENT 2021-118E) in GEO with precise astrometric positions determined from LT observations demonstrating the telescope's sensitivity to faint objects (Figure 6).
- **GALILEO 21** (2017-079C) in MEO detected with the CAHA telescope (Figure 7).
- **GALILEO 21** (2017-079C) in MEO detected with the LT telescope (Figure 8).

6. Results and Discussion

To evaluate the accuracy of orbit determination, it is essential to quantify the differences between observed and computed values. This process involves several steps. Firstly, data collection involves gathering observed values from telescopes. These observed values typically include the satellite's position and velocity at specific times. On the other hand, computed values are derived from the mathematical model of the satellite's orbit. Using the laws of celestial mechanics and the initial conditions of the orbit (position and velocity at a given time), the satellite's future positions and velocities are predicted.

To compare observed and computed values accurately, it is necessary to ensure that both sets of data correspond to the same time points. Any time discrepancies between observed and computed data should be corrected through interpolation or other time-alignment techniques.

For each observation, the differences (residuals) between the observed values and the computed values are calculated for each component of the position and velocity vectors separately. Analyzing the residuals helps to understand the accuracy and precision of the orbit determination. Common

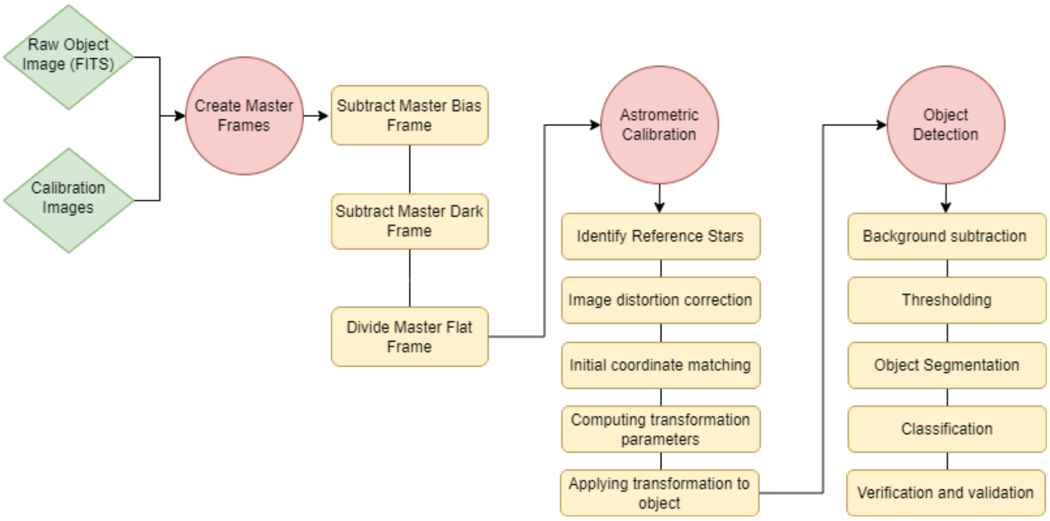

Fig. 5. Data reduction and analysis workflow. This diagram outlines the steps in the data reduction and analysis of astronomical images. It includes creation of master calibration frames, astrometric calibration, and object detection. This process ensures accurate and reliable data for further analysis.

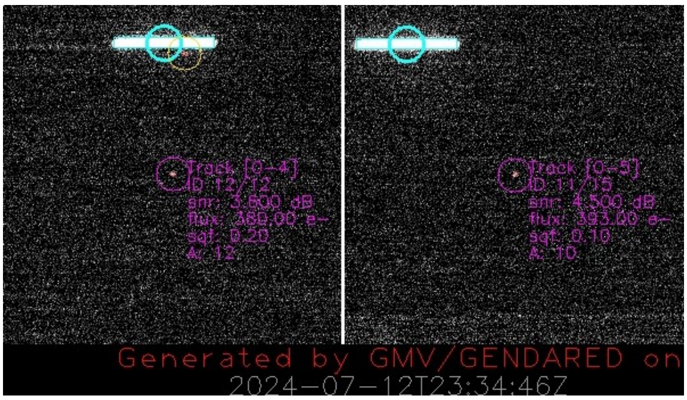

Fig. 6. ***Gendared*** satelite detection of ASCENT 2021-118E in GEO detected with the LT. This image illustrates the effectiveness of the LT in detecting the satellite and demonstrates the capability of the ***Gendared*** algorithm to process this data, even though there were not many stars detected.

statistical measures used in this analysis include the mean residual, which indicates any systematic bias in the measurements. The Root Mean Square (RMS) measures the dispersion of the residuals.

Next, error analysis is performed to evaluate the sources of errors that contribute to the differences between observed and computed values. Based on the statistical analysis of the residuals, the orbit determination model is refined to improve accuracy. This may involve incorporating additional perturbative forces (e.g., atmospheric drag, gravitational influences from other celestial bodies), improving measurement techniques, or correcting systematic biases in observed data. Finally, the refined model is validated by comparing new sets of observed and computed values and performing the residual analysis again. Continuous validation and refinement help ensure the long-term accuracy and reliability of the orbit determination process.

For the telescope calibration and time stability estimation, the following Galileo satellites were used: the CAHA calculations included satellites 2017-079C, 2016-030A, 2017-079B, and 2016-069B, while the LT covered satellites 2017-079C and 2016-030A.

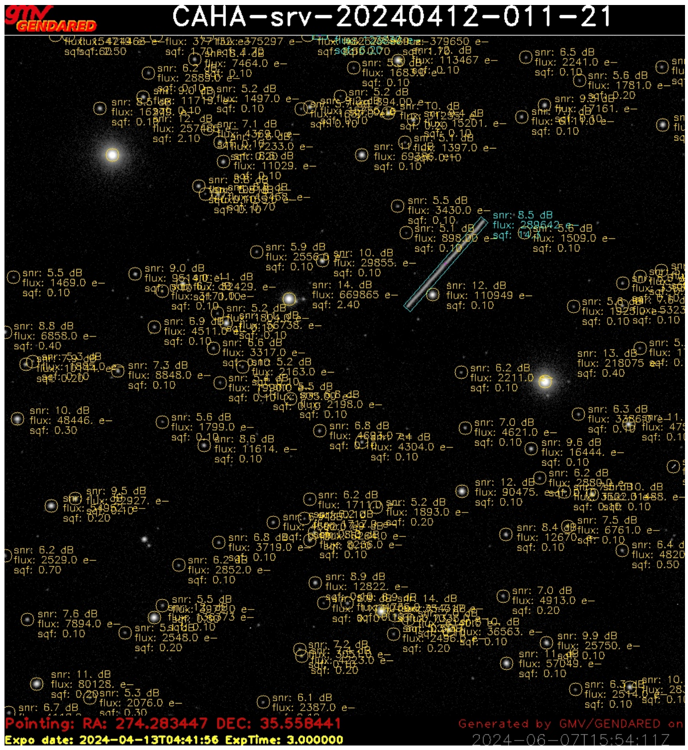

Fig. 7. ***Gendared*** satelite detection of GALILEO 21 2017-079C in MEO detected with the CAHA

The discussion focuses on the findings and implications of the residual analysis for these satellites. Through this detailed examination, we highlight the strengths and areas for improvement in current satellite tracking methodologies.

6.1. Angular Residuals and Observational Data

We analyzed the residual data of the satellites to assess the accuracy of the determined orbits. The observations include right ascension and declination, measured in millidegrees,

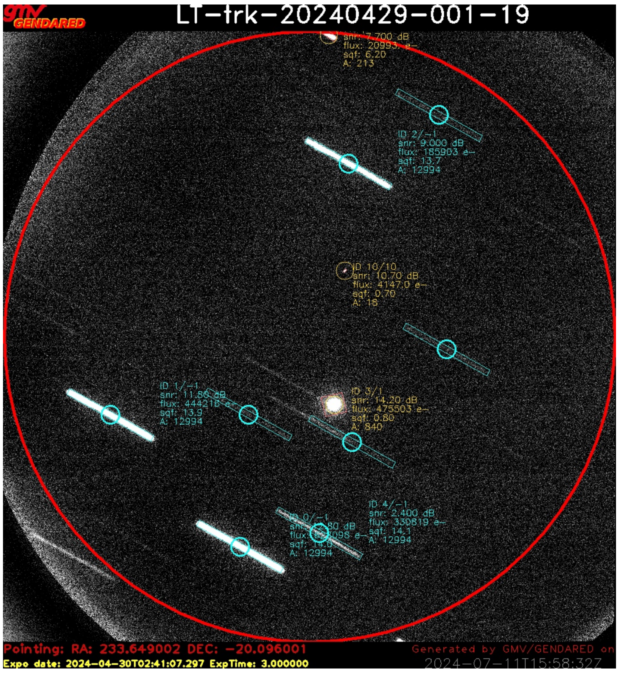

Fig. 8. ***Gendared*** satelite detection of GALILEO 21 2017-079C in MEO detected with the LT

Satellite	RA (millideg)	DEC (millideg)
2016-069B	0.60 ± 0.97	1.0 ± 1.6
2016-030A	0.06 ± 1.6	0.16 ± 2.4
2017-079B	0.63 ± 2.15	0.22 ± 0.95
2017-079C	−0.85 ± 1.4	−0.45 ± 2.1

Table 3. CAHA: Mean and RMS of residuals for satellites in right ascension (RA) and declination (DEC) in millidegrees.

Satellite	RA (millideg)	DEC (millideg)
2017-079C	−0.00 ± 0.06	0.01 ± 0.15
2016-030A	−0.02 ± 0.29	0.07 ± 0.22

Table 4. LT: Mean and RMS of residuals for satellites in right ascension (RA) and declination (DEC) in millidegrees.

compared against computed values. Figure 9 and 10 present the mean residuals of right ascension and declination of satellites for CAHA and LT observations. The residuals are plotted over time, showing deviations from the computed positions.

In the case of CAHA, as shown in Figure 9, the right ascension residuals range from -2.2 to 3.1 millidegrees. The declination residuals show a similar range, indicating consistent observational accuracy. The points below zero in the first night of CAHA observations might indicate an initial calibration issue or transient atmospheric conditions affecting the measurements. These points suggest an early bias that could be corrected in subsequent observations. For LT (Fig. 10), the right ascension residuals, exhibit a tighter range around the zero line, indicating higher accuracy. They range from -0.8 to 0.6 millidegrees. The declination residuals show similar trends, with most points within ±0.4 millidegrees. This consistent accuracy and minimal deviation in LT's measurements underscore its effectiveness in satellite tracking.

The larger residuals observed in CAHA are likely due to the limited precision of time information, recorded to only one decimal place (0.1 seconds). In this interval, a satellite can move 2 arcseconds (TBC), comparable to the derived RMS. Increasing the number of decimal places in the FITS keywords could improve the accuracy of satellite positioning. Additionally, enhancing time stability could further enhance this accuracy.

The differences between observed and computed values were quantified to evaluate the accuracy of orbit determination. Table 3 summarizes the mean and RMS of residuals for satellites observed by the CAHA, while the Table 4 presents similar data for satellites observed by the LT.

As seen in the obtained data for CAHA, 2016-069B and 2017-079B exhibit moderate precision with some bias, indicating reliable but variable accuracy. 2016-030A demonstrates low bias but higher variability, suggesting the need for improved consistency in measurements. 2017-079C shows a noticeable negative bias and significant spread, highlighting potential issues with the accuracy and precision of the observations for this satellite.

The rejection rate of 6.06% due to the weighted root mean square (WRMS) criteria indicates the importance of refining observational techniques and addressing external factors that may affect measurement quality. Despite these challenges, the alignment between predicted and computed sigma of unit weight suggests that the overall precision remains within acceptable limits.

On the other hand, the analysis for LT shows the low means and RMS, that indicate the residuals centered around zero with minimal spread, demonstrating good agreement between observations and computed values. The consistency and quality of the data, with no rejections and a close match between predicted and computed sigma of unit weight, highlight the effectiveness of the LT in satellite tracking. These results are promising for ongoing and future observations, ensuring reliable data for further analysis.

The enhanced precision observed in the LT data is primarily due to the tracking methods employed. The LT used object tracking, following the satellite's motion and keeping its image stationary on the detector. This method concentrates the satellite's signal into a small, localized pixel zone, significantly enhancing the SNR and improving the accuracy of the astrometric measurements. In contrast, the CAHA telescope employed sidereal tracking, where the telescope tracks the stars and keeps them fixed in the FoV. Consequently, the satellite appears as a streak due to its relative motion against the starry background. This streaking effect spreads the satellite's signal over multiple pixels, reducing the SNR and thus decreasing the precision of the astrometric measurements.

6.2. Time Bias

Time bias is a critical parameter in the observation of satellites, referring to the systematic offset between the recorded observation time and the true event time. This offset can arise due to various factors, including instrumental delays, processing lags, and synchronization errors. While the existence of a time bias is not inherently detrimental, its impact on satellite tracking and orbit determination is contingent upon its stability and consistency.

A stable and predictable time bias can be accurately quantified and corrected for, thereby allowing for precise satellite orbit calculations. This correction is essential for ensuring

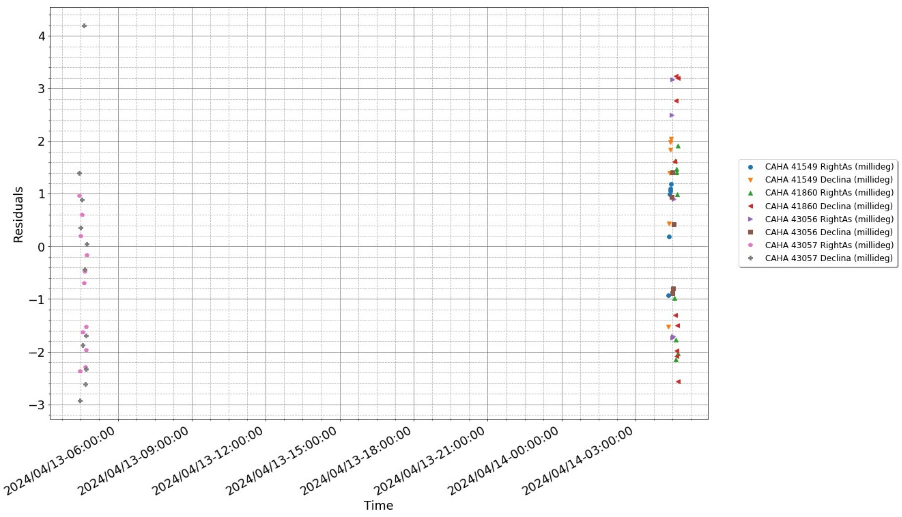

Fig. 9. CAHA: the distribution of mean residuals (in millidegrees) for the two dates, April 13, 2024, and April 14, 2024. The x-axis represents the date and time of the observation, while the y-axis represents the residual values.

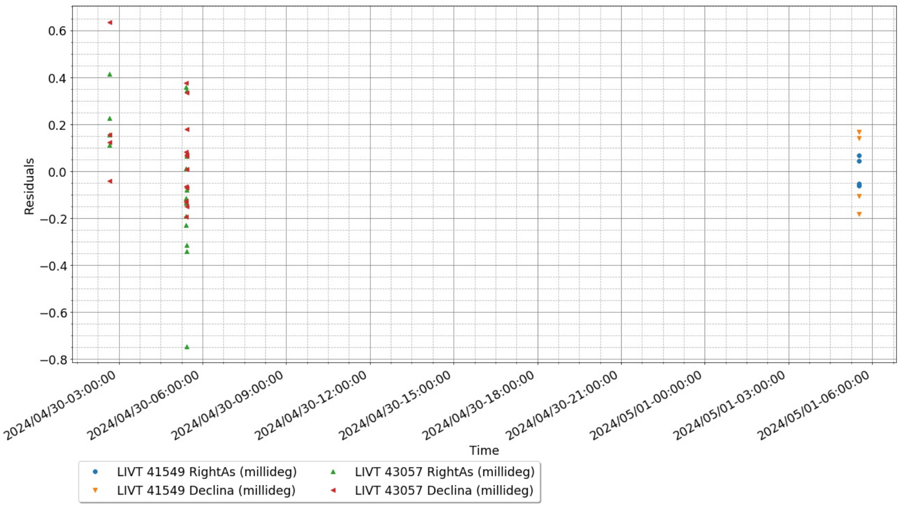

Fig. 10. LT: the distribution of mean residuals (in millidegrees) for 2017-079C and 2016-030A for the two dates, April 30, 2024, and May 1, 2024. The x-axis represents the date and time of the observation, while the y-axis represents the residual values.

the reliability and accuracy of data used in navigation, communication, and scientific research. Consistent time bias enables the precise alignment of observed and computed satellite positions, which is crucial for the overall performance of global navigation systems.

Conversely, an inconsistent or fluctuating time bias introduces significant errors in satellite positioning and tracking. Such variability indicates potential issues with the stability of the observational setup or the timing system, leading to inaccuracies in orbit determination. These inconsistencies complicate the alignment of observational data with computed satellite positions, thereby undermining the reliability of the data.

Table 5 presents the result of the ***Sstod*** software analysis, focusing on the time bias parameter for the CAHA and the LT telescopes over a specific observation period.

In the CAHA observations, three different time biases were computed: between the first and second observations, the second and third observations, and the first and last observations. The variation in time biases highlights the difficulty in maintaining consistent timing and synchronization across different periods. Notably, the difference of around 100 ms between two consecutive periods is within the acceptable range of astronomical error, indicating that these discrepancies are manageable and expected in the context of astronomical observations.

Telescope	Period	Time bias [ms]	Sigma [ms]
CAHA	24/04/13 - 24/04/14	7009.56	10.83
CAHA	24/04/14 - 24/04/15	7179.34	7.61
CAHA	24/04/13 - 24/04/15	7119.68	6.23
LT	24/04/30 - 24/05/02	-133.89	7.3

Table 5. Time bias and its standard deviation in milliseconds for both telescopes, obtained from ***Sstod*** software analysis. The CAHA observations show a difference in time bias of around 100 milliseconds over consecutive periods, which is within the acceptable range of astronomical error.

7. Conclusion

In this section one can find summarized the key findings and highlight the conclusions derived from our study on the use of 2-meter class telescopes for SST.

- **Efficacy of 2-meter class telescopes for SST**
  The results from both CAHA and LT demonstrate that 2-meter class telescopes are highly effective in detecting and tracking VFOs (Figures 6– 8). Their advanced imaging capabilities allow for precise astrometric measurements, which are crucial for maintaining an up-to-date catalog of space objects and ensuring accurate tracking of CubeSats and small debris.
  Both telescopes demonstrated effective tracking capabilities, with CAHA using sidereal tracking and LT employing non-sidereal tracking. The orbit determination and sensor calibration processes, supported by ***Sstod*** COTS software, ensured accurate and reliable orbital parameters, essential for collision avoidance and STM. The close match between predicted and computed sigma of unit weight confirmed robust uncertainty estimation.
- **Capability to track VFOs in GEO**
  The LT successfully detected and tracked a CubeSat in GEO, ASCENT 2021-118E (Figure 6), providing precise astrometric data. This capability underscores the potential of 2-meter class telescopes to monitor and characterize VFOs in high orbits.
- **Receptivity and support for SST requests**
  The LT's allocation of observation time specifically for this study under the Reactive Time program highlights the receptivity and support for SST requests by institutions managing 2-meter class telescopes. The successful acquisition of observation time and subsequent data collection demonstrate the feasibility of using such telescopes for SST purposes.
- **Stability and precision of time bias**
  The study showed that the LT exhibited minimal time bias with high stability, making it a reliable instrument for precise satellite tracking and orbit determination. In contrast, the CAHA showed more variability in time bias, indicating the need for improved consistency in its observational setup. However, the fluctuation of time bias of 100 ms is within acceptable limits, corresponding to the astrometry.
- **Astrometric accuracy and data quality**
  The astrometric reductions performed using the ***Gendared*** framework showed minimal residuals in both right ascension and declination for the observed satellites. The mean residuals for the CAHA observations were within acceptable ranges, and the LT observations demonstrated even higher precision with residuals centered around zero and minimal spread. This superior precision observed in the LT can be attributed to the tracking methods employed. In the LT campaigns we used object tracking, where the telescope follows the satellite's motion, ensuring that the satellite's image remains stationary on the detector. This approach concentrates the satellite's signal into a small, localized pixel zone, significantly enhancing the SNR and thereby improving the accuracy of the astrometric measurements.
- **Contribution to STM**
  Accurate detection, tracking, and orbit determination of CubeSats and VFOs enable timely and precise maneuvering instructions to active satellites, minimizing the risk of collisions in space. The data collected supports effective debris mitigation strategies and the development of regulatory frameworks for space traffic management.

The research showed that 2-meter class telescopes can provide high-precision astrometric data, essential for accurate orbit determination and characterization of VFOs. The study also underscored the importance of interdisciplinary collaboration and the need for enhanced observation networks and advanced data processing tools.

7.1. Future Work

The study of CubeSats and VFOs using 2-meter class telescopes has provided valuable insights into the capabilities of these instruments for SST. The findings have highlighted both the potential and the challenges of using larger telescopes for monitoring small, faint objects in orbit. However, this work is only the beginning, and there are several promising directions for future research to build on these results.

- **Improving CAHA observations**
  To enhance the precision of CAHA observations, several improvements could be made. Implementing object tracking, similar to the methods employed by the LT, could significantly increase the SNR by keeping the satellite's image stationary on the detector, thus concentrating its signal into a small, localized pixel zone. Additionally, increasing the number of decimal places in the FITS keywords for time information could improve the accuracy of satellite positioning. Enhancing the stability of timekeeping would further refine the precision of astrometric measurements.
- **Maintaining a catalogue of VFOs**
  A key aspect of 2-meter class telescopes is their potential to provide precise, regular ephemerides of faint objects. Maintaining a catalogue of VFOs with these telescopes would be a major contribution to SST. While requesting continuous monitoring of VFOs may be challenging due to their dedication to other projects, contributing to SST may help to make these observatories sustainable in the long term, as SST observations are usually funded.
- **Addressing time bias**
  Future work could focus on the long-term analysis of time bias to ensure the consistency and reliability of observations over extended periods. Continuous monitoring and calibration are essential to detect and correct any systematic offsets in observation timing. Understanding and mitigating time bias is crucial for maintaining the accuracy of orbit determinations and improving the overall quality of SST data.
- **Collaborative efforts with other telescopes**
  Expanding the study to include other 2-meter class telescopes could provide a broader perspective on the capabilities and limitations of these instruments. By comparing data from multiple telescopes at different locations, researchers can identify common issues and develop standardized methods for calibration and data reduction. This collaborative approach can enhance the overall effectiveness of the global SST network.
- **Tracking lost objects**
  New research could focus on the challenging task of searching for lost objects. These are satellites or debris that have become difficult to track due to various factors such as orbital changes, decreased reflectivity, or technical failures. Developing techniques to rediscover and

accurately track these lost objects would significantly enhance space situational awareness and help mitigate the risks they pose.

While significant progress has been made in utilizing 2-meter class telescopes for VFO tracking, numerous opportunities for future research remain. By addressing these areas, we can further enhance our capabilities in SSA and ensure the sustainable use of space for scientific and commercial purposes. The ongoing refinement of observational techniques and the expansion of collaborative efforts will play a crucial role in the continued success of SST initiatives.

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