DESIGN AND TEST OF OPTICAL SURVEILLANCE STRATEGIES FOR EU-SST NETWORK PERFORMANCES STUDIES

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ABSTRACT

Within the frame of EU-SST R&D Activities, CNES & Arianegroup have designed and developed new optical surveillance strategies in order to catalog space objects in LEO, MEO and HEO in coordinated or non-coordinated ways. The first part of this activities was to analyze the state of art within the open literature, and build our own solution from elements found on those papers.

Then surveillance strategies were developed for each orbital region with a focus on LEO and MEO. Both have a coordination mode: its means the strategies optimize the sky zone to survey taking into account the station location and the sky zone that each station could survey; an uncoordinated mode has also been developed for each strategy allowing to evaluate the impact on the performance.

Several surveillance modes have been developed for each orbital regime and are described in this paper. The simulated performances of those strategies on a theoretical optical network formed by EU-SST sensors will be described in this paper based on CNES BA3E simulator and ArianeGroup tools.

Finally an operational experiment has been performed during a two weeks campaign using GEOTracker® sensors in order to challenge and evaluate the performances of those strategies in operational conditions.

1. INTRODUCTION

With more than 10 000 objects expected to be launched in Low Earth Orbit by 2025 and the activation of new space surveillance systems, the LEO object catalogue is expected to grow by a factor of at least 2. The direct impact for space safety is that the number of collision risks in orbit is expected to be multiplied by 3 or 5, leading to a need for more space surveillance system and more accuracy to prevent those risks.

Optical system have the advantage to be deployed quickly in a very large number of sites around the world and they are also cheaper than radar systems. However they need good meteorological to perform operational observation, which result in

This paper will present the work performed by ArianeGroup under CNES leadership within the EU-SST R&D activities in order to contribute to the architectural system studies of the future EU-SST sensors network by assessing how we can optimize the use of optical sensors for space surveillance, it will especially concentrate on surveillance strategies that have been developed and tested in operation for MEO and LEO orbit.

2. PRELIMINARY STUDY OF THE SURVEILLANCE STRATEGIES

Based on the analysis of space object orbital parameters available in the public catalogs and study of several papers (especially [1], [2] and [3]), we have identified patterns to observe space in order to cover the entire area and tend to a leak proof strategy if an appropriate number of sensors is used.

For the MEO regime, the basic idea of the strategy is to construct a pattern of right ascension scanning by a ground optical station based on a function of time.

In Figure 2, we have plotted the right ascension areas that can be observed by a network of 4 stations (Japan, Spain, French Polynesia and Chili) as a function of time, and the evolution of the MEO space objet population crossing a circle of null declination and a 10° width.

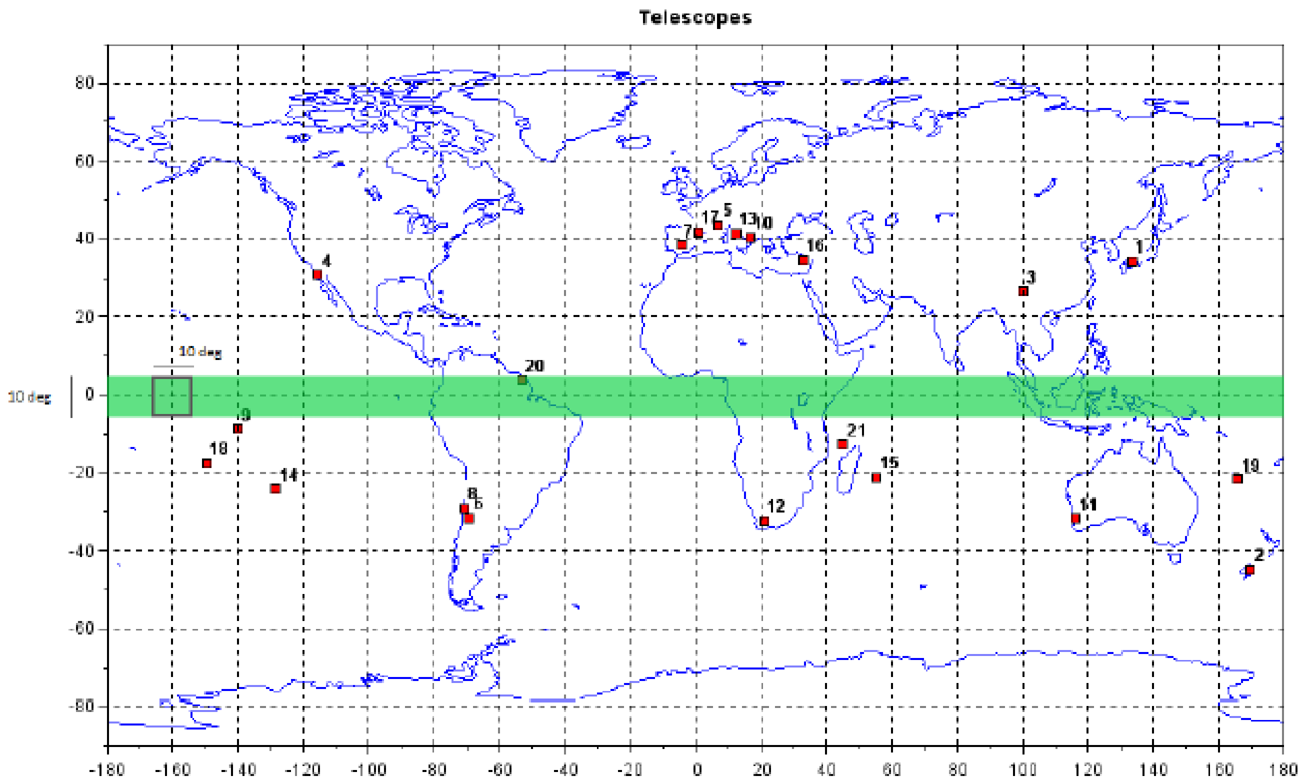

Figure 1: Theoretical telescope network studied

The brown pattern allows to scan part of the circle in right ascension at 15°/h, whereas the orange pattern works at constant right ascension. The pattern depends on the nature of the space surveillance need for the brow pattern we are searching to scan and catalog the zone with here a focus on the most densified area, whereas for the orange pattern, we are searching to detect all objects crossing a node.

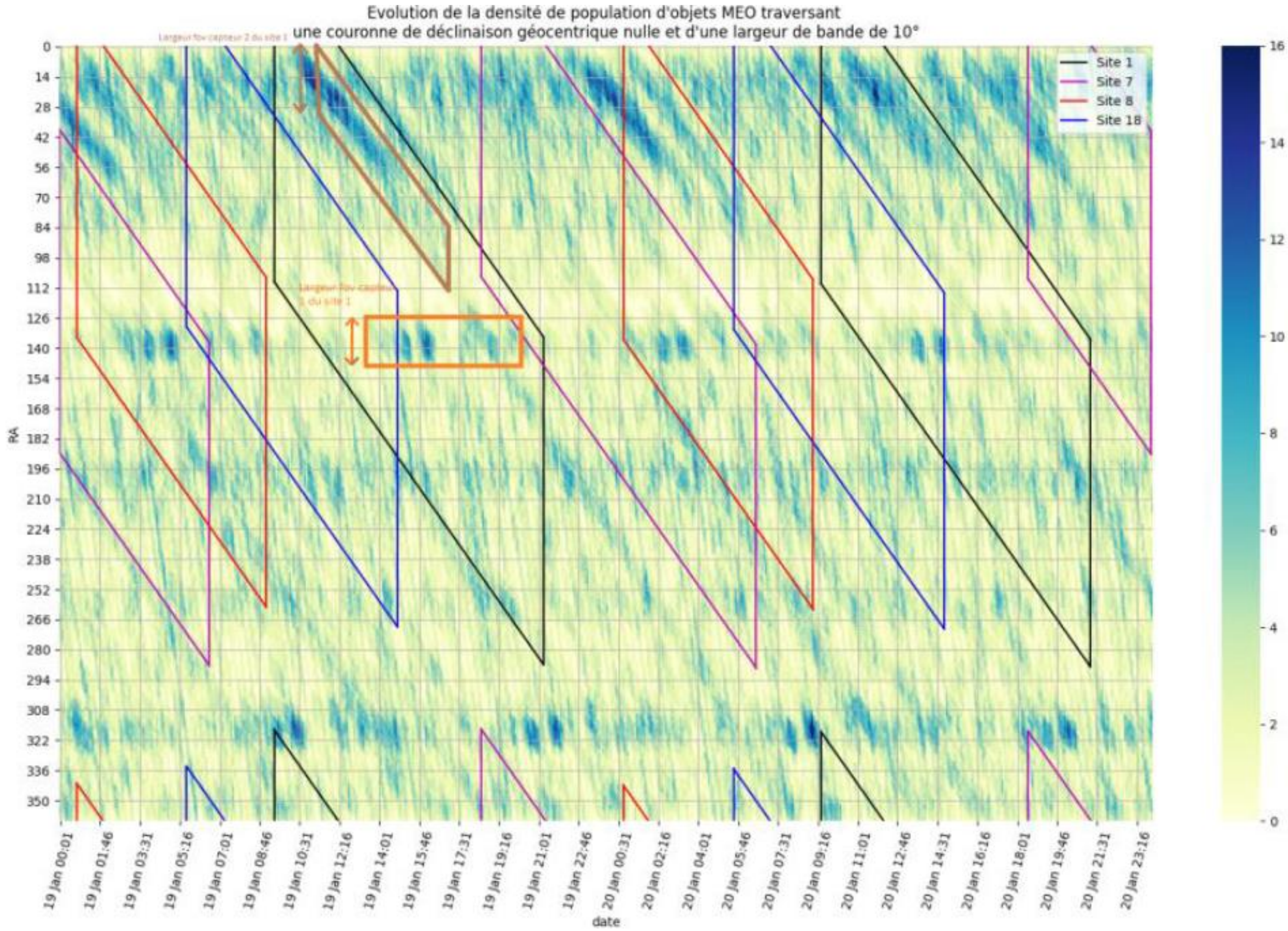

Figure 2: Scanning pattern in Right Ascension and MEO space object density map

In order to analyze what parameters influence this type of strategy, a first rough evaluation of the number of objects that can theoretically be observed by this network has been performed using ArianeGroup internal tools.

By simulating the observation pattern of the network during 6 nights, and doing this with sensors having a FOV of 10 square degrees, 20 square degrees of 40 square degrees (those values are representative of ArianeGroup GEOTracker® operational survey sensors FOV), we got the following results :

	10°x10° FOV sensors	20°x20° FOV sensors	40°x40° FOV sensors
Number of TDM generated	36080	57266	82635
Number of unique objects detected by the network	474	501	536
% of unique objects detected vs the MEO known public population	83,3%	88,05%	94,2%

Table 1: Rough performance results of the MEO strategy with a network of 4 stationq

As expected, the performance depends on the FOV of the optical sensors used and theoretical results are quite good with a small network. In order to improve the performance, coordination between the stations will be considered as well as the slope of the pattern, the number of stations and their geographical repartition.

The same approach has been used for the LEO orbit, using a network of 3 sensors (France, French Guyana and Western Australia).

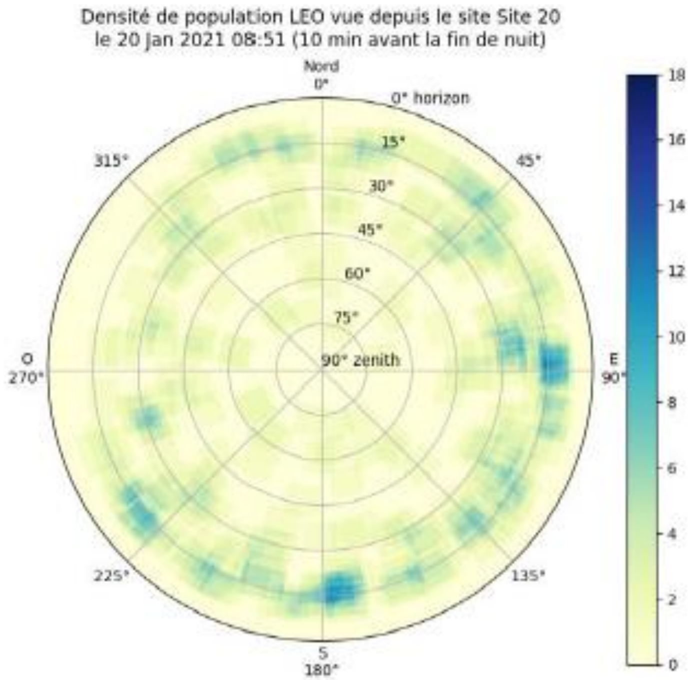

Figure 3: LEO space objet density map

As expected, for the LEO orbit, most of the objects are only visible at the beginning of the night and at end of the night and that we need to concentrate the observation at specific elevations and also take into account the phase angle in order to maximize the detection probability, a compromise between the phase angle and the elevation is necessary depending on the type of strategy we want to implement. The observation azimuth will also depends on the latitude of the station and the time of the year, a specific simple pattern has been designed in order to maximize the number of objects that would be detected by the network.

The simulation results using ArianeGroup internal tools gives the following results in LEO with a surveillance strategy applied during 4 nights on the network of 3 sensors with a space population reduced to 1000 objects in LEO.

	10°x10° FOV sensors	20°x20° FOV sensors	40°x40° FOV sensors
Number of TDM generated	999	2683	7439
Number of unique objects detected by the network	292	407	506
% of unique objects detected vs theoretical maximum observable object at station level (927 objects)	31,5%	43,91%	54,58%
% of unique objects detected vs the reduced LEO simulated population (1000 objects)	29,2%	40,7%	50,6%

Table 2: Rough performance results in LEO with a network of 3 sensors

The same approach has been used for the HEO orbit with the objective to re-use the strategies that have been defined for MEO and LEO in order to minimize complexity and development effort as those objects can be observed using either a MEO or LEO strategy, or a combination of both.

3. COORDINATION AND SURVEILLANCE MODES

Following the preliminary studies, different surveillance modes have been defined for each orbital regime, each with a coordination between sensors or not.

MEO regime:

MEO surveillance Mode	Coordination mode	Description
Redundancy : aim at maximizing the detection probability of objects without being leak proof by design	**Coordinated**	**This strategy consist into re-observing the same area in space every dwell time by optimizing the recovery between the stations observation pattern**
	Un-coordinated	**This strategy consist into re-observing the same area in space every dwell time**
Orbito : aim at maximizing the accuracy of the computed orbit by observing different zones	**Coordinated**	**Circle strategy a different declinations**
	Un-coordinated	**Not applicable as we need at least two sensors for this**
Coverage : aim at maximizing the number of objects by covering the entire area that can be observed by a station	**Coordinated**	**Null declination strategy with avoidance of recovery between stations observation pattern**
	Un-coordinated	**Null declination strategy**

Table 3: MEO surveillance modes developed during the project

The coordination for the MEO redundancy surveillance strategy is performed by identifying the recovery between the observation pattern of different stations and optimizing them :

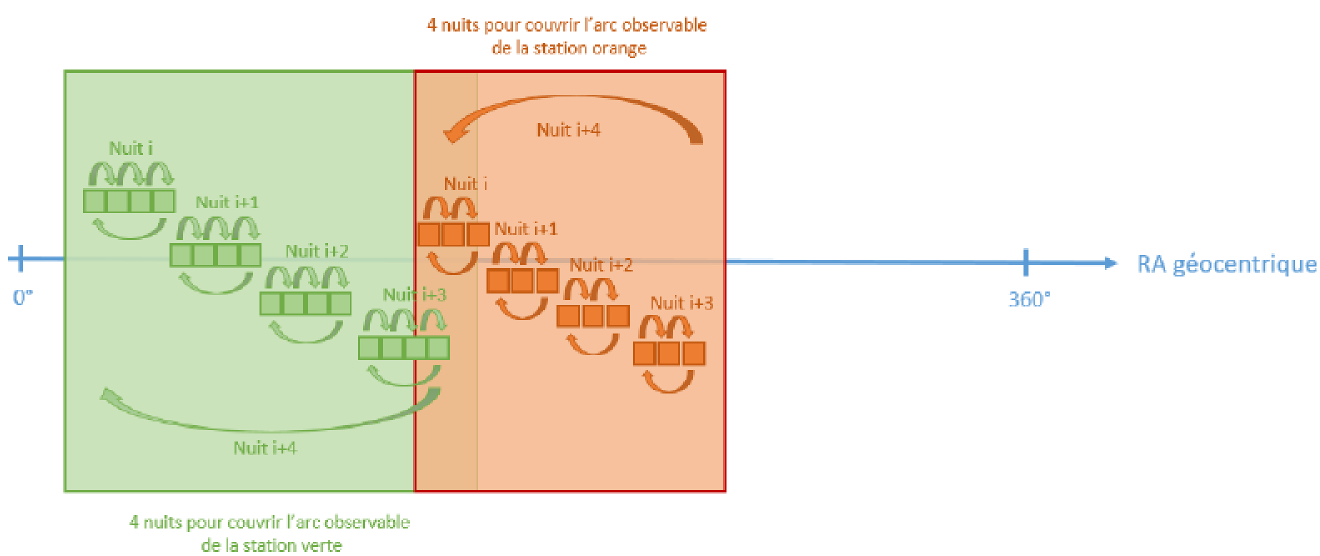

Figure 4 : Coordinated observation pattern between two stations during one night (one in green and one in orange)

LEO regime:

LEO surveillance Mode	Coordination mode	Description
Density : aim at optimizing the pointing direction to maximize the number of objects that can be observed	**Coordinated**	**This strategy is based on the un-coordinated version, the coordination is performed by construction of an equivalent FOV built using different sensors, see** Figure 5
	Un-coordinated	**This strategy consist into pointing the telescope in order to go out of the earth umbra as soon as possible**
Phase angle : aim at optimizing the pointing direction to maximize the phase angle in the area observed	**Coordinated**	**This strategy is based on the un-coordinated version, the coordination is performed by construction of an equivalent FOV built using two different sensors, see** Figure 5
	Un-coordinated	**This strategy consist into pointing the telescope in order to maximize the phase angle**

Table 4: LEO surveillance modes developed during the project

The coordination for LEO density and phase angle is illustrated in the following figure using STK :

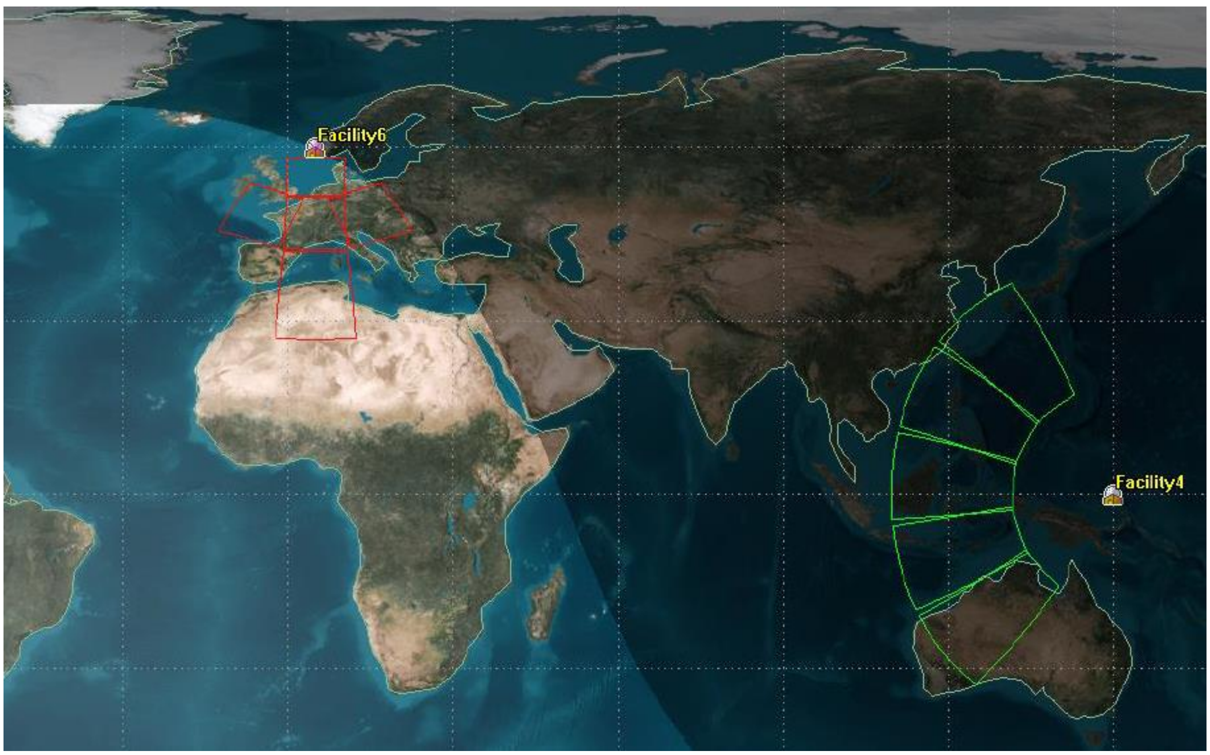

Figure 5: Coordination scheme for LEO surveillance modes

HEO regime:

HEO surveillance Mode		Description
Classical survey : aim at optimizing the pointing direction to favor the observation of objects in HEO, 4 sub modes have been defined. For each mode, the network is divided in two groups A and B based on the capabilities of the stations. A regroup the station with LEO capabilities, B regroup the stations with MEO/GEO capabilities.	**Sub-Mode 1**	**LEO density mode is used for group A, MEO redundancy mode is used for group B with an altitude constraint of 35000km and a null declination. Coordination mode is the one corresponding to the LEO or MEO strategy.**
	Sub-Mode 2	**LEO density mode is used for group A, MEO redundancy mode is used for group B with an altitude constraint of 5000km, a null declination and specific computation of the dwell time. Coordination mode is the one corresponding to the LEO or MEO strategy.**
	Sub-Mode 3	**LEO density mode is used for group A, MEO redundancy mode is used for group B with an altitude constraint of 20000km, a null declination and specific computation of the dwell time. Coordination mode is the one corresponding to the LEO or MEO strategy.**
	Sub-Mode 4	**LEO density mode is used for group A, MEO redundancy mode is used for group B with an altitude constraint of 15000km, a null declination and specific computation of the dwell time. Coordination mode is the one corresponding to the LEO or MEO strategy.**
Molniya mode : aim at optimizing the pointing direction to favor the observation of objects in Molniya. The network is divided in two groups A and B based on the capabilities of the stations. A regroup the station in the northern hemisphere, B regroup the one in the southern hemisphere	**N/A**	**The MEO redundancy strategy is used for group A with an altitude constraint of 39000km, a declination of 60° and a specific computation for the dwell time. The MEO redundancy strategy is used for group B with an altitude constraint of 37000km, a declination of -40° and a specific computation for the dwell time. Coordination mode is the one corresponding to the LEO or MEO strategy.**
GTO mode : aim at optimizing the pointing direction to favor the observation of objects in GTO	**N/A**	**The MEO redundancy strategy is used for all the stations with an altitude constraint of 35000km, a null declination and a specific dwell time.**

4. SIMULATION ON A THEORETICAL EU-SST OPTICAL NETWORK

Using the surveillance strategies presented previously, ArianeGroup has developed a software which aims at providing the observation direction of a network of stations defined as an input in order to execute the strategy chosen by the user. This software has been integrated to BAS3E SST software by CNES and used to evaluate the performance of the strategies using a theoretical EU-SST optical network of 23 stations, with variable dedication to MEO survey, and a theoretical space object population generated using ESA MASTER tool.

The following results have been produced for the MEO regime using the MEO surveillance modes:

Strategy	Coverage respec to simulated (%)				%Well-observed respect to simulated			
	>=35cm	>=50cm	>=100cm	>=500cm	>=35cm	>=50cm	>=100cm	>=500cm
Coverage uncoordinated	90	91	94	97	39	38	35	35
Coverage coordinated	90	91	94	97	44	43	37	32
Redundancy uncoordinated	91	92	96	99	84	85	89	88
Redundancy coordinated	92	93	96	100	84	85	88	88
Orbital coordinated	92	93	97	100	85	86	89	90

Figure 6 : Percentage of the MEO simulated population observed by the theoretical EU-SST optical network using the strategies

Those results show that the performances regarding observed objects are not so much different between the strategies, but we can see that regarding the well-observed objects (defined as a maximum time of 72h without any observation), the redundancy strategy perform quite well. The coordination does not seem to provide performance improvement.

The redundancy uncoordinated strategy has then been chosen by CNES to continue the architectural studies of the EU-SST network taking into account cataloging simulation, weather and sensor failure impact.

The results of the simulations for the LEO and HEO regime were not available at the time of writing this paper, they are still under analysis.

In order to prepare the operational tests of the strategies, the same simulation has been executed on the sub-part of ArianeGroup GEOTracker® network that will be used and which consists into 6 sensors including 3 survey sensors, 2 tracking sensors and one daylight prototype sensor. The following results were produced by the different strategies:

MEO NETWORK RESSULTS	Coverage respec to simulated (%)				%Well-observed respect to simulated			
Name	>=35cm	>=50cm	>=100cm	>=500cm	>=35cm	>=50cm	>=100cm	>=500cm
ALL_COVERAGE_COORDINATED	55	61	72	85	3	4	4	3
ALL_COVERAGE_NOT_COORDINATED	53	59	70	83	4	4	5	5
ALL_REDUNDANCY_COORDINATED	53	58	68	91	13	15	21	35
ALL_REDUNDANCY_NOT_COORDINATED	54	60	70	88	13	15	21	36
ALL_ORBITAL_COORDINATED	51	57	68	91	12	14	19	33

Figure 7: Percentage of the MEO simulated population observed by a sub-part of the GEOTracker® network using the strategies

We can see that even with a small network, the redundancy un-coordinated strategy is able to observe 54% of the 35cm space debris population in MEO. Considering that ArianeGroup is currently improving the detection limit and FOV of its survey stations, we can expect to improve a lot this figure by using even more sensors within the network.

5. OPERATIONAL TEST OF THE STRATEGIES

MEO Operational test :

During the MEO operational test campaign, we have used 3 survey sensors with a FOV of 32°x24° (in France, in Namibia and in Australia), one tracking sensor in Australia with a FOV of 1,55°x1,55° and a daylight tracking prototype built by ArianeGroup with a FOV of 0,15°x0,12°.

The MEO campaign lasted 7 nights and the Redundancy un-coordinated strategy has been used. The observation directions have been produced by the software developed by ArianeGroup and automatically fed to the GEOTracker® operational sensors involved in the campaign through a duplicated operational Control&Command SW (C2 of the network) in order to not corrupt the operational database of the GEOTracker® system, this was performed without impact for our end-user customers.

During the operational test, we have been able to generate 2105 pointing directions and 1052 were successful considering the weather impact, among those observations we have generated 11606 measurements and we have detected 87 unique MEO objects.

The following reparation of objects has been produced by the C2 (taking into account correlation process) for correlated objects. For uncorrelated objects we have performed an apparent speed analysis to determine the orbital classification, but since the computation method used is not adapted to the GEO regime no GEO classification has been considered.

	LEO	MEO	GEO	HEO	Total
Correlated tracklets	48	233	7619	3706	11606
Number of unique correlated object	41	87	525	389	1042
Classification of uncorrelated tracklets by apparent speed analysis	64	26	N/A	1880	1970

Table 5: Number of tracklets and objects produced during the MEO operational campaign

The huge number of GEO objects observed by the strategy is well explained by two facts:

- Since our survey sensors FOV is large and can detect objects in high orbits, the GEO belt can be observed
- A GEO object is observed several time in a night since the revisit time of an area is high as defined by the strategy

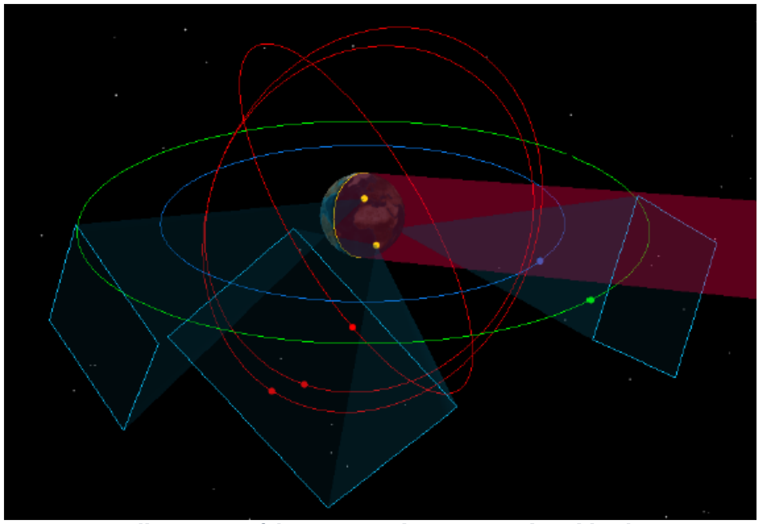

Figure 8: Illustration of the pointing direction produced by the strategy

In order to better understand the performance of this strategy, we have compared the operational results to the theoretical ones by performing a simulation of the strategy using the network, the SpaceTrack public database in MEO and taking into account only observation that were successful in real operations.

The result is presented in the following figure where we can see that our strategy predict that using the small network, we could have observed up to 412 unique MEO objects in 7 days, so 72% of the total MEO population (and 96% of the LARGE RCS population in MEO). This show that our strategy has a good performance.

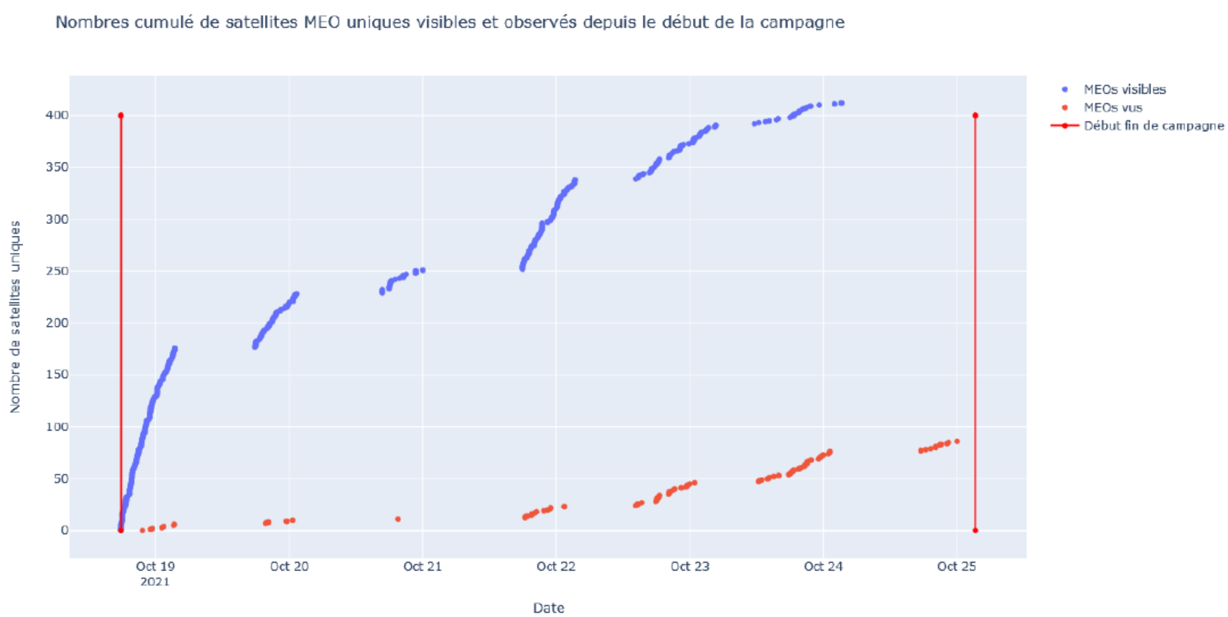

Figure 9: Number of MEO objects that can be theoretically observed by the MEO strategy (in blue) and number of objects detected during the operational campaign as a function of time

It shows also that the weather conditions at the beginning of the campaign impacted us a lot as we have only observed 12% of the MEO population during the 3 first days. But on the fourth day we have observed 50 new MEO objects, which a 57% improvement regarding the total number of unique MEO objects observed during the campaign.

By deeply analyzing the results at sensor level, we have seen that some objects were not detected by our survey sensors, which is explained by the limit magnitude of those first generation sensor which is around 12, and we have already anticipated to change upgrade our survey sensor in order to reach magnitude 14, this will be available within the GEOTracker® network in 2022.

Using the tracking sensor, we have been able to produce 207 successful measurements corresponding to 53 unique objects, and using the daylight tracking prototype 23 TDM have been generated with one observation performed at -4° solar elevation.

The measurement produced on the same space object by the survey sensors, the tracking sensor and the daylight tracking prototype have been used for data fusion and production of operational orbit.

LEO Operational test:

During the LEO operational test campaign, we have used 3 survey sensors with a FOV of 32°x24° (in Chili, in Namibia and in Australia), one tracking sensor in Australia with a FOV of 1,55°x1,55°, a daylight tracking prototype built by ArianeGroup with a FOV of 0,15°x0,12°, and the GRAZ SLR station.

The LEO campaign lasted 7 nights and the Density un-coordinated strategy has been used. The observation directions have been produced as for the MEO campaign (see MEO operation test).

During the operational test, we have been able to generate 1299 pointing directions and 968 were successful considering the weather impact, among those observations we have generated 380 tracklets and we have detected only 25 unique LEO objects.

The following reparation of objects has been produced by the C2 (taking into account correlation process) for correlated objects. For uncorrelated objects, we have performed an apparent speed analysis to determine the orbital classification, but since the computation method used is not adapted to the GEO regime no GEO classification has been considered.

	LEO	MEO	GEO	HEO	Total
Correlated tracklets	25	93	32	230	380
Number of unique correlated object	25	25	10	38	98
Classification of uncorrelated tracklets by apparent speed analysis	4	1	N/A	241	246

Figure 10: Number of tracklets and objects produced during the LEO operational campaign

In order to better understand the performance of this strategy, we have compared the operational results to the theoretical ones by performing a simulation of the strategy using the network, the SpaceTrack public database in LEO and taking into account only observation that were successful in real operations.

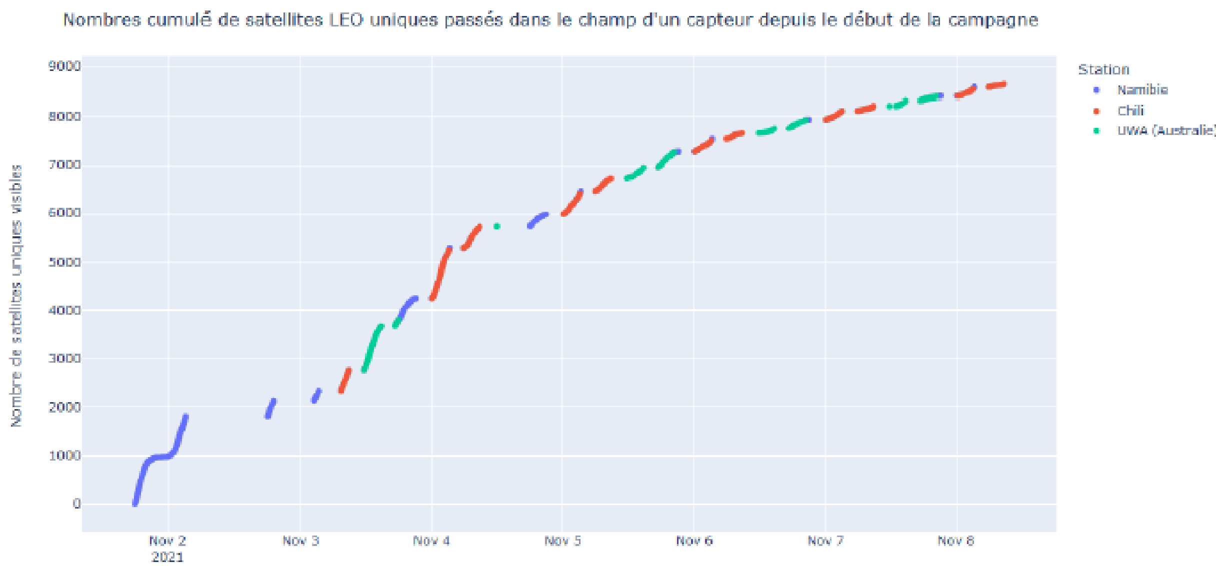

Figure 11: Number of unique LEO objects that can theoretically be observed by the LEO strategy

This simulation shows that using our strategy, we could have expected to see up to 8637 unique LEO objects using the density un-coordinated strategy during 7 nights, so 18% of the total LEO catalogued population according to SpaceTrack (47300 including all objects from all orbit in August 2022) with only 3 survey sensors.

The results obtained in LEO are explained by an image processing error discovered lately and that has been corrected after the campaign. By performing a reprocessing of 9 series of images collected by our survey sensor in Namibia, we were able to detect 51 objects in LEO whereas no one was detected during the campaign. Based on this improvement, we could have expected up to 4900 detection of LEO objects with our strategy.

Using the tracking sensor, we have been able to produce 253 successful measurements corresponding to 25 unique objects, and using the daylight tracking prototype 32 TDM have been generated for 23 unique LEO objects with one observation performed at +29.2° solar elevation. The GRAZ station has been able to provide ranging measurement for 34 objects during two nights (because of unfavorable weather conditions).

The measurement produced on the same space object from the tracking sensor, the daylight tracking prototype and the laser have been used for data fusion and production of operational orbit.

6. CONCLUSION

Under CNES direction, ArianeGroup has developed new surveillance strategies for LEO, MEO and HEO regime. The MEO redundancy un-coordinated strategy performance has been evaluated in simulation using CNES BAS3E simulator and a theoretical network, the results shown that 91% of the MEO orbital population greater than 35cm can be detected and 88% with a revisit time lower than 72h.

MEO and LEO operational campaign have been performed using a sub-part of the GEOTracker® network as well as one prototype daylight tracking sensor and the GRAZ laser station. Those campaigns produced interesting results but have not performed as planned in simulation especially due to real life weather conditions. We have demonstrated that even if we could expect good results in simulation, we shall expect less in operational conditions.

We have also identified several ways to improve the strategies and corrections to be applied to our operational sensors for LEO observations. Those improvements have already been applied to our GEOTracker® network in order to mass produce LEO measurement by end of 2022 using our third generation of sensors and provide first services in LEO in 2023 by combining survey sensors, tracking sensors and daylight tracking capability.

7. ACKNOWLEDGMENT

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