Development and deployment of SWIR optical station for daytime space object observations

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ABSTRACT

Optical sensors are now widely used as a cost-effective solution for space objects surveillance. ArianeGroup Helix® network (former GEOTracker® network) is entirely based on optical sensors and can provide accurate angular data on a wide range of space objects.
However, classical optical observations of orbital objects are usually limited to nighttime. Consequently, favorable spans of time for observations are limited, especially for objects on low Earth orbits, which are often situated in Earth shadow with respect to the station. Therefore, the ability to observe at daytime would allow the extension of the observing periods and multiply the observation opportunities. In 2021, ArianeGroup built a prototype of short wave infrared (SWIR) sensor that was used for the first tests and allowed the successful detection of objects at daytime. After this proof of concept, ArianeGroup kept working on the optimization of the station and its associated algorithm, so as to enhance the performances.
In this paper, we will describe the configuration of the station, the first results obtained and the way forward to an industrialized operational station that will be integrated in the existing network.

1. INTRODUCTION

More than 7000 active satellites are currently in orbit around the Earth. Much more debris are above us (+28000 with a size greater than 10cm, more than 1 million considering a size greater than 1cm). In the following years, number of objects will keep increasing, driven by the launch of numerous constellations of satellites. By 2025, it is estimated that the number of objects will be multiplied by 5.
It will then increase the risk of collision between satellites, with the dreaded Kessler syndrome in sight.
Moreover, space is a mirror of the geopolitical context on Earth. Countries must be able to protect their assets days and nights in order to ward off any hostile maneuver by a foreign satellite: jamming, espionage, etc...
If optical observations are typically performed in visible wavelengths, and then limited to nighttime, short wave infrared (SWIR) stations, which makes it possible to observe at daytime, are a fundamental and essential contribution in the knowledge at any moment of the spatial situation.
ArianeGroup had already developed in 2021 a first prototype of such a sensor, with a successful demonstration of detections at daytime for multi orbit. After a short presentation of the ArianeGroup Helix® network, the results of this first prototype are reminded in paragraph 3. Since, ArianeGroup kept on developing and improving a new SWIR station which configuration and first results are described paragraph 4.

2. THE HELIX® NETWORK

ArianeGroup has been developing for more than 10 years a worldwide optical space surveillance network. The first operational station was launched in 2014, the network has since grown with the addition of a Command and Control center (C2) and almost 20 additional sensors around the world. This network, previously called GEOTracker®, first focused on tracking satellites on high orbits. The current network covers 100% of the geostationary arc, with multiple redundancy zone to be robust to bad weather or unavailability on one site as can be seen figure 1.

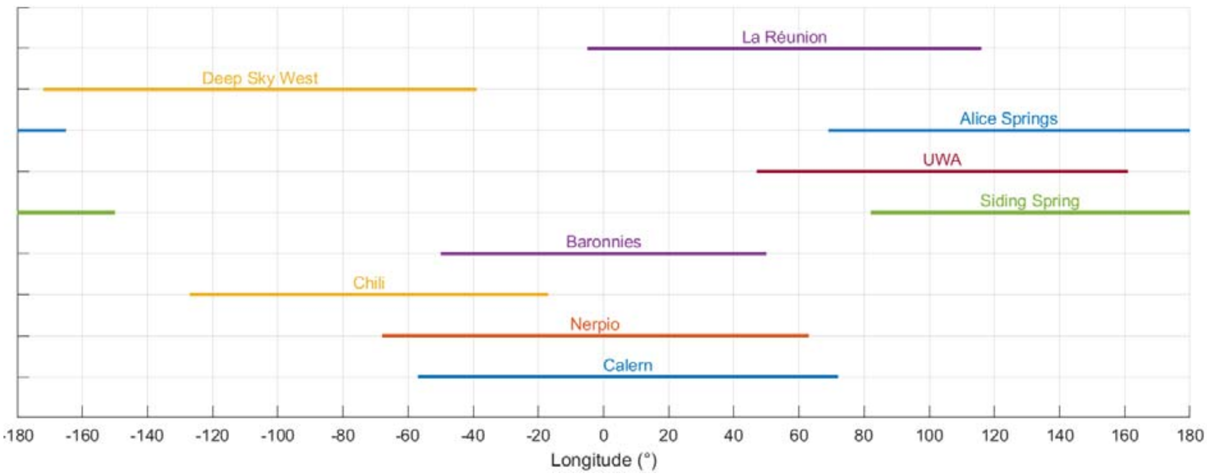

Fig. 1. Accessible longitude of the stations of the current Helix® network

With the deployment of new type of sensors and new capabilities, GEOTracker® becomes Helix® and provide multiple new services for commercial and military customers.

Thanks to Helix®, ArianeGroup has a global optical observation system for space surveillance.

- Monitoring of satellites and space debris in low (LEO), medium (MEO) and geostationary (GEO) orbit with high accuracy orbit determination
- Catalog of space object positioning, orbitography and analysis data
- Provision of personalized and secure operational services and products, 24/7, day and night
- Custom-made programming adapted to the needs of civil and military satellite operators (surveillance, tracking, characterization, photometric characterization, Space Traffic Management, Space assets surveillance, manoeuver detection, decision-making support, provision of anti-collision services)
- Sensitivity up to magnitude 17

Three types of sensors are composing the network:

- Tracking sensor
- High sensitivity tracking sensor
- Survey sensor: this wide field of view sensor allow to detect the objects over a very large area above the site, and to give indications to the tracking sensors for very precise measurement and orbit determination. In optimal conditions, with an adapted strategy, our wide field stations allow to reach a coverage of 120° - the equivalent of 12 times the area of Europe one the geostationary arc.

Characteristics	Tracking sensor T355	Tracking sensor T500	Survey Sensor
Diameter	356mm	500mm	75mm
Field of View	2.69° x 2.69°	1.54° x 1.54°	20.7° x 20.7°
Angular accuracy	< 0.5mdeg	< 0.25mdeg	< 5mdeg

Table 1. Helix® network type of sensor

One Centralized command and control center (C2) has been developed and is in charge of:

- monitoring the status of the complete sensors network
- controlling the optical stations of the network
- retrieving angular measurements and magnitude from the optical stations
- performing object identification
- performing environment analysis
- performing analysis on a specific object or space area
- the automatic sensors planning

- cataloguing Space objects
- monitoring and tracking Space objects

The Helix® system proposes several customers interfaces to retrieve data, such as access the angular measurements or several analysis tools to make the understanding of the space situation easier

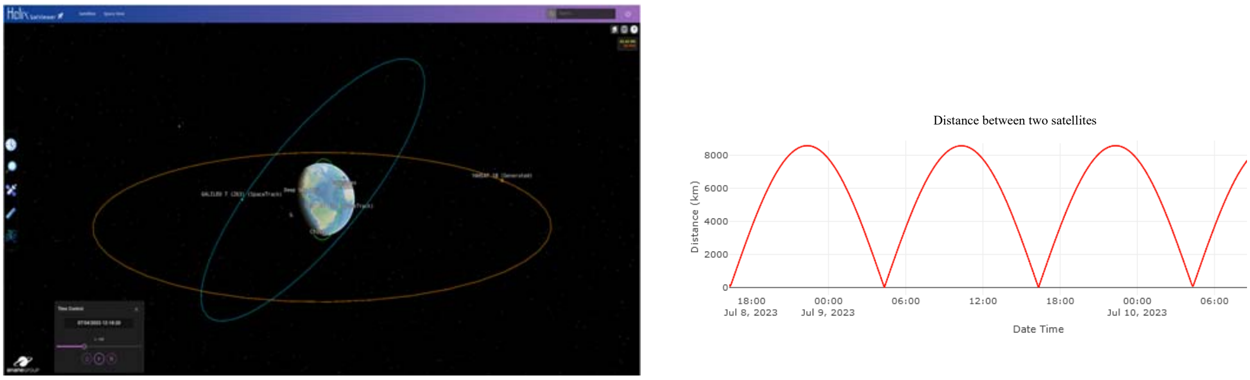

Fig. 2. Example of representation on C2 Helix®

Helix® is now a fully operational and automatic system for LEO, MEO and GEO orbits. By 2025, around 35 sensors will compose the network.
In addition, in order to improve its capabilities, ArianeGroup foresee to deploy infrared stations in the network by 2024.
The following paragraphs detail the results obtained so far on the development, test and industrialization of such a sensor.

3. FIRST PROTOTYPE AND RESULT IN 2021

ArianeGroup started developing SWIR station in 2021 within the 23SST2018-20 R&D EUSST WP7 activities. Reference [1] presented the first encouraging results, summarized below.

The first station was made of essentially Commercial Off-The-Shelf (COTS) equipments (telescope, camera and mount). Specific image processing chain had been developed by ArianeGroup.

The experimentations showed good results. For instance, Fig. 3 below gives an example of the resulting graph on a bright GEO satellite, with and without flat correction. It plots the Signal to Noise Ratio (SNR) versus solar elevation for a bright GEO satellite.
GEO satellites were observed for solar elevations between -15° and 15° at dawn and dusk.

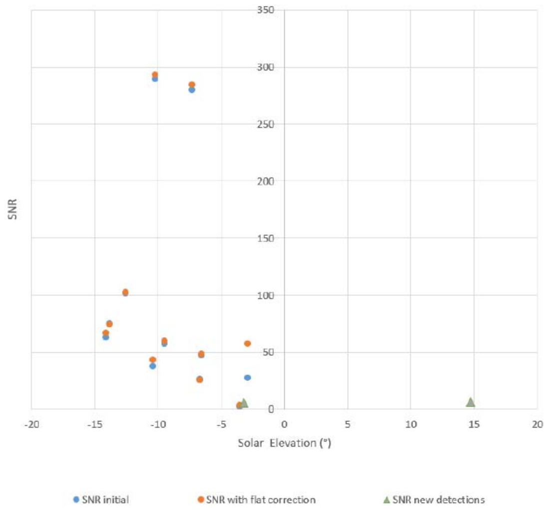

Fig. 3. SNR vs solar elevation for a bright GEO satellite

For LEO objects, 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, as seen on Fig.4.

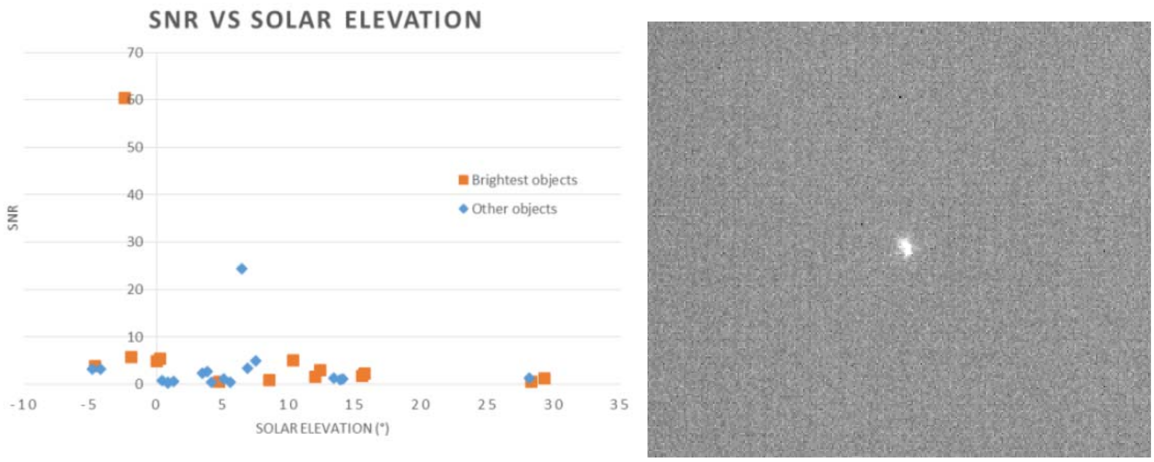

Fig. 4. SNR vs solar elevation for LEO satellites observed during experiments (left) and Zoom on image obtained of LEO satellite, for solar elevation = 28°(right)

This experiment showed that it is possible to detect spatial objects in full daytime or at least at dawn or dusk. Nevertheless, the configuration had some limitations:

- The pointing accuracy was not optimum
- The telescope was not optimized for IR wavelengths.

Since, ArianeGroup kept on developing a new optimized SWIR station, presented in the following paragraph.

4. NEW OPTIMIZED IR STATION

The new design of the station has been optimized through 3 major axis:

- A new telescope

- New image processing to improve the detection and the tracking
- New architecture to link the IR image with its dating and the positioning of the mount to improve the accuracy measurement.

New telescope

One of the main limitations of the initial experimentation [1] was related to the optical performance of the telescope in IR (for the configuration used for the LEO tests).

After internal studies, we specified a telescope taking into account the following drivers:

- The transmission of surfaces: it is generally optimized only for visible wavelengths. It is therefore a question of opting for specific surface treatments, with good performance in SWIR wavelengths.
- The design of the telescope: the image quality must be mastered in the IR for the entire extent of the field that will be covered by the camera. A telescope that includes dioptric corrections (lenses) can present chromatic aberrations and therefore a strong degradation of the image quality in the IR A telescope made up purely of mirrors can intrinsically have good performance in the visible and in the IR.
- A maximum aperture (to ensure a wide enough field of view)

The final configuration of the optical station is given Tab.2

Collection Diameter	400 mm
Aperture	f/6
Resolution (pixels)	640x512
Pixel pitch (µm)	15µm
Field Of View (FOV)	0,23°x0,18°

Table 2. New optimized IR telescope configuration

New image processing

The image processing algorithms were prototyped internally by ArianeGroup in Matlab language and tested during the first experiments. In order to get closer to an industrialized sensor, the image processing algorithms have been transcoded into JAVA language and packaged in an executable that can be easily used by the operator.

The Command Control and Image Acquisition Software have also been improved and is now user friendly.
An auto-exposure algorithm has also been developed in order to systematize the choice of exposure time according to the current sky background (and therefore the filling of the camera). This ultimately optimizes the signal-to-noise ratio.

Solar exclusion zone is a new functionality which has also been developed to prevent the sun being in the field of view of the camera. The high energy of the sun could destroy the camera so an automatic algorithm is running while the telescope automatic tracks the satellite. If the apparent satellite trajectory is coming close to the sun (20° for instance), the telescope stop tracking the satellite but extrapolate the trajectory of the satellite and point in the closest safe position to track the satellite again when it goes out the solar exclusion zone.

New architecture

In visible wavelengths, the precise position of the satellite is obtained thanks to its relative position to the stars in the images. In SWIR and during daytime, there are not enough stars in the field of view to perform accurate astrometric restitution. Therefore, the line of sight restitution is based solely on pointing coordinates given by the mount and the final accuracy of the measurements is directly linked with the mount pointing accuracy.

To improve the accuracy, we are now making an image timestamp using the following data:

- Positioning of encoders of the mount
- Camera shooting start signal (TRIG)

- Dating

Each station has 2 absolute encoders to return the azimuth and elevation position of the mount. So far, this encoder data was only read by the motor drive via a specific bus (bus BiSS for bidirectional/serial/synchronous) but the return of this information to the control software, done via Ethernet, is long and non-deterministic.

We then installed a spy bus between the encoder and the motor drive: a dedicated chip is used to interface with the BiSS bus and to recover the raw data from the encoder. This component only spies this bus, with no interference with information in transit (This chip is intended to be a watchdog for systems using this type of protocol).
It is therefore possible to retrieve encoder information in real time via what we called a BOTS (Box Of Time Stamping).

The processing of the acquisition of the 2 encoder positions and the transmission of this information to the control software on triggering of camera is then entrusted to a raspberry PI Pico and an Ethernet module.

One camera connector allows us to recover a signal on a shooting trigger. This signal from the camera is then conditioned to generate an event on the time server. The architecture is presented Fig. 5.

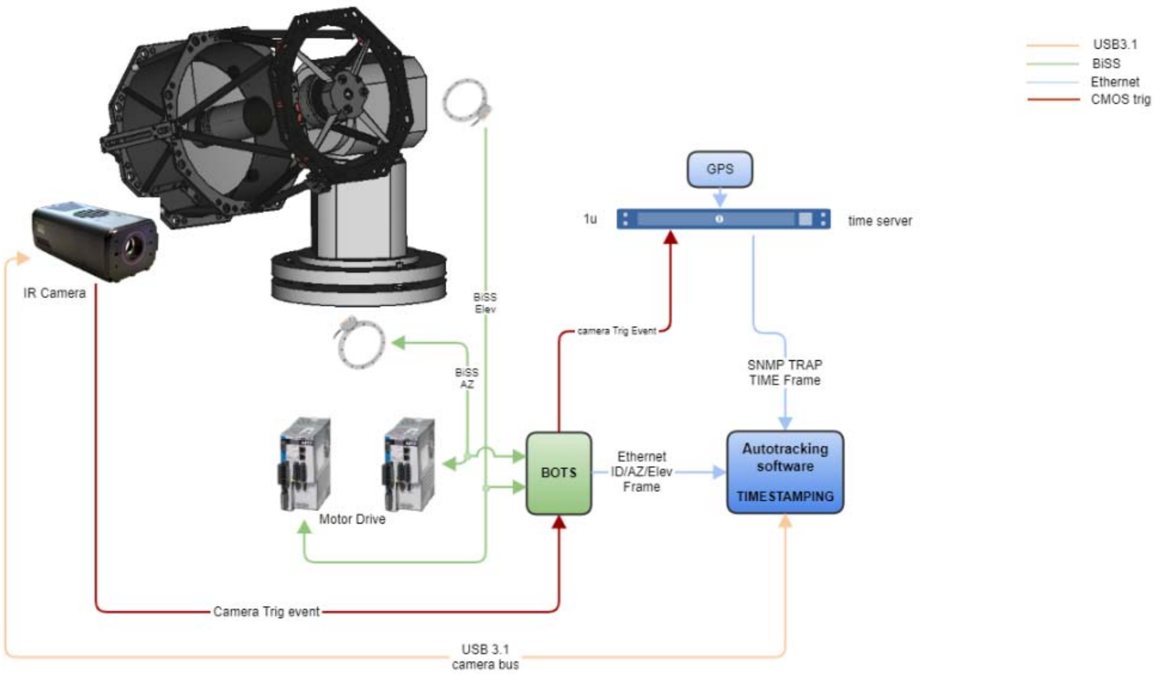

Fig. 5. Timestamp architecture

First results

The optical station has been located at St Michel L'Observatoire, in the south of France, since June 2023. A picture of the telescope is shown Fig. 6

Fig. 6. New optimized telescope

Two first campaigns in June have already been done. They allowed us to install this new station, refine the settings of the telescope and check the first performances of the system.

The preliminary results are that:
- The solar exclusion zone correctly works
- The BOTS retrieves encoder information in real time at the specified frequency
- The new image processing process improves the image quality

Fig.7 shows an example of an image of the LEO satellite SL-16 R/B taken at 11h30 AM, local time. The satellite is easily detected.

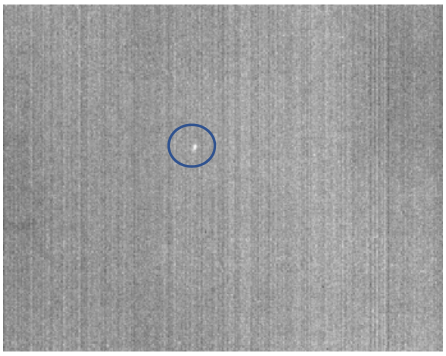

Fig. 7. SL-16 R/B detected at 11h30 AM local time (zoom)

Another campaign is foreseen in September 2023. Meanwhile, new improvements of the station are already ongoing, for instance the industrialization of the BOTS, now that the proof of concept has been achieved.

At the end of this year, a robust and efficient definition of an IR station will be available. The next step is to deploy, by 2024, such a station in one of the Helix® Australian site.

5. CONCLUSION

With the Helix® network, ArianeGroup proposes a fully operational and automatic system for LEO, MEO and GEO orbits, providing services for multipurpose customers.

The number of optical station in the network in visible wavelength is still growing and retrofit of first stations has already started, further improving the performances of the system.
After its previous successful IR experimentation in 2021, ArianeGroup kept on developing an industrializing a new IR station with a specific and optimized IR telescope and a new architecture allowing better performances. This new system is currently under test and first results are very promising.

Once the design of the station is validated by the end of this year, an IR station will be deployed in the Helix® network next year.

6. ACKNOWLEDGMENT

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7. REFERENCES

[1] Marine Pyanet, Théo Joffre, Laurent Hennegrave, Gaëtan Eyheramono, Sébastien Vourc'h (ArianeGroup), Vincent Morand, Juan-Carlos Dolado Perez, Pascal Richard, Megane Diet (CNES), IAC-22-A6.1. *Design and test of an optical daylight tracking capability for LEO, MEO, GEO*, 73rd International Astronautical Congress (IAC), Paris, France, 18-22 September 2022.