IAC-22-A6.1

Design and test of an optical daylight tracking capability for LEO, MEO, GEO

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Abstract

Within the 23SST2018-20 R&D EUSST WP7 activities, the study concerning the use of telescope networks and lasers has been granted to ArianeGroup by CNES following a call for tender. Within this study, one workpackage objective was to study what is the current limit of daytime observation capabilities for telescopes. In order to answer this question, ArianeGroup has developed a prototype daytime observation capable telescope (HW and SW based on existing GEOTracker elementary bricks) and tested its performances during real observation trials on GEO, MEO and LEO targets. In this paper, we will describe the experimentation that have been performed, the limits that we have observed regarding daytime capability of such telescopes and wayforward for the introduction of this technology in operational service.

Keywords: SST, Daylight tracking, SWIR

Acronyms/Abbreviations

COTS	Commercial Off-The-Shelf
DC	Dark Current
FOV	Field-Of-View
GEO	Geostationary Earth Orbit
GNSS	Global Navigation Satellite System
iFOV	Instantaneous Field-Of-View
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
R/B	Rocket Body
RON	Read-Out Noise
SNR	Signal to Noise Ratio
SWIR	Short Wave InfraRed

1. Introduction

Optical instruments are commonly used for Space Surveillance purposes, as cost-effective complement to radar sensors. They are able to provide data for objects on any orbits with good accuracy. However, the avalaibility of the sensors is sometimes reduced by the physical observability of the objects. Indeed, a successful observation requires: clear sky conditions, observation station at night time, and object illuminated by the Sun. The accumulation of these criteria can reduce drastically the observation opportunities, especially for LEO objects that are often situated in Earth shadow.

The objective of this work is to assess our ability to observe at daytime with simple hardware elements (COTS or already available for other applications).

2. Technical challenge and method

Observing at daytime with the same techniques as night time observations is usually impossible due to sensor saturation. The signal coming from the sky background fills the pixels and the signal coming from the target is flooded in background signal.

One way of reducing background signal is to change the wavelength of observation. Indeed, background signal is composed of sun emitted light, which level is lower in SWIR than in visible. Moreover, atmospheric scattering is stronger in visible wavelengths. Observing in SWIR then results in higher SNR. At daytime, it is more favorable to observe in SWIR than in visible wavelengths. [1]

However, the SWIR sensor can still be saturated from background signal if the exposure time is too high. Therefore, there is an absolute need to keep the images well-exposed: exposure time shall be set in order to have reasonable signal level (50% to 75% of the dynamic of the sensor) in order to avoid saturation while reaching maximum possible SNR. In some cases, the SNR might not be high enough to allow object detection. In that case, we can use common cumulative methods [2][3] to stack short-exposure images into an equivalent longer exposure images, allowing an improvement of the SNR.

The experiment aims at observing satellites at various altitudes (GEO, MEO, LEO orbits) and at various solar elevations, in order to estimate the detection capacities at daytime.

3. Experiment

3.1 Camera trade-off

The camera has been chosen amongst available state-of-the-art COTS equipment. The chosen camera is based on a cooled InGaAs detector, sensitive in waveband 0,9 µm to 1,7 µm. Detailed characteristics are given below.

Table 1. Camera characteristics

	COTS SWIR camera
Resolution (pixels)	640x512
Pixel pitch (µm)	15
RON (e-)	<30
DC (e/p/s)	<600
Max framerate (fps) (full frame)	600

The choice of SWIR detectors (thus cameras) is less wide than visible detectors. State-of-the art SWIR cameras have relatively small sensors and big pixels pitch, which makes the system resolution and coverage less favorable than in classical visible system. The choice of the optical system will determine the performance of the whole system in terms of detection capability, but also in terms of field-of-view and angular resolution, which are essential criteria to meet operational needs.

3.2 Observation configuration #1

The first observation configuration consists in a 60cm diameter Newton telescope on which we mounted the camera described before. The observatory is located at St Michel L'Observatoire (France), which is a well-known site for astronomy with good sky conditions. The resulting characteristics are given in the table below.

Note that this telescope is a regular telescope used for astronomical observations in visible wavelengths on a regular basis. It has not been modified for this experiment. The telescope is mounted on a motorized equatorial mount allowing sidereal and slow motion tracking. That is why it has been used only for GEO satellites observations.

Table 2. Observation configuration n°1

	Configuration 1
FOV (°)	0,23x0,20
Resolution (arcsec)	1,37
Collection diameter (cm)	60

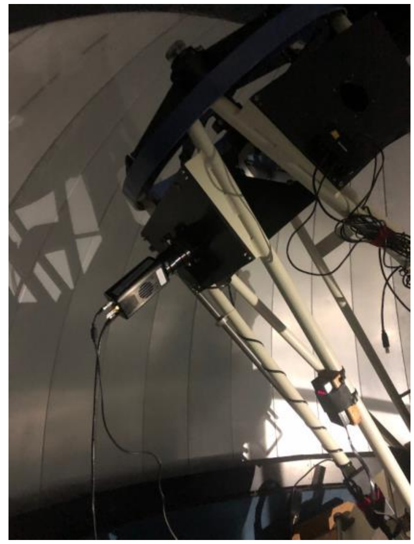

Fig. 1. Observation configuration n°1, telescope and SWIR camera

3.3 Observation configuration #2

The second configuration has been designed to allow MEO and LEO satellites tracking, meaning higher slew speed for the mount. The mount used is a COTS system allowing slew rates up to 15°/s. The maximum apparent angular speed of LEO objects is a few degrees per second, which is easily reachable with this mount. The telescope used is a COTS 14" telescope with Schmidt corrector. Note that this design is optimized for visible wavelengths, either regarding transmission or optical quality (PSF). However, it has been used with no modifications.

The observation site is located at ArianeGroup premises, near Bordeaux (France). Thus, the sky conditions are not as good as in St Michel L'Observatoire in terms of seeing and light pollution.

The resulting observation characteristics are given in the table below.

Table 3. Observation configuration n°2

	Configuration 2
FOV (°)	0,15x0,12
Resolution (arcsec)	0,84
Collection diameter (cm)	35,5cm

3.4 Image acquisition

Images are acquired in satellite tracking mode based on TLE data. The camera settings are chosen empirically in order to have the best trade-off for exposition (exposure time/gain vs background signal). This trade-off changes with respect to the pointing direction and to the current solar elevation. The settings (exposure time and gain) are adjusted for each observation, using the histogram of the grey levels of the image.
In order to ease this process, camera presets are recorded beforehand, and the user can easily switch between the available presets. Calibration data are also acquired for each preset at the beginning of the session.

3.5 Image processing

The image processing chain was developed by ArianeGroup, and adapted from the processing algorithms used on GEOTracker sensors. It includes a flat field correction to account for the non-uniformity of the sensor.
The main difference with images taken at night is that we cannot detect enough stars to perform accurate astrometric restitution. Therefore, the line of sight restitution is based solely on pointing coordinates given by the mount. Thus, the final accuracy of the measurements is closely linked with the mount pointing accuracy. The mounts as used for the observation campaigns have a pointing accuracy around one arcminute, which means that this is the maximum reachable accuracy for the data produced. However, in a future system, it would be technically feasible to upgrade the mount and the pointing models to improve the pointing accuracy (thus the data accuracy) by one order of magnitude.

4. Results

4.1 GEO results

Several GEO satellites have been selected as targets for observations to have:

- Various apparent magnitude (as estimated on visible images),
- Various pointing directions,
- Various types of platforms.

Ten individual satellites visible from the station have been selected. Those satellites were observed sequentially for solar elevations between -15° and 15° at dawn and dusk.

Once the image processing was performed, when a detection occurred, a SNR calculation was computed. We could then plot the evolution of SNR with respect to solar elevation.

The figure below gives an example of the resulting graph on a bright GEO satellite, with and without flat correction. When observed in visible wavelengths at night, this satellite is estimated between visual magnitude 8 and 10, depending on phase angle conditions. We do not have information on its magnitude in SWIR, and even less at daytime (phase angle less favourable). The blue dots are the SNR obtained before flat correction; the orange dots are the SNR obtained after flat correction. The green triangles correspond to the detection that were only possible after flat correction.

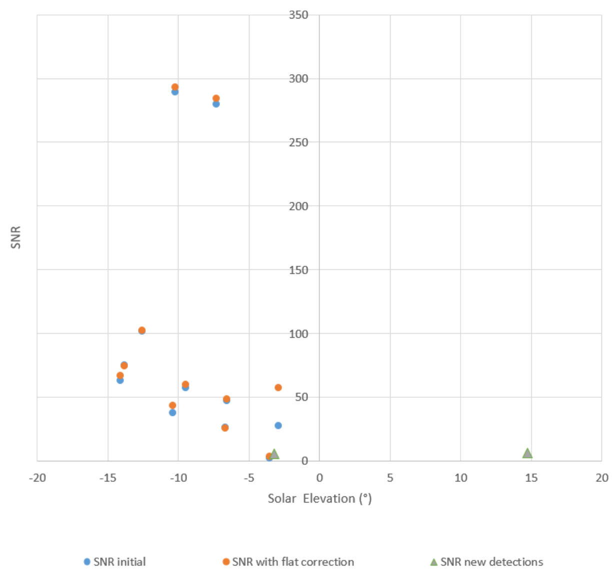

Fig. 2. SNR vs solar elevation for a bright GEO satellite

We can report a detection at solar elevation 14,7°, meaning full daytime (see Fig.2). Several detections were also possible between -5° and 0° solar elevation (usually, night-time observations are stopped at nautical twilight – solar elevation -12°).

Fig. 3. Zoom on image obtained of GEO satellite, for solar elevation = 14,7°

We also note that depending on the satellite position, the detection is more or less favourable at dawn or at dusk. Indeed, for satellites at azimuth > 180°, the detection is easier at dawn. On the contrary, for satellites at azimuth < 180°, the detection is easier at dusk. In the case of the satellite showed before, the SNR are better at dusk. The highest SNR seen on Fig.2 correspond to observations at dusk. This can be easily explained by two phenomena:

- The phase angle is more favourable at dusk, meaning the satellite appears brighter,
- The direction of observation is further from the sunset direction, which means the background signal is lower.

An operational scheduling algorithm planning observations on that type of stations shall take into account these results to gain efficiency.

4.2 MEO results

During the MEO experiments, we have targeted operational GNSS satellites and rocket bodies, around dawn and dusk, as we did for GEO targets. During this experiment, we used the observation configuration n°2, in order to be able to track MEO objects. The counterpart is that we use a smaller and less sensitive telescope.

When detections were possible, we also calculated the SNR and plotted it with respect to solar elevation.

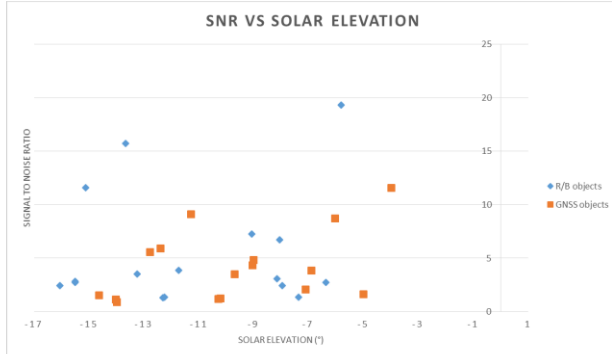

Fig. 4. SNR vs solar elevation for MEO satellites observed during experiments

We could not establish a trend on SNR variation with respect to solar elevation, which can be explained by the fact that this graph does not take into account the phase angle and the intrinsic difference of magnitude between the platforms. We also note that SNR are not especially higher on GNSS satellites than on rocket bodies, as we could have expected regarding their relative size.

We can report a detection of GNSS satellite at solar elevation -4°. These results are not as good as in GEO for two reasons:

- The observation configuration is less sensitive due, to the smaller diameter of the telescope. The quality of the sky is also worse than what we had for the GEO campaign.
- All the satellites in MEO are fainter than the brightest GEO objects.

However, we still report several detections after nautical twilight, which we found promising and we do expect a significative improvement with a more optimized detection system (dedicated SWIR optimized telescope, larger collection diameter).

4.3 LEO results

During the LEO experiments, we have tried to observe every object that was in visibility of the station during the tests. We have demonstrated that we were able to perform full daylight detection (up to 30° solar elevation, which is close to the highest possible solar elevation at that time of the year and in that place) on a lot of objects.

The graph hereafter shows the SNR obtained on LEO objects observed vs solar elevation at the time of observation. We distinguished the objects being classified as "brightest" by SpaceTrack (https://www.space-track.org/) from the other objects. We can see than detections at full daytime were also obtained on objects that are not from the brightest list.

Fig. 6 gives an example of an image obtained on a LEO satellite at high solar elevation.

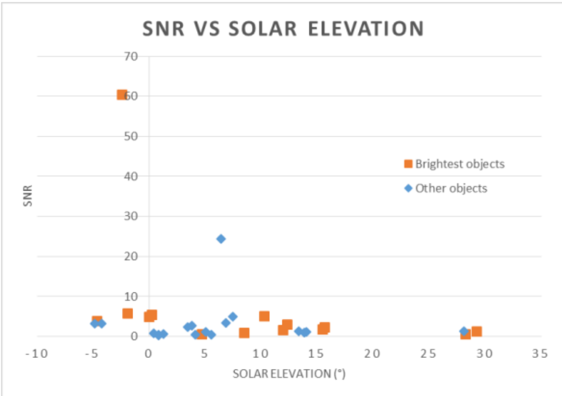

Fig. 5. SNR vs solar elevation for LEO satellites observed during experiments

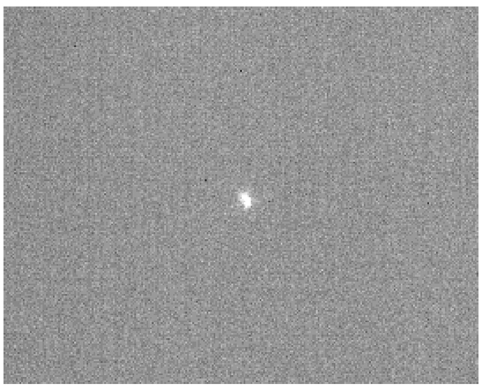

Fig. 6. Zoom on image obtained of a LEO satellite, solar elevation = 28°

These results are even more promising than those obtained on higher orbit satellites. This is due to the fact that LEO objects are much closer, thus usually appear brighter. Since we do not have the associated magnitude of the objects we observed, it is difficult to conclude with a sensitivity performance assessment. More tests would be necessary in order to evaluate the maximum detectable magnitude of the system.

6. Conclusions

This experiment showed that it is possible to detect spatial objects in full daytime or at least at dawn or dusk, with an observation station essentially based on COTS equipments and an ad hoc image processing chain. This is especially interesting for LEO surveillance, where observation opportunities at night for a given object are very limited due to Earth shadow. For GEO and MEO orbits, even if full daylight detection might not be possible, we still expect to gain around 2 hours of observation per day.
ArianeGroup plans to go forward with this study and foresees the deployment of operational SWIR stations as part of GEOTracker network in the coming years. The definition of an optimized and industrialized SWIR station has already started.

References

[1] Thomas, G. and Cobb, R., “Ground-Based, Daytime Modeling and Observations in SWIR for Satellite Custody”, Advanced Maui Optical and Space Surveillance Technologies Conference, 2019.
[2] https://aishack.in/tutorials/noise-reduction-averaging/
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Acknowledgements

This work has been partially funded by the European Space Surveillance and Tracking (EU-SST) program. The EU SST activities have received funding from the European Union programmes, notably from the Horizon 2020 research and innovation programme under grant agreements No 952852, No 785257, No 760459, No 713630 and No 713762,

We would like to sincerely acknowledge CNES and EU-SST teams for making this work possible.

We would also like to express our special thanks to the “Centre Astronomique” of Saint-Michel L’Observatoire (France) for our fruitful and dynamic collaboration.