Towards an All-Orbit Optical Data Service Provisioning Based on ArianeGroup Helix System

Thibault DE LA VILLEGEORGES, Théophile MONTAGNE, Gabriel DAGUERRE, Lancelot PANAGET, Baptiste DAILLY, Clément BEGASSE
ArianeGroup, 51 route de Verneuil, 78133 Les Mureaux, France

Billy BARBIER, Léo BOULARD, Valentin LEMIESZ, Nicolas ROUX, Guillaume DELOMENIE
ArianeGroup, rue du général Niox, 33166 Saint Médard en Jalles, France

ABSTRACT

Optical sensors are now widely used as a cost-effective solution for space objects surveillance and tracking. ArianeGroup Helix network has been continuously providing optical data to its customers for more than 10 years. Initially focused on high-orbits surveillance, the system is constantly evolving to enhance its cataloguing capabilities. Hence, the continuous expansion of the network leads to enhanced performances in terms of coverage and revisit time, covering LEO to GEO orbits data service provisioning. Helix is now covering 100% of the GEO belt with a revisit time less than 12 hours. In addition, ArianeGroup keeps working on innovative sensors to improve the quantity and quality of SSA data, especially for LEO:

- A prototype SWIR sensor has been successfully tested to provide daytime data, and operational SWIR stations are currently under deployment in the Helix network, allowing an improved coverage in LEO
- Very wide field of view sensors have been developed, qualified and are integrated in the network for all orbit detections allowing to produce very large quantities of measurement data in LEO.

In this paper, we will describe the latest evolutions of the ArianeGroup system and its capacities, the newest sensors development and deployment, as well as the way forward to a comprehensive all-orbits data provisioning system.

1. INTRODUCTION

Optical sensors are now widely used as a cost-effective solution for space objects surveillance. ArianeGroup Helix network has been expanding and evolving since 2014 to enhance its performance following, progressing from GEO, to all orbits and now towards new optical technologies to access more information on the observed objects and offer new services to its customers.

The problem posed by the increasing number of objects in LEO has been very widely discussed and presented. In the European SSA landscape, contributions of private SSA data providers are now very much necessary, both for volume and quality. Since optical systems can very well be adapted to providing large amount of good quality data, Helix thus naturally evolved in this direction. The complementarity between tracking and survey sensors in LEO, allows to offer both volume and high precision measurements depending on the customer's needs.

The LEO orbits saturation and associated collision risks, will necessarily steer the need for even more accurate data in the future, but also end to end timeliness will be critical. Although the accuracy of optical tracking sensors is very good, the object range not being accessible limits the accuracy of the calculated orbits. Laser ranging is one option to solve this issue, and ArianeGroup has been working since several years to setup an optical system similar to the Helix sensors which includes a laser ranging capability.

LEO orbits are already a strategical field for military assets and this trend is increasing with the appearance of very maneuvering objects and a worldwide variety of space operations demonstrations and projects. ArianeGroup has been leading the SAURON project aiming to develop new capabilities for space object's characterization. In the frame of this project, ArianeGroup's laser ranging prototype was upgraded and demonstrated a ranging capability on an uncooperative target with an eye-safe system. A high frequency imaging system prototyped was also developed and demonstrated low resolution imaging of LEO objects with a small aperture telescope, which gives a capability to provide affordable "first-level" characterization information of large targets of interest in LEO but also a very high resolving power, valuable to analyze RPO (Rendezvous and Proximity Operations) scenarios.

2. HELIX

The Helix network in 2023 was described in [1]. Since then, sensor deployment has been continuing according to Helix's primary objective which was to efficiently cover the GEO belt. Although 100% of the GEO belt is covered since 2021, additional deployments allow achieving a more robust performance and lower the revisit rate. Fig. 1. shows the longitude ranges visible for each Helix sensor, highlighting that all longitudes are now covered by several sensors.

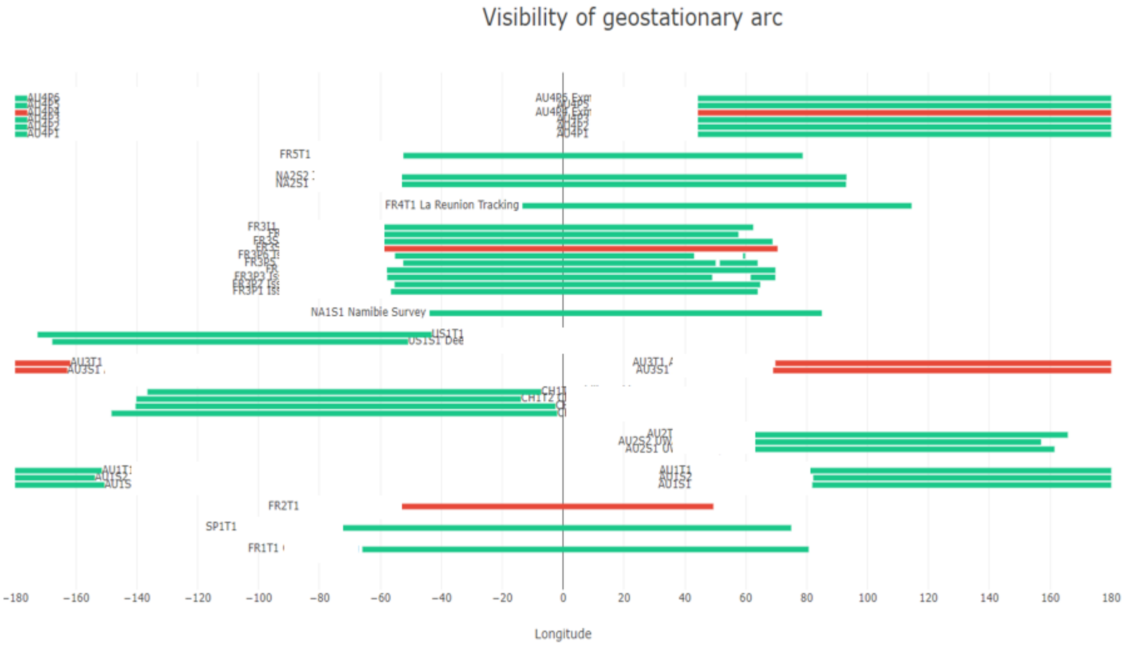

Fig. 1. Accessible longitudes of the Helix sensors
(green indicates the sensor is operational and red that it is not)

Helix currently maintains around 1000 GEO objects but the level of interest for these objects is obviously very variable. It is mandatory to spend sufficient effort on those considered critical in order to ensure resilience to weather fluctuations or object maneuvers and stay independent from external sources as much as possible. Fig. 2 shows the orbit stability (stable orbit means at least one valid orbit was computed for the object in the last 48 hours) over time for Helix with and without integration of public data, on the GEO objects considered most critical by ArianeGroup. The graph shows that Helix now complements public data by adding a significant number of objects, and also that the orbit stability is very resilient in general and in particular to unexpected variations from public data as occurred in January 2024.

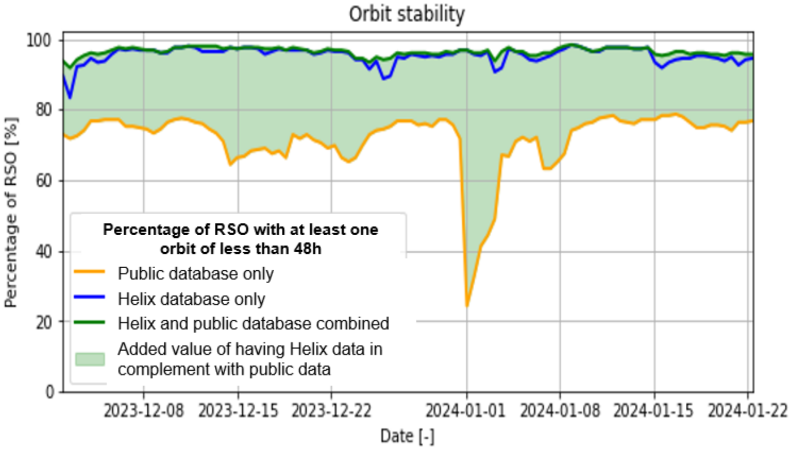

Fig. 2. Critical GEO objects' orbit's stability with and without public data

During the latest network expansion, Helix adapted its sensors' image processing techniques and C2 (Command and control) to LEO orbits. Tracking sensors were already performing in LEO in 2021 and the survey sensors also now have this capability. A LEO dedicated pointing strategy was developed to have the 20°*20° fields of view operate in a "step and stare" mode maximizing the number of visible objects over time. Fig. 3 shows a typical example of the objects detected in a survey sensor FOV (Field Of View) over a 10 min time period. All Helix sensors are thus now capable of operating in either orbital regime, allowing the central C2 to setup optimized strategies depending on the overall needs.

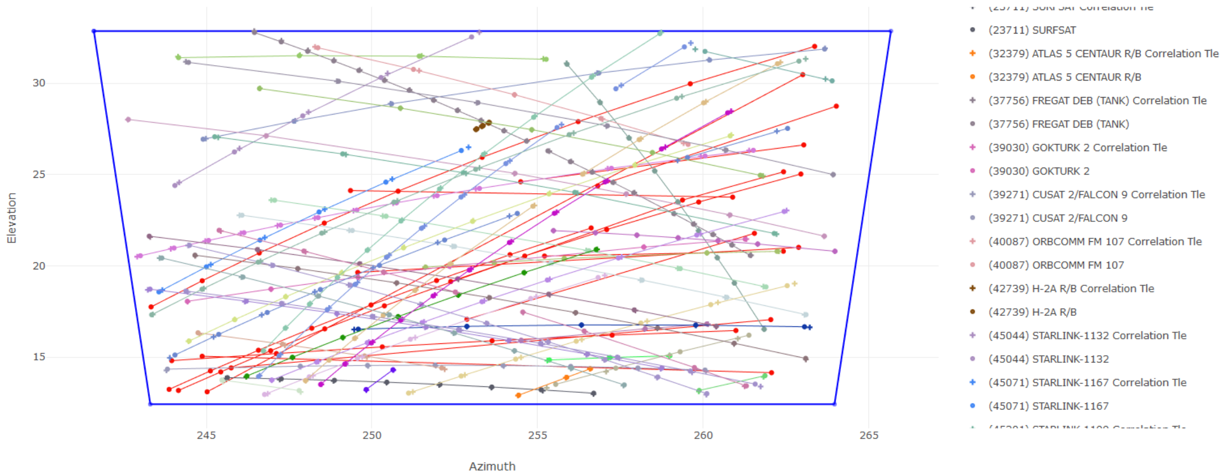

Fig. 3. Typical 10 min observation with a survey sensor operating in LEO

A new sensor has been developed based on the same hardware and software as the "regular" Helix survey sensors, except it holds 6 different optical systems. These 6 FOV are fully independent and can be operated separately, allowing for a variety of strategies to cover various portions of the sky. Fig. 4 shows pictures of the two type of survey sensors now available in Helix. The 6-FOV version, called Panoptès, is already operational in France and will be deployed in Australia in late 2024.

Fig. 4. "Classical" survey sensor and (left) and "Panoptès" survey sensor (right)

Network coverage in LEO is less straightforward to quantify than in GEO. One useful approach can be a visual representation of the sensors' field or regard for various objects' altitude. Fig. 5 shows this coverage in early 2024 for objects at 400 and 800 km altitude. Helix is now planning to continue its extension focusing on LEO orbits to optimize LEO coverage.

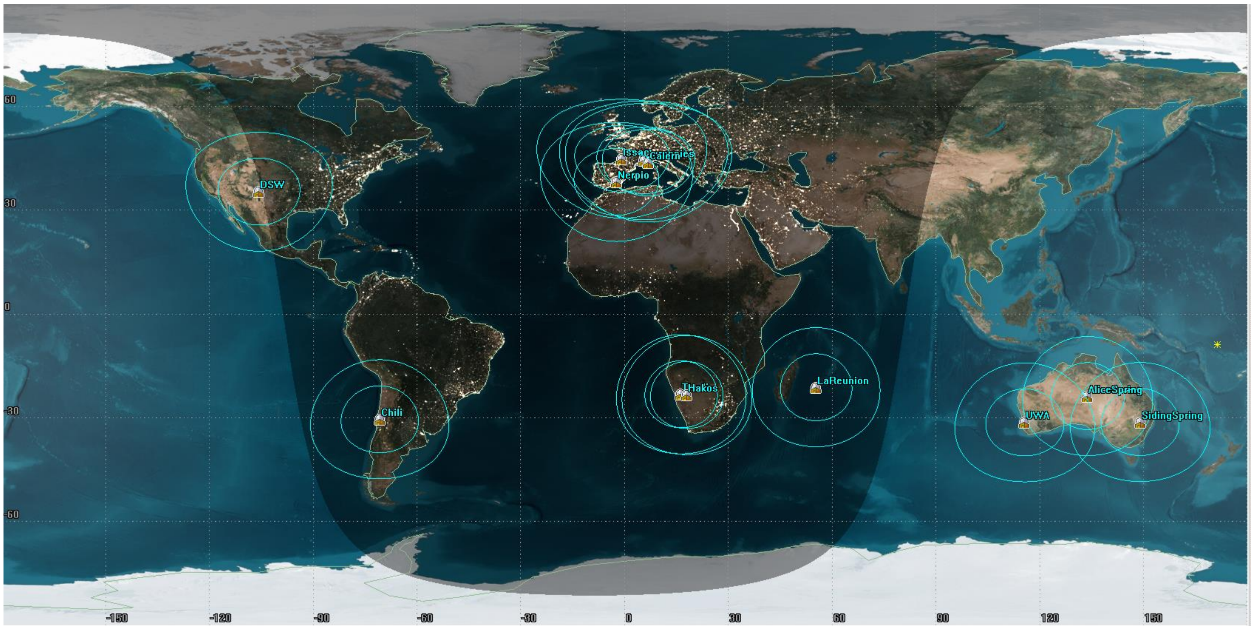

Fig. 5. Helix sensors FOR for objects at 400 km (small circles) and 800 km (large circles) altitudes

3. SWIR sensors

The main drawback of optical sensors is that their use is limited to nighttime. This is fairly easily overcome for GEO objects with a sufficient coverage ensured by well dispatched sensors around the globe. But for LEO objects, the situation can be more difficult: the visibility slots are much shorter and very much depend on the orbit inclination: for high inclination orbits such as SSO, phasing with the network is sometimes favorable and sometimes not. In the latter case, it becomes very hard to ensure a good revisit rate.

Fig. 6. Industrialized SWIR sensor

SWIR sensors can solve this issue by offering a daytime observation capability. ArianeGroup’s developments on this topic have been presented in [1]: after some promising results with a prototype in 2021, this type of sensor was industrialized in 2022-2024 and additional improvements turned out to be necessary:

- The command and control infrastructure was upgraded to a more performant system in terms of memory and calculation speed, and adapted to withstand daytime climatic environments

- The BOTS (Box Of Time Stamping) was industrialized and qualified; the delay between the reference trigger signal and the encoder data retrieval is 50 µs
- The mount pointing model was completely redefined after it was assessed not sufficiently precise; the new model, based on residuals weighting, improved point accuracy by one order of magnitude down to 0.1'
- A custom mechanical piece was implemented to hold the camera, ensuring no misalignments
- A bistable shutter was installed to increase the system's life duration
- The camera cooling system was upgraded to withstand the foreseen thermic environments in operation
- Finally the Helix C2 was adapted to be capable of scheduling and tasking during daytime and perform data fusion between day and night sensors

In late 2024, the first industrial SWIR version is connected to the C2 and qualified and another SWIR sensor is planned for deployment in Australia by the end of the year. Helix teams plan for some intensive testing in various conditions in order to later optimize the observation strategy even though the sensors will start contributing to the network before that.

4. SATELLITE LASER RANGING SENSOR

ArianeGroup's SLR results up to 2022 have been presented in [2]. The SAURON project allowed us to continue upgrading the system: significant changes were decided during the design phase, aiming to overcome critical limitations in the link budget. Extensive testing also showed the need for some software adaptations.

Emission path

Laser divergence is obviously very critical for the link budget since it varies with an invested squared relationship. The use of COTS (Components Of The Shelf) elements in preliminary experiments had shown that these were not good enough in optical quality but also flux density turned out to be a major issue.

A first performance increase was achieved by purchasing a custom beam expander. The possibility to specify the piece directly allowed to have on unique piece instead of two which drastically simplified mechanical housings and alignment processes. Overall magnification ratio was increased to *60 and the entrance pupil was nicely fitted to our laser. However, measuring experimentally the real divergence turned out to be quite a challenge. Several well-known techniques were tested but all exhibited some limitations or infeasibilities, mostly due to the very large exit pupil diameter. The most reliable way to proceed in the end was to fire the laser on a distant forest (7 km away) and acquire images of the spot. Even if the target is obviously not very homogenous, reasonable quality images could be obtained. The main limitation of this approach is due to atmospheric turbulence: with a 7 km long horizontal propagation path, the contribution of atmospheric turbulence to beam spreading isn't negligible at all. Measured divergence thus accounted for an unknown contribution of turbulence, but this contribution could be at least roughly estimated with some theoretical models and the final fit proved to be fairly reasonable, at least sufficient to confirm divergence was mastered (results are shown below).

The second step in performance increase was achieved via a collaboration with SED (Safran Electronics and Defense), partner of ArianeGroup in SAURON laser activities. A co-engineering phase allowed to setup some requirements for a new beam expander installed on a controllable mechanical steering system to have a controllable fast and accurate pointing of the complete emission path. Target divergence was lowered down to 26 µrad and the beam expander was able to withstand maximal laser power (26 mJ at 200 Hz). This design was also chosen so that a very small decrease of the laser power leads to and eye-safe laser beam already at the output of the beam expander. In this situation, laser safety issues are drastically simplified: the system still has to be handled appropriately since it contains a class 4 laser, but once it is installed and checked properly, it no longer poses any threat to air traffic which is a huge advantage for future deployments and operations.

The laser beam profiles extracted from the measurements at 7 km for both beam expanders are shown in Fig. 7. Divergences of respectively and 82 and 79 µrad are measured, when simulations with atmospheric turbulences led to expect 86 and 77 µrad respectively. It shall be noted that the laser has a M^2 of 1.3, obviously contributing to measured (and simulated) divergence. The match with the theoretical values is actually closer than the overall setup would let hope for. Nevertheless, we consider both beam expander to perform close to nominally and thus used their theoretical output divergences in the future link budgets.

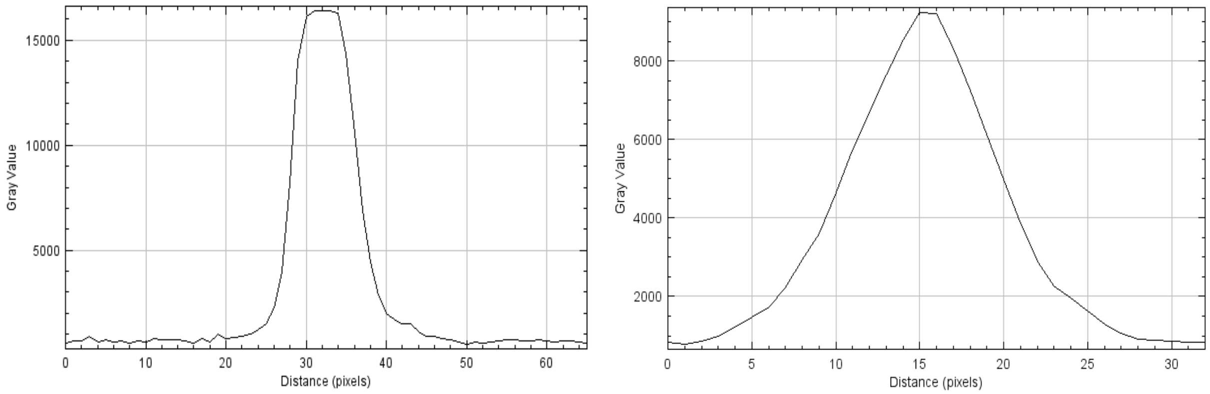

Fig. 7. Measured laser profiles at 7 km with custom (left) and SED (right) beam expanders

Telescope and reception path

SLR demonstrations before SAURON had already highlighted some limitations due to the telescope: the telescope initially used was not optimized for the SWIR wavelengths and the observed point spread functions (PSF) indicated that a significant amount of energy was lost because of that. Also some additional optical elements in the path degraded the PSF. A new telescope was specified and purchased to recover from these limitations. The beamsplitter mechanical housing was adapted to ensure it underwent no constraints which introduced some aberrations. The various components of the reception path were mechanically secured to reduce some misalignments which appeared to be non-negligible contributors when the link budget began to be precisely mastered.

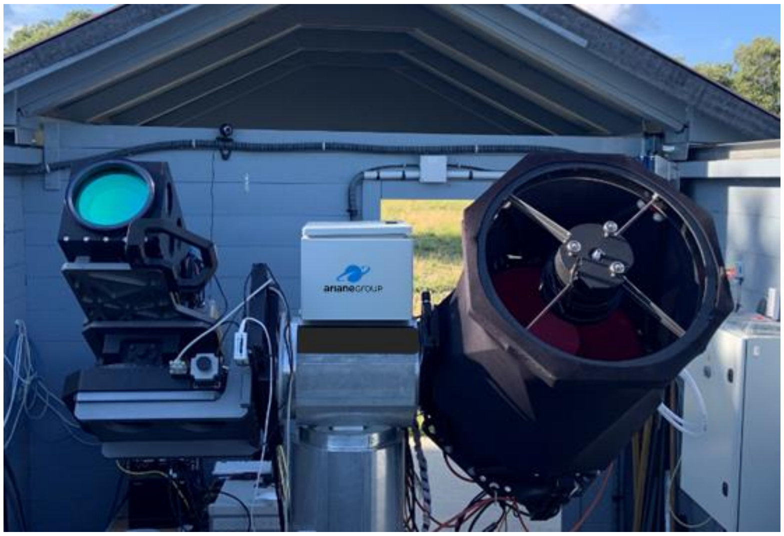

Fig. 7. SLR prototype at the end of SAURON (with SED emission path)

Object tracking and laser pointing

With both emission and reception path performing correctly, overall alignment becomes the critical issue: the object must be tracked very accurately aligned with the detector (a Single Photon Avalanche Diode with 62 µm entrance pupil) and the laser beam must remain accurately aligned on that target.

First step was to upgrade the tracking algorithm and chain: some minor bugs in the PID (Proportional Integral Derivative) were corrected and an effort was put on the fine tuning of the mount azimuth and elevation motors PID. Indeed, having changed several HW elements, the overall system mass, centering and inertia also changed and the pointing closed loop showed to be very sensitive to this tuning. After optimization, target tracking stability was assessed in operation to be lower than 10 µrad. This performance is critical for alignment but not only: if it were significantly higher, it would make the divergence performance rapidly useless. Indeed tracking precision increase to values approaching the laser divergence, the beam statically hits aside from the target or at least in a region were the flux density is much lower, were badly deteriorating the link budget. Calculations show that ideally the tracking accuracy should be 1/10 of the laser divergence, up to 1/5 is acceptable. Given the divergence assessment with the SED laser, tracking accuracy is actually not sufficient (the ratio is 1/2.5 so a factor 2 is still missing). However this doesn't account for beam spreading due to atmospheric turbulence. Theoretical calculations show that this contribution in operation (very different from a horizontal path) isn't negligible although not first order contributor. This achieved laser divergence should be considered larger than the theoretical value and the ratio with pointing accuracy reasonable. Further investigations on this topic will be done in the future. If the pointing accuracy cannot be further improved, it could be decided that the laser divergence is actually over specified. At least a compromise has to be found.

Finally laser pointing turned out to be a real issue: aligning the beam on a target was no deal, but it appeared that the laser pointing changed with the pointing direction by a very significant amount. The root cause couldn't be traced in detail since it seemed to be an overall contribution of the mechanical systems: there are many interfaces from the emission path to the telescope and they likely all slightly contribute to overall misalignment when gravity direction changes (basically when pointing elevation changes). In order to compensate this, a dedicated SW (SoftWare) was developed to detect the laser beam and correct the pointing direction via a closed-loop. Fig. 8 shows the kind of image on which laser pointing direction is calculated. This additional SW required quite some effort but showed in the end an accuracy of 10 µrad. A perfect compensation seems out of range, making the previous question on pointing and divergence even more important since this laser pointing variation can be considered as an additional contributor to the overall tracking precision of previous assessment, making the compromise with divergence now out of bounds.

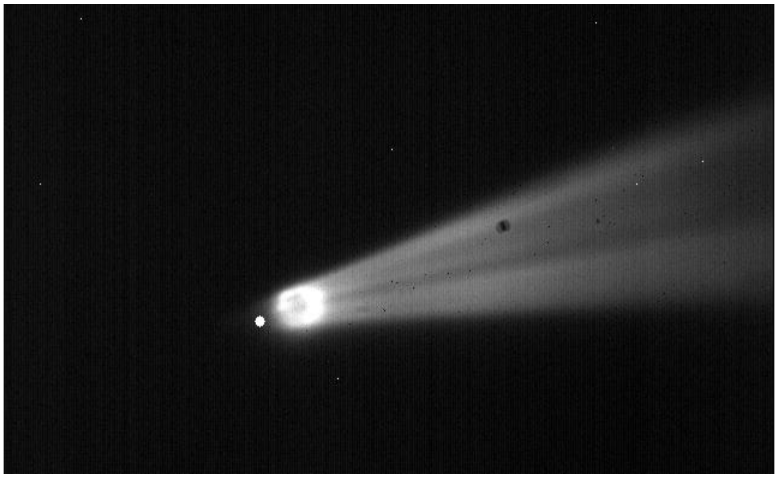

Fig. 8. View of the laser beam being pointed towards the target (bright spot) via a closed-loop

Results

With all these improvements, system performance gradually increased. First steps were to recover previous achievements in terms of cooperative ranging since the system had significantly changed. This was achieved fairly quickly since the required link budgets are not very challenging. Typically ranging of cooperative targets was possible even with laser point direction compensation. LAGEOS 1 for instance was ranged at a distance of 6500 km, later followed by COSMOS 25259 at a distance of 19400 km (results in Fig. 9).

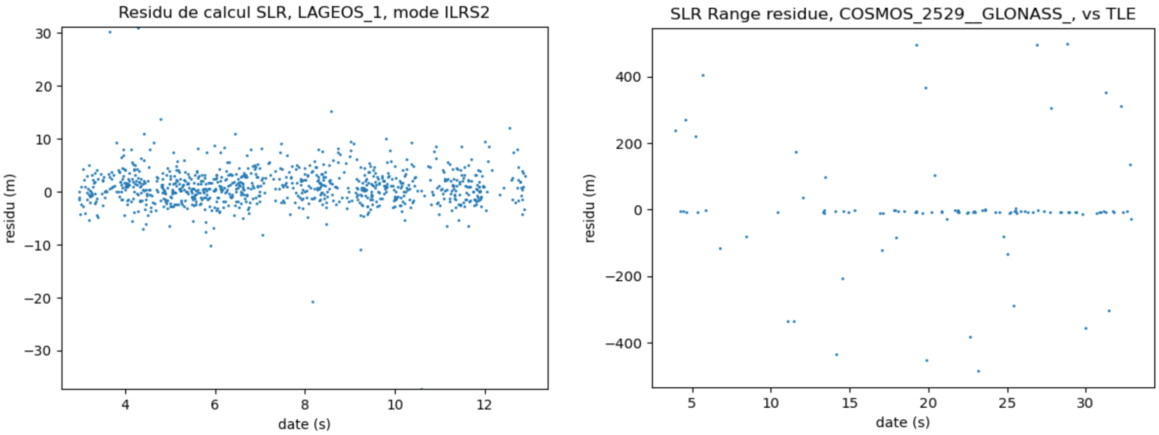

Fig. 9. Residues (range variation wrt. TLE) of cooperative targets at 6500 and 19400 km

Once the system was fully optimized, the increase in link budgeted finally allowed for ranging of uncooperative targets, which is the key objective. This was achieved in June 2024 with the ranging of several rocket bodies at distance of 1000 km approximately. Fig 10. Shows the results obtained on an SL-16 rocket body which has an RCS of 12 m², at a distance of 1100 km.

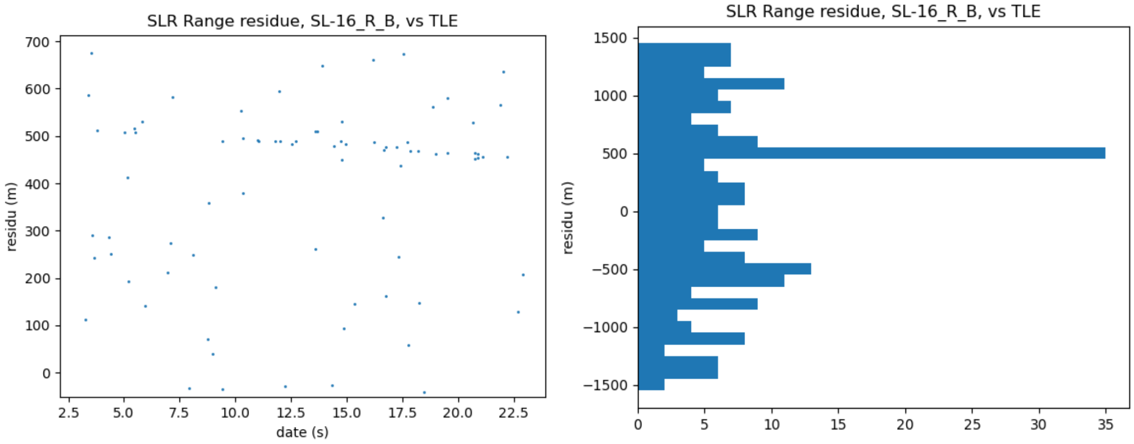

Fig. 10. Residues (range variation wrt. TLE) of an uncooperative target at 1100 km

As can be seen on the plots, link budget is at the limit of detectability for a visual assessment, however, adequate treatment with histograms for instance shows that there is no doubt with the detection.

Additional tests were done on ILRS satellites to assess ranging accuracy and have shown a residual error of 10 m RMS.

Repeated ranging of uncooperative targets in LEO with an eye-safe system was the main objective of the SLR part of SAURON. This success demonstrates the potential of such a concept to add a range measurement to classical optical sensor, which will significantly increase the orbit determination performance, both in accuracy and speed. There is still a lot to do on the prototype to optimize its performance and upgrade it to a fully automatic system which will in the end be remotely operated as any other sensor of Helix.

5. HIGH FREQUENCY IMAGING

The second technology under ArianeGroup’s lead in SAURON was HFI (High Frequency Imaging). The concept of HFI is to acquire a large amount of very short exposure images of a LEO target. Theory of atmospheric turbulence shows that among this quantity of images, a few of them will be statically better than others. The idea is to extract these best images and further process them to further improve the quality. Obviously, diffraction limit will never be overcome so it seems advantageous to use large telescopes, offering a potential for high resolutions when turbulence is low, but HFI theory actually shows that there is a comprise to be found: if the ratio between the telescope pupil and the Fried parameter characterizing turbulence (r0) is too important, the probability of getting good images drops drastically. This obviously points towards a site with favorable turbulence conditions, but this isn't always easily found or rather accessible quickly to limited cost. For these reasons, we decided to install the prototype at the same location as our SLR prototype in Saint Michel l'Observatoire in the south of France. Local turbulence conditions could not be anticipated but some data from nearby sites (a few kilometers) were analyzed. It is well known that turbulence conditions can vary significantly across small distances, so the bet was not to get the same conditions, rather we hoped benefiting from the same long term trends shown in Fig 11: we can see that the median r0 parameter is significantly better more or less between June and end of September. It also shows that there are some short term variations which let us hope that during a week of tests, we might benefit from a few favorable slots.

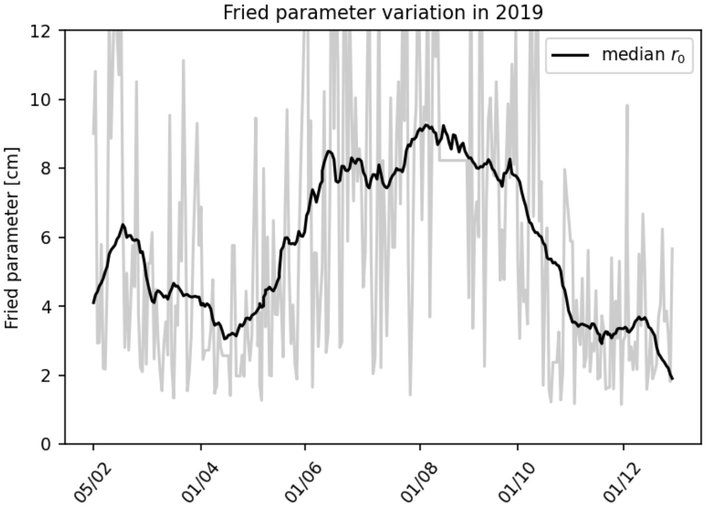

Fig. 11. Fried parameter (r0) variation over a year near the HFI prototype

Despite a limited number of test campaigns during which atmospheric conditions were rather bad, the system design and prototyping phases went smoothly and the HFI prototype was fully functional. In order to be able to operate in bad turbulence conditions, we designed a set of circular masks which served as makes to artificially lower the telescope entrance pupil, degrading the theoretical diffraction limit but also moving the D/r0 ratio towards values compatible with HFI. Although this doesn't take advantage of the full potential of the telescope, it allows to test HFI and this actually proved to be very efficient: some images of the ISS were acquired with an apparent r0 of 6.6 cm (the best we could get during the test campaigns), and the setup image processing techniques could finally be tested successfully. The results are shown in Fig 12.

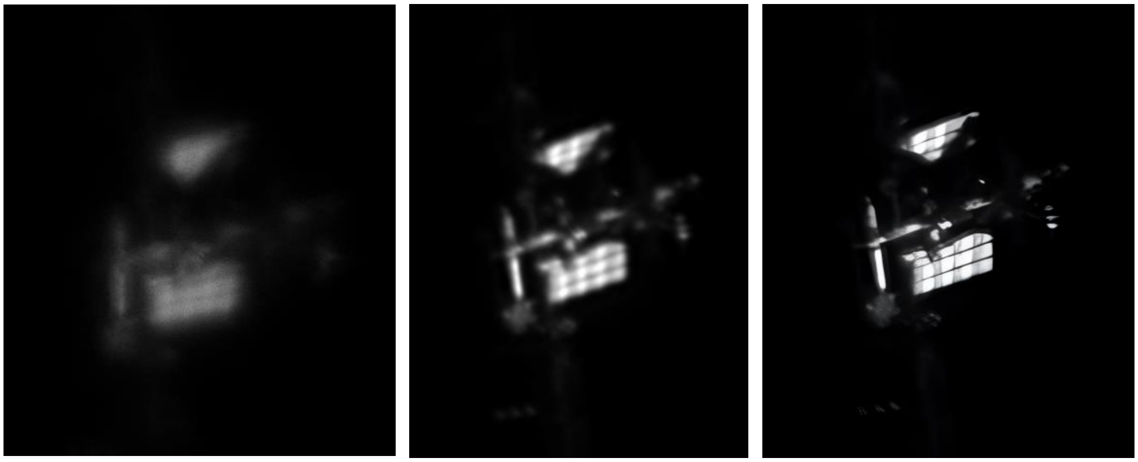

Fig. 12. Views of the ISS: raw image (left), image after HFI processing (middle), image after ML processing (right)

The images of Fig 12. Are slightly misleading since the full ISS is not visible: the bright squares that appear in the center are the ISS radiators and not the solar panels which are further on the extremities but not visible on the images likely because of an unfavorable aspect angle.
First image (left) is an example of “good” short-exposure raw image. As already mentioned, with a 6.6 cm r0, no better is expected. The second image (middle) is obtained by selecting the best images of the sequence and performing some centering and stacking techniques plus some sharpening algorithms. The final image (right) was obtained after some machine learning (ML) techniques were implemented.
The benefit of each step is nicely visible, proving the concept relevancy, even if the conditions remain very unfavorable (due to the strong r0, the images are taken with a telescope aperture reduced to 350 mm).
Several more tests were done but in even worse conditions, making the results of little interest. However it did show that HFI techniques (centering, staking…) work even on bad results conditions (although they do not produce anything spectacular), whereas the ML techniques simply fail if the initial image isn’t good enough.
The radiators in the lower part of the image are nicely visible: they are constituted of 3 sets of 8 panels and the width of one panel is 3m. This shows that the resolution of the reconstructed image is better than 1m which is the order of magnitude of the diffraction limit.

More than proving the concept, these results are very encouraging. We are now planning to install the system in an adequate site and make it remotely operable in order to finally benefit of the full telescope aperture together with better r0 values. When this is accessible, some more tuning and adaptations of the image processing techniques will likely be necessary.
HFI technique cannot provide high resolution images of objects. The only way to do this is imaging from another satellite which is obviously much more performant but also much more costly. The prototyped developed here will be handled as any other “classical” optical sensor, making it suited to deployment in series in a network, just as Helix already does. This is critical in order to offer a characterization capability with reasonable timeliness: very large imaging telescopes with adaptive optics systems obviously can offer higher resolutions, but the likelihood of these systems to image an object in a short laps of time after a request is very low. These technologies are thus fully complementary.

6. CONCLUSION

The SSA problematics and needs require very intensive capabilities extension. Helix is now fully operational on all orbits and plans to continue expanding its network, in particular its survey and SWIR systems in order to increase coverage and revisit rates in LEO. The C2 capabilities that come with these were not detailed in this article but obviously follow the same dynamic.
We are also preparing to face the LEO domain continuous evolution towards an even more dynamic and strategical environment in which timeliness and accuracy of measurements will be more and more critical. Characterization capabilities will also become increasingly necessary. This is obvious for military needs and HFI is very well suited to monitoring large LEO objects behavior by assessing their shape, attitude or even reflectivity per sub-element. In some more years, it could also bring useful information to a variety of applications such as debris removal or on orbit assembly and manufacturing.

7. ACKNOWLEDGMENT

We would once more like to thank the Centre d’Astronomie de Saint Michel l’Observatoire, our trusted partner for our SLR and HFI prototypes, in particular for their reactivity to install the HFI facilities.

Many thanks also to SED teams for the successful collaboration on the SLR beam expander system.

We also thank the European Commission for funding the SAURON project and all the SAURON partners with which we worked on SLR and HFI. This project has received funding from the European Defence Industrial Development Programme (EDIDP) under grant agreement No EDIDP-SSAEW-SSAS-2020-086-SAURON. The work performed reflects only the authors’ view and the Commission is not responsible for any use that may be made of the information it contains.

8. REFERENCES

[1] M. Drieux, M. Pyanet, T. Joffre, P. Giraud, B. Barbier, N. Roux, V. Lemiesz (ArianeGroup), AMOS2023, Development and deployment of SWIR optical station for daytime space object observation

[2] L. Hennegrave, G. Eyheramono, M. Paynet, S. Vourc'h, G. Fournier (ArianeGroup), AMOS2022, Advances of ArianeGroup capabilities for laser optical observation of LEO objects