SST LASER TRACKING EX-ANTE IMPACT ASSESSMENT

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ABSTRACT

As part of a broader PwC assignment conducted for ESA in the context of ESA Space Safety Programme, PwC team with the support of GMV carried out an ex-ante impact assessment (socio-economic analysis) of an envisaged ESA ground-based laser for testing potential future tracking services targeting LEO satellite operators.

A summary of the main results is included in this paper.

In line with overall study methodology, the SST laser tracking ex-ante impact assessment entailed the completion of several activities, such as:

- definition with client of envisaged ESA SST laser program main characteristics and evolution
- analysis of SST broad context (e.g., debris population/threats, current SST capabilities)
- analysis of US SST benchmark radar based CSpOC basic services and emerging tracking on demand services
- definition, of measurable indicators along the three given benefits categories: i) Innovation (e.g., Tech gap shortening from a service perspective), ii) Industry/service competitiveness (e.g., cost savings for LEO satellite operators), and iii) Market opportunities (e.g., sizing addressable LEO market and willingness to pay)
- data gathering and stakeholder consultation (e.g., with LEO satellite operators)
- assessment of potential benefits of a hypothetical SST laser program by indicator.

The ex-ante impact assessment of the envisaged ESA SST laser tracking has estimated its potential benefits in terms of:

- Innovation (e.g., technology gap shortening from a service perspective)
- Industry/service competitiveness (e.g., cost savings for LEO satellite operators)
- Market opportunities (e.g., addressable market and willingness to pay).

1 SPACE SURVEILLANCE AND TRACKING CONTEXT

The scope of the paper is an ex-ante socio-economic impact assessment of the envisaged ESA laser tracking test-bed station for technology demonstration, which is expected to lay the technical foundation for potential future laser-based tracking services in the Low Earth Orbit (LEO) region.

Before diving into the actual impact assessment, this section includes a brief introduction of the relevant Space Surveillance and Tracking (SST) context in LEO and of the expected main characteristics of ESA SST laser.

SST context in LEO region

To put things into context, currently, it is estimated that US SST system (Space Fence radar/CSpOC civil services) catalogue about 30K objects across all orbital regions of which 27K objects are in LEO region including about 4000 active satellites (of all sizes) and roughly 23000 debris. So, of the LEO objects that are detected and catalogued by US SST systems about 15% are satellites and 85% are debris.

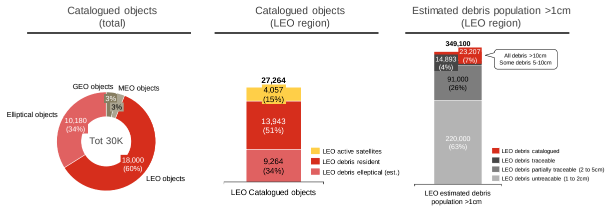

Figure 1: Catalogued objects in all regions and in LEO versus estimated debris population >1cm [1,2]

Roughly, Space Fence is basically cataloguing the LEO debris >10cm (~20K) and some of those between 5-10cm (~3K). Most debris between 5-10 cm (~15K) are occasionally detected and tracked but not catalogued. Debris below 5cm are possibly detected in favourable conditions but tend to be beyond cataloguing capability.

The SST capability to detect and cataloguing debris is key because is the first step for SST providers (such as US CSpOC) to acquire data to then perform conjunction predictions, issue warnings to satellite operators about potential conjunction risks (nominally 3 days ahead) and provide timely information (nominally 12 hours ahead) so that a LEO satellite operator can take an informed decision to either maintain the satellite flying along its orbital path or perform a collision avoidance manoeuvre (CAM) to save their assets from a potential collision.

Space Fence excellent surveillance capability (best radar in the world) excels in cataloguing (>27K objects in

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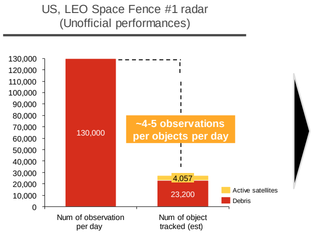
LEO) but because was built essentially to be a surveillance radar to generate an independent catalogue, due to its design, it tracks what is surveyed by the system and does not have a truly follow-up tracking capability.

As such, Space Fence detects many objects daily and provides roughly 4-5 observations/measurements per object per day (good but not great) and although the accuracy at radar sensor level is better (possibly, few hundred meters along track), the Space Fence enabled CSpOC data/basic services (relevant for satellite operators CAM decision) are such that LEO satellite operators experience many warnings (tens of thousands per satellite per year) with a high false alert rate (~ 99%) and modest accuracy at 3 days ahead of the conjunction event (about 1km in flight direction), which leads to the current 1-2 CAM performed per satellite per year [3,4].



US, CSpOC LEO services – KPIs
(based on satellite operators' experiences)

KPIs	US CSpOC
Primary mission	Space debris
Object size in LEO	5-10 cm (tracking), 2 cm (best)
Cataloguing in LEO	>20K objects
Accuracy* (at 3 days) In-flight direction	Radar ~150-200m CAM estimation ~1km (sometime 1-2Km)
Accuracy* (at 12h) In-flight direction	CAM estimation ~ 200m to 1 km
Operations	24/7 all weather
Warnings at 3 days ahead	Tens of thousands per satellite per year
False alerts	~99%

(*) CAM accuracy from CSpOC shared data

Figure 2: Space Fence radar based CSpOC services, performance experience of LEO satellite operators [1,3,4,5]

We should all be very thankful to US Air Force/CSpOC (formerly JSpOC) for sharing Space Fence generated SST data and providing basic services that LEO satellite operators all over the world (including in Europe) regularly use on a free-of-charge basis.

However, in the context of this study, we need to highlight the tracking limitations because the provision of these Space Fence radar enabled CSpOC basic services combined with the tracking follow-up limitations have created favourable conditions for other SST operators to provide complementary tracking services, including commercial services that are pioneered in US by SST radar operator Leo Labs.

Complementary tracking services focus mainly on:

- developing an enhanced catalogue (compared to CSpOC) using own SST systems
- tasking own SST tracking systems on customer request to take additional measurements of specific objects (e.g., debris near a customer satellite)
- combining and analysing data from multiple sources (e.g., CSpOC data, own SST systems data, satellite customer ephemeris), and ultimately
- providing more accurate/reliable warnings and data products to customers' satellite operators, so they are better informed at time of deciding to do a collision avoidance manoeuvre or not.

When mapping the main peculiarities of the emerging commercial tracking services over the classic US CSpOC services process become clearer their value added along the main steps of the process, as shown in figure below.

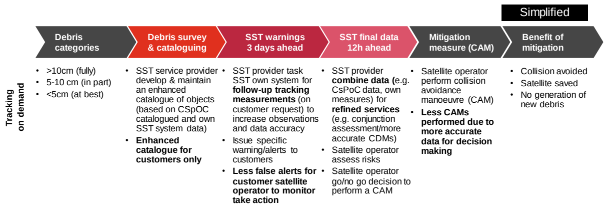


Figure 3: Main steps from SST service provider enhanced catalogue to mitigation action of satellite operator

In this introduction, it suffices to mention that the value added of complementary tracking services when viewed from the perspective of LEO satellite operators is mainly in the reduction of false alerts, and better accuracy leading to a reduction in the numbers of CAMs.

ESA SST laser tracking

ESA SST programme aims at developing a laser station with a power of about 5Kw that is expected to track debris down to about 5cm (not catalogue) and to reach an all-new level of accuracy (well below the 100m in-flight accuracy) and bring (once operational) the percentage of false alerts down to roughly about 10% [3,6,7]. The main characteristics of such laser station are summarised in the figure below.

Characteristics	Laser tracking
Primary mission	Space debris
Object size in LEO	~5 cm (tracking)
Cataloguing in LEO	~120 objects (enhanced catalogue)
Accuracy (at 3 days) inflight direction	Laser ~10-20 m CAM estimation ~50 m
Operations	Down & dusk weather limits to be minimized by tracking also in daylight
Operation	Within ESA S2P limited to testing
False alerts	~10%

Figure 4: ESA laser tracking station main characteristics [3,6,7]

The scope of ESA programme for the laser tracking station is limited to a test-bed station for technology demonstration, which is expected to lay the foundation for potential future laser-based tracking services.

The deployment of a network of laser stations for the provision of tracking services is beyond ESA mandate.

For the sole purpose of this impact assessment, because for some (not all) indicators the benefit can only materialise if the laser becomes operational and the service is provided, it is hypothesised a theoretical scenario with five laser stations for tracking services.

2 IMPACT ASESSMENT

The ex-ante socio-economic impact assessment for SST laser tracking has been done as a case study in line with the methodology used by PwC also for other case studies for ESA Space Safety Programme along three macro-categories of benefits (Innovation, Industry/Service competitiveness, and Market opportunity) and using various measurable indicators, which have been prioritised with ESA accounting for programmatic aspects as well as actual data availability.

This section summarises the findings and analysis along the three categories of benefit indicators:

- Innovation
- Industry/service competitiveness
- Market opportunities

Within the following three subsections (one per benefit indicator category) findings and analysis are presented for each indicator included in this paper.

2.1 SST laser tracking and innovation

This subsection summarises findings and analysis about one innovation indicator: technology gap shortening.

Laser tracking and technology gap shortening

Currently, Europe top tracking lasers have a significant technology gap (from a service perspective) to US best tracking radars on the order of a factor 10-20 (based on size of object tracked) and an absolute gap (based on warnings/alerts and accuracy of data at 3 days before a conjunction event) because they have a different mission and do not provide SST CAM services.

GAP	KPI	US best track radar (current)	Europe best track laser (current)	ESA laser tracking (future)		
Absolute	Tracking as a service	**Service in place**	Service not in place	Establish service foundation		
10-20	Object size (tracked)	**~5-10cm**	~1m	Wipe out gap	**on par**	~5cm tracking
Absolute	Accuracy at 3days (in-flight direction)	**~500m***	No service	Wipe out gap	**~10 better**	~50 m CAM accuracy
Absolute	Warning/alerts (and false%)	**~99%****	No service	Wipe out gap	**~9 better**	~10% false alerts

(*) CAM accuracy, Leolabs S-band radar ROM estimate CAM accuracy Space Fence radar CSpOC, about 1km (**) False alerts %, Space Fence radar CSPoC, expert judgement

Figure 5:Europe current gap to US tracking systems and potential shortening

The current technology gap between Europe best tracking lasers (Graz and Zimmerwald) and current US best tracking S-band radars is estimated at service level on the order of:

- a factor 10-20 based on size of object that the system can track, about 5-10cm for the US S-band radars (2 cm at best, low altitudes [8]) and ~1m for Europe best tracking lasers [9]
- an absolute gap in term of accuracy in-flight direction at 3 days ahead of a conjunction event because US radars provide CAM services (Space Fence/CSpOC with an estimated accuracy on the order of 1km and LeoLabs of few hundred meters) [4,8] and neither Graz nor Zimmerwald provide CAM services because their primary mission is science rather than space debris mitigation [9]
- An absolute gap in terms of providing warning/alerts because US radars provide such services (Space Fence/CSpOC with high rate of alerts 99%) [4] but Europe best tracking lasers do not provide such services (no matter the rate) because their primary mission is science and not space debris mitigation [9]

ESA laser tracking is expected to establish the technical foundation for future laser-based SST tracking services that are not an alternative to CSpOC basic services but complementary. However, from a gap perspective, ESA laser tracking is expected to overcome the existing gap by having on par performances on size of object tracked (~5cm tracking) or better performances in terms of reliability of warnings and alerts (by providing 10% false alerts, which is ~9 times better than current) and of accuracy of data (in-flight direction) at 3 days before conjunction event (about 50m CAM accuracy [3], which is >10 times better than current).

For completion, it can be expected that radars will retain two technical advantages over lasers due to their capability of:

- cold start operation i.e., radars can detect an object independently and then track it, opposite to lasers that are dependent on radar surveys to detect the object first, and then they can track it and provide more accurate measurements. So, lasers cannot build an independent catalogue, but they can build an enhanced catalogue
- operation day/night (24h) in all weather conditions as opposed to lasers down-dusk operation (cannot function 24h) that are subject to weather limitations (e.g., lasers do not go through clouds).

However, ESA laser tracking is expected to excel in the two most important criteria from SST civil service perspective of LEO satellite operators: i) reliability of warning/alerts (low percentage of false alerts) and ii) accuracy of data at 3 days before a conjunction event. This is further analysed in subsection 2.2 below.

2.2 SST laser tracking and industry service competitiveness

This subsection summarises findings and analysis about three service competitiveness indicators for laser tracking services: i) reduction of CAM preparation, ii) reduction of impact of CAM execution on EO satellite service outages, and iii) reduction of CAM execution and impact on satellite lifetime shortening. And it also provides a mini case study on saving on satellite loss (asset value) of Sentinel 3A.

A network of 5 ESA alike laser tracking stations would enable cost savings for LEO satellite operators in terms of: i) reduction of CAM preparation, ii) reduction of impact of CAM execution on EO satellite service outages, and iii) reduction of CAM execution and impact on satellite lifetime shortening enabling additional revenues, globally, which have been estimated potentially more than 20 Mln euro over a 10-year period

Indicator	Current costs generation	Description of LT savings	Value of savings with 5 LT stations
CAM preparation	Cost of CAM preparation for satellites > 50 kg over one year (2021)	Savings generated from 90% reduction of warning/false alerts and equivalent reduction of labour time	About **2 Mln Euro** globally over 10 years
CAM execution (EO service outage)	Cost of CAM execution in terms of loss of EO data acquisition time for satellite >50kg and loss of revenues due to service outages for EO commercial satellite >50kg	Savings generated from 90% reduction of number of CAMs and consequent reduction of losses of EO data acquisition	Between **1.4 Mln** and just **over 3 Mln Euro** globally over 10 years
CAM execution (satellite lifetime shortening)	Cost of CAM execution in terms of loss of revenues due to shortening of satellite lifetime caused by CAM propellant consumption for LEO commercial satellites <50kg	Savings generated from 90% reduction of number of CAMs and consequent reduction of shortening of satellite lifetime	Between **19 Mln** and **40 Mln Euro** globally over 10 years

Figure 6: Overview of costs and savings per indicator

When considering the different outputs of the analysis about costs faced by LEO satellite operators currently and savings potentially enables by ESA laser tracking technology, the following caveats must be acknowledged:

Baseline SST CSpOC basic services: The baseline for the analysis has been the usage of SST Space Fence radar technology enabled CSpOC data/basic services because currently these are the SST services mostly used by LEO satellite operators, affect the operators' behaviour (e.g., number of CAMs performed per satellite per year) and best represent the status quo

Usage of Low/Medium/High scenario to capture results. To best reflect different responses of LEO satellite operators to key variables (e.g., # of manhours for CAM preparation, or hours of service outage for EO satellites due to CAM execution) we model our economic analysis for each relevant indicator (e.g., cost and saving of CAM preparation, or of CAM execution) under 3 main scenarios (Low/Medium/High) to obtain a range of results

Yearly values: Outputs of analysis are in yearly values and based on 2021 data. To put things into perspective, a laser can generate cost savings for multiple years (expected operational lifetime >10 years)

1,5 CAM per satellite per year: Number of CAMs performed on average in LEO per satellite per year [4]

>50kg satellites: Satellites with a launch mass of >50kg have (rule of thumb) a propulsion system with sufficient thrust capabilities to perform CAMs [4]

CAM preparation labour manhours: Number of manhours for CAM preparation per LEO satellite per year between 31and 61-man hours [4], with main reference value of 51-man hours per year

CAM execution/EO data service outage: EO fresh data acquisition gap between 4 and 9 hours per CAM [4]

CAM execution/satellite lifetime impact: About 95% of CAMs in LEO burn additional propellant equivalent for roughly 6 to 12 days of satellite station keeping and thus shortens the satellite lifetime [4]

LEO global satellite population >50Kg: Satellites in-obit below 2000km with launch mass >50Kg as of December 2021 that accounts to 2905 satellites [2]. So, resulting estimates can be viewed as conservative because the number of LEO satellites is expected to increase in coming years

Cost savings potentially enabled by ESA alike laser tracking: Reference a hypothetical deployment of a network of five (5) ESA alike laser tracking stations enabling an enhanced cataloguing of 600 objects and follow-up tracking service for 90 LEO satellites >50Kg globally [3,6] and including coverage of European satellites which vary by LEO altitudes from ~20 satellites between 700-900km and ~40 satellites at 550-700km altitude and current population profile (e.g., number of EO commercial satellites)[2]

Main cost savings' drivers enabled by ESA alike laser tracking: Expected reduction of number of warnings/alerts for ~90% of CAM preparation labour time and of ~90% of CAMs being performed per year.

Cost and saving of CAM preparation

Currently, the total yearly cost of CAM preparation for the population of LEO satellites >50Kg is estimated to range:

- Globally (2905 satellites), between ~4.8 Mln and ~9.4 Mln Euro
- For the European satellites (94 satellite), between ~155k and ~300k Euro.

The efforts and activities that are performed by LEO satellite operators receiving initial SST warnings and tracking data generate additional labour costs that can be quantified by examining the number of man-hours that are dedicated to these activities.

The analysis of initial SST issued warnings is usually automated by satellite operators (without the involvement of personnel) as several tens of thousands of these warnings are issued for most satellites. However, when a certain collision risk threshold is reached (vary by operator)[1] satellite operators task their flight dynamic team to start closely monitoring these warnings/alerts and their evolution (typically starting 3 days ahead of the potential conjunction) initiate analyses to further determine conjunction predictions and the risk of a

[1] Note: Most used threshold is 1: 10000

potential collision, up to escalating the issue to flight control management to take a go/no go decision (typically at 12 hours before event) to perform a collision avoidance manoeuvre or not.

Based on the analysis of activities that are necessary for CAM preparation (e.g., monitoring of SST warning/alerts, carrying-out collision risk analysis, escalating to management CAM go/no-go decision) and feedback from stakeholder consultation with several LEO satellite operators, it is estimated that are spent between 31 and 61 manhours per year per satellite.

Considering this range of manhours dedicated to CAM preparation, these variables induce a total yearly cost ranging between 4.8 Mln and 9.4 Mln Euro for the current global LEO satellite population >50Kg (2905 satellites). For the European satellites, the yearly cost of CAMs for European operators ranges between 155k and 304k Euro (considering 94 European satellites and not accounting for 393 OneWeb satellites).

After using the key variable across the three scenarios (low/medium/high) of the *amount of labour time (manhours)* spent by LEO satellite operators per satellite per year for estimating the current cost of CAM preparation, we have then defined and used the other key variable: *the number of satellites (European)* that are expected to be served by a network of 5 ESA alike laser stations and would ultimately benefit from a reduction of labour time for CAM preparation.

Scenario	Changing variable for cost of CAM preparation	Changing variable for saving enabled by LT for European operators
Low	**31 manhours** per year per satellite dedicated to CAM preparation	**20 European satellites** benefiting from laser tracking
Medium	**51 manhours** per year per satellite dedicated to CAM preparation	**30 European satellites** benefiting from laser tracking
High	**61 manhours** per year per satellite dedicated to CAM preparation	**40 European satellites** benefiting from laser tracking

Table 1: Number of man hours and European satellites used in the scenarios for cost of CAM and potential savings by laser tracking

With a deployment of a network of five (5) ESA alike laser tracking stations, it is estimated that the tracking capability would be able to:

- generate an enhanced catalogue of approximately 600 objects (including debris and operational satellites), which implies the provision of follow-up tracking measurements for about 90 satellites globally [3,6] given that of the total current population of LEO objects roughly 85% are debris and 15% are operational satellites
- provide follow-up tracking measurements for a range of LEO orbits on the order of roughly 100-200km altitude each (vary by altitude) [3] that would include potentially any of the three (3) most important LEO regions for Europe (which are between 450 and 900km) considering the distribution of European satellites >50Kg by altitude, which has its lowest between 700-900km (~20 satellites orbit in that range) and its pick between 550-700km (~40 European satellites orbit in that range).

LEO region	# of European Satellites (>50kg)	Example of Satellites
Between 700 and 900km	20	Sentinel 2A, 2B, 3A, 3B, CSO-1, PLEIADES NEO 3
Between 550 and 700km	39	Sentinel 1A, 1B, COSMO SKYMED, ICEYE, CERES
Between 450 and 550km	24	Swarm, CSO 2, Astrocast, Paz, SAR-LUPE

Table 2: Distribution of European satellites >50Kg for most populated LEO altitudes

The ESA Laser Tracking capabilities by providing less false warnings/alerts (expected 10% false alerts as opposed to 99% from CSpOC currently) would allow an equivalent reduction of roughly 90% of labour time incurred by LEO satellite operators for CAM preparation activities.

Thus, the usage of the ESA Laser Tracking technology within a network of 5 laser tracking stations would enable cost savings for CAM preparation (per year of laser tracking operation):

- Globally of ~219k Euro (based on 90 satellites served and in relation to the intermediate value of 51 manhours for cost of CAM preparation per satellite per year).
- For European satellites, the yearly savings would range between ~49k and ~97K Euro (depending on the number of satellites covered which vary by LEO region from 20 satellites between 700-900km and 40 satellites at 550-700km altitude).

The following table summarises the estimated yearly labour costs for CAM preparation (for current total population of satellites >50Kg in LEO) and potential cost saving enabled by a 5-laser tracking network serving 90 satellites globally, incl. 20 to 40 European satellites by scenario.

Scenario	Costs of CAM preparation, yearly (current satellite population)	Costs of CAM preparation, yearly (90 satellites served globally)	Saving enabled by Laser Tracking, yearly (90 satellites served globally)
Low (Global)	4.8 Mln €	243k €	219k €
Low (Europe)	154k €	54k €	**49k €**
Medium (Global)	7.9 Mln €	243k €	219k €
Medium (Europe)	254k €	81k €	**73k €**
High (Global)	9.4 Mln €	243k €	219k €
High (Europe)	304k €	108k €	**97k €**

Table 3: Summary of CAM preparation current costs and potential savings

In view of providing an appreciation of the potential yearly cost saving generated by a network of 5 ESA alike laser tracking stations that could serve about 90 satellites globally; we have:

- Estimated the cost of CAM preparation (mid column in the above table) that currently 90 LEO satellites would incur based on SST CSpOC basic services using as starting point the reference medium scenario of 51 hours of labour time for CAM preparation per satellite per year, which gives about 243K euro in total (global) and modelled that considering the distribution of European satellites across LEO regions, which gives ~54K euro for 20 satellites (low Europe) and ~108 K euro for 40 satellites (high Europe).
- Estimated the cost saving due to laser tracking (right column in the above table) of 90% of labour costs for 90 LEO satellites using ESA alike laser tracking services (~219 K euro, globally), and then modelled that considering the distribution of European satellites across LEO regions, which gives a saving from ~49 K euro for 20 satellites (low Europe) to ~97K euro for 40 satellites (high Europe) per year of SST laser tracking operation.

This means that over a period of 10 years of operation, a network of 5 laser tracking stations would potentially generate labour cost savings for CAM preparation for more than 2 Mln Euro, globally.

Cost and saving of CAM execution/EO service outage

Currently, the total yearly loss of EO data acquisition time and revenues due to service outage caused by CAM execution to LEO EO satellites >50Kg is estimated to range:

- Globally, between ~2500 hours and ~5600 hours (413 EO satellites) and between ~158K and ~355K Euro (92 EO commercial satellites)
- For European satellites between ~370 hours and ~840 hours (62 EO satellites) and between ~24k and ~54k Euro (14 EO commercial satellites) of yearly loss of revenues.

The execution of CAMs requires moving a satellite to a different orbit and once the danger has passed to move it back. As a result, it negatively affects the ability of remote sensing instruments to perform the targeted and stable measurements and this causes temporary service outages (e.g., gap in EO data acquisition or EO data acquired but of too poor quality to be sellable). Depending on the characteristics of the EO satellite and the operational procedures of satellite operators the *duration of service outage caused by 1 CAM varies between 4 and 9 hours*, typically [4]

Scenario	Changing variable for service outage of EO satellites per CAM execution
Low	**4 hours** of EO service outage per CAM
Medium	**7 hours** of EO service outage per CAM
High	**9 hours** of EO service outage per CAM

Table 4: Number of hours of EO service outage per CAM in LEO by scenario

On the basis of: i) the average of 1,5 CAM per year per satellite, ii) the estimated average of average of daily revenues for an EO commercial satellite from fresh data[2], and iii) the service outage duration (from 4 to 9 hours per CAM), the total loss of EO data acquisition time (data gap) caused by CAMs to the current global population of EO satellites (413 EO satellites >50Kg) ranges between ~2500 hours and ~5600 hours a year and EO data sales' revenues loss for the global EO commercial satellites (92 EO commercial satellites >50Kg) ranges conservatively between ~158k and ~355K Euro yearly.

For European EO satellites (~62 EO satellites >50Kg) the performance of CAMs per year causes a total loss of EO data acquisition time (data gap) between ~370 hours and ~840 hours a year (across institutional and commercial satellites) and EO data revenues losses for the commercial satellites (~14 EO commercial satellites >50kg) between 24k and 54k Euro yearly.

The deployment of a network of five ESA alike laser tracking stations would be expected to enable a 90% reduction of CAMs for about 90 satellites worldwide. On this basis, the ESA laser tracking capabilities could provide services to between 20 and 40 European satellites in total. The reduction of the number of collision avoidance manoeuvres by 90% would proportionally reduce the amount of service outage time and therefore reduce the revenue losses for commercial EO satellites.

The ultimate benefit of the five-laser tracking network will depend on how many EO satellites there will be within the total 90 satellites served and how many are EO commercial satellites.

Assuming the 90 satellites were all EO satellites, the expected 90% reduction of service outage time would shorten the loss of EO data acquisition time (saving) between ~490 hours and ~1100 hours per year and assuming these were all EO commercial satellites, the reduction of revenue losses (savings) would be expected

[2] Based on current global EO data sales market, assuming 70% of revenues are from fresh data and 30% from archive data divided the total number of current EO commercial satellites of all sizes.

to range between ~139k and ~313k Euro for the global satellites benefiting from the laser services per year.

Similarly, for European EO satellites, the yearly saving reached through 90% reduction of service outage time would be in terms of reduced loss of EO data acquisition time between ~220hours and ~490 hours (based on 40 European EO satellites) and reduced revenue loss would range between ~22k and ~49K Euro (based on 14 European commercial EO satellites).

The following table summarises the estimated yearly loss of revenues due to CAM execution for current total population of EO commercial satellites >50Kg in LEO and potential saving enabled by a network of 5 ESA alike laser tracking stations serving 90 EO commercial satellites >50Kg globally, including 14 European per year of tracking operation.

Scenario	Revenue losses caused by CAM yearly for EO commercial satellites >50Kg (current population)	Revenue losses caused by CAM for EO commercial satellites >50Kg (90 global satellites, 14 European)	Saving enabled by Laser Tracking yearly (90 satellites globally, 14 European)
Low (Global)	158k €	155k €	139k €
Low (Europe)	24k €	24k €	**22k €**
Medium (Global)	276k €	270k €	243k €
Medium (Europe)	42k €	42k €	**38k €**
High (Global)	355K €	348k €	313k €
High (Europe)	54k €	54k €	**49k €**

Table 5: Summary of CAM execution current cost of EO data service outage and potential savings

This means that over a period of 10 years of operation, a network of 5 ESA alike laser tracking stations servicing 90 EO commercial satellites would save them revenues losses from CAM execution/service outages for roughly between ~1.4 Mln and just over 3 Mln Euro (at current economic conditions), globally.

Cost and saving of CAM execution/satellite lifetime

Currently, the total yearly cost of satellite lifetime shortening that is induced by CAM execution for the current population of LEO commercial satellites >50Kg is estimated to range in terms of revenue losses:

- Globally (2304 satellites) between ~22 Mln Euro and ~44 Mln Euro
- For the European satellites (15 satellites) between ~830k and ~1.6 Mln Euro.

When performing CAMs to move the satellite away from the danger (e.g., debris potentially on collision course) and then to bring it back to its nominal orbital path, the operator burns satellite propellant, which in turn shortens the satellite lifetime. In most cases, the propellant budget that is planned for a satellite mission includes an amount envisaged for station keeping activities and an extra amount for other activities, including the potential need to perform several CAMs during the lifetime of the satellite. This is clear evidence of how serious the CAM issue has become in recent years.

The lifetime of a satellite is not only dependent on its propellant consumption but also conditioned by the longevity of other subsystems such as the mission payload, on-board computer, solar panels, etc. Nonetheless, operators tend to push the satellite beyond its design lifetime if there is propellant available to maximise the duration of the satellite's services, and the resulting revenues if the satellite is commercially used.

As such, a reduction of the number of CAMs performed by a satellite over its lifetime would allow satellites to expand their lifetime and therefore reach additional operating days that the commercial operator can translate into additional revenues.

Depending on several factors such as the type of chemical propulsion system, the size of the spacecraft/platform, its altitude, the operators' operational procedures; the amount of propellant that each CAM burns vary significantly and in view of normalising the results across different satellites we referred to the equivalent number of days that such propellant consumption causes in terms of shortening the satellite lifetime.

Based on inputs from stakeholder consultation with LEO satellite operators: i) about 95% of CAMs executed cannot be accommodated by rescheduling an already planned manoeuvre (for reasons other than CAM) and thus, are viewed as burning additional propellant, and ii) *one CAM burns on average an amount of propellant that is equivalent roughly of 6 to 12 days of satellite station keeping activities* and thus it shortens its lifetime [4].

Scenario	Changing variable for Number of days of satellite lifetime shortening per CAM execution
Low	**6 days** of satellite lifetime shortening per CAM
Medium	**9 days** of satellite lifetime shortening per CAM
High	**12 days** of satellite lifetime shorting per CAM

Table 6:Number of days of satellite lifetime shortening per CAM in LEO by scenario

On the basis of: i) 1,5 collision avoidance manoeuvres performed per year and per satellite, ii) 95% of CAMs executed burn additional propellant and cause a shortening of the satellite lifetime, iii) the number of days of shortening of the lifetime of satellite due to the CAM execution (vary from 6 to 12 days), and iv) the average of average daily revenues generated by an EO satellite from fresh data and a Communication satellite, the total loss of revenues caused by reduced satellite lifetime from CAM for the global population of LEO commercial satellites >50Kg (92 EO commercial and 2212 Satcom commercial) is estimated to range between ~22 Mln and ~44 Mln Euro yearly.

For European LEO commercial satellites >50Kg providing Earth Observation data (14 satellites) or Communication services (1 satellite only), the cumulated revenues losses caused by reduced satellite lifetime from CAM execution range between ~830k and ~1.6 Mln Euro yearly. So, these estimated revenue losses can be viewed as conservative because some European EO Institutional satellites in LEO are also utilized (at least in part) for commercial purposes.

The ultimate benefit of a network of five ESA alike laser tracking stations will depend on how many commercial satellites there will be within the total 90 satellites >50Kg served in LEO and how many are EO commercial satellites, and how many are commercial Satcom.

Assuming the 90 satellites >50Kg served in LEO by the laser tracking network were all commercial satellites (30 EO and 60 Satcom); the additional revenues achieved through the extension of satellite lifetime would be expected to range between ~1.9 Mln and ~3.9 Mln, globally, per year of laser tracking operation.

For European commercial satellites >50Kg served in LEO by the laser tracking network, the additional revenues enabled by the 90% reduction of CAMs and resulting extended satellite lifetime would represent between ~747k and ~1.5 Mln Euro per year of laser tracking operation (based on 15 European commercial satellites served).

The following table summarises the estimated yearly loss of revenues induced by satellite lifetime shortage due to CAM execution for current population of LEO commercial satellites >50Kg, and potential saving enabled by a network of 5 ESA alike laser tracking stations serving 90 commercial satellites globally, including 15 European per year of tracking operation.

Scenario	Commercial revenue losses caused by reduced satellite lifetime due to CAM yearly (current population)	Commercial revenue losses caused by reduced satellite lifetime due to CAM yearly (90 commercial satellites globally, incl. 15 European)	Saving enabled by Laser Tracking, yearly (90 commercial satellite globally, incl. 15 European)
Low (Global)	22 Mln €	2.2 Mln €	1.9 Mln €
Low (Europe)	830k €	830k €	**747k €**
Medium (Global)	33 Mln €	3.3 Mln €	2.9 Mln €
Medium (Europe)	1.2 Mln €	1.2Mln €	**1.1 Mln €**
High (Global)	44 Mln €	4.4 Mln €	3.9Mln €
High (Europe)	1.6 Mln €	1.6 Mln €	**1.5 Mln €**

Table 7: Summary of CAM execution current revenues losses for satellite lifetime shortening & potential saving

This means that over a period of 10 years of operation, a network of 5 ESA alike laser tracking stations serving 90 commercial satellites would enable revenues resulting from the reduction of CAMs executed/satellite lifetime shortening for roughly between ~19 Mln and ~40 Mln Euro (at current economic conditions), globally.

Cost & saving of satellite loss (asset value), Sentinel 3A

The cost of a LEO satellite loss such as Sentinel 3A (reference satellite victim of this mini case study) from a lethal in-orbit collision with a debris is estimated to range in term of asset loss between ~82 Mln and ~246 Mln Euro depending on the time the collision occurs relative to the remaining satellite lifetime.

Scenario	Cost of satellite asset loss and savings by avoiding a lethal collision (Sentinel 3A example)	Occurrence time of lethal collision event (Sentinel 3A example)
Low	82 Mln €	At 25% of satellite lifetime remaining (for Sentinel 3A, 9 years after launch)
Medium	164 Mln €	At 50% of satellite lifetime remaining (for Sentinel 3A, 6 years after launch)
High	246 Mln €	At 75% of satellite lifetime remaining (for Sentinel 3A, 3 years after launch)

Table 8: Cost of asset loss and saving by avoiding a lethal collision (Sentinel 3A case study)

Sentinel 3A has been selected as the “reference victim” for this analysis because encompasses the following criteria:

- European satellite programme funded by EU and ESA Member States
- orbiting in LEO at an altitude which is expected to be within the potential coverage of laser tracking
- orbiting at an altitude where there is a high density of debris, and the collision risk is at its highest (between 700 and 900km)
- a large satellite (>1000Kg at launch) that due to its size is an easier target for debris
- a satellite that represents the upper end of the LEO satellite market (manufacturing and launch costs)
- satellite is currently operational and about at mid-life (6 years old with 12 years life expectancy).

The costs of asset loss are modelled based on the satellite manufacturing cost and launch cost.

Based on desk research, the manufacturing cost of Sentinel 3A satellite was estimated at 305 Mln Euro [10]. The launch cost of Sentinel 3A was estimated by using as proxy the launch cost of the Swarm satellites that were launch by the same launch service provider (Eurockot) [11]. The launch per kg for Swarm was utilised to estimate the launch cost of Sentinel 3A and led to the identification of a launch cost of about 23 Mln Euro. Thus, the total asset value of Sentinel 3A was estimated at 328 Mln Euro.

When assessing the cost of asset loss, a set of three scenarios has been used and the key *variable is the lethal collision time, considering that the satellite asset value depreciates linearly over time.*

The high scenario assumes that the satellite is loss due to a lethal collision with a debris early in its nominal mission lifetime (at year 3 for Sentinel 3A, so at 75% of its remaining lifetime), the medium scenario assumes that the lethal collision would happen at midlife (year 6 for Sentinel 3A, at 50% of the satellite lifetime); and the low scenario assumes that the lethal collision would take place towards the end of the satellite's lifetime (year 9 for Sentinel 3A, at 25% of the remaining satellite's mission).

It is further assumed that the lethal collision of the satellite with a debris result in the total loss of the asset at time of the collision. Therefore:

- when assuming a lethal collision occurring at 25% of the remaining lifetime of the reference satellite victim, the total asset loss would reach 82 Mln Euro
- when assuming a lethal collision occurring at 50% of the remaining lifetime of the reference satellite victim, the total asset loss would reach 164 Mln Euro
- when assuming a lethal collision occurring at 75% of the remaining lifetime of the reference satellite victim, the total asset loss would reach 246 Mln Euro.

Although the deployment of a network of 5 ESA alike laser tracking stations is not expected to reduce the lethal collision risk in LEO (which according to some is, or will be in the near future, on the order of 1 satellite loss every 5 years globally); laser tracking by providing much less false alerts and much more accurate measurements (compared to current CSpOC basic services) will conceptually reduce the risk that LEO satellite operators would overlook SST data concerning a lethal collision (currently, they receive an overwhelming amount of warnings/alerts) or misjudge the necessity to perform a CAM (currently, they receive SST data of modest in-flight direction accuracy).

If laser tracking services by providing less distracting false alerts and more accurate in-flight data were to avoid the occurrence of an in-orbit lethal collision for a satellite such as Sentinel 3A (even only once over the laser tracking operational lifetime), the asset savings would range between 82 and 246 Mln Euro depending on the time of the avoided lethal collision.

2.3 SST laser tracking and market opportunities

This subsection summarises findings and analysis about two market opportunity indicators for laser tracking services: the size of the addressable market and the willingness to pay of LEO satellite operators

Laser tracking services and addressable market

ESA Laser Tracking capabilities are the foundation for future SST laser tracking services whose potential users are in principle all satellite operators (globally) that have a satellite in LEO region with a propulsion system powerful enough to perform a collision avoidance manoeuvre. And industry interview suggests that currently these are (rule of thumb) those satellites with a launch mass above 50Kg.

Thus, the current addressable market by laser tracking services is (potentially) of ~160 operators & over 2900 satellites globally, and of ~24 operators & >400 satellites in Europe, as illustrated in the figure below.

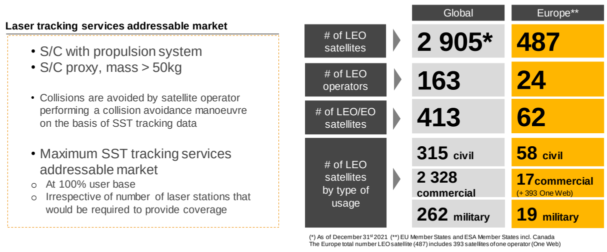


Figure 7: Laser tracking services addressable market [2]

These 2905 LEO satellites (>50Kg), of which 487 are European (when including One Web constellation), is the theoretical maximum current addressable market by SST laser tracking services and does neither take into account the number of laser stations that would be required to provide such a coverage (certainly more than the 5 laser tracking stations used as the reference scenario for other indicators in this case study), nor how many satellite operators would opt to make use of laser tracking services or not (basically provides the theoretical maximum of a 100% user base).

When examining the satellite by type of usage, as of December 2021, 58 European satellites in LEO with a launch mass >50kg are operated by Civil entities (Institutions and Universities); 17 satellites are operated by private entities for commercial purposes; and 19 satellites for military purposes. It is important to mention that these numbers do not entail OneWeb satellites that are operated by 1 commercial operator (393 units as of December 2021), which alone highly affects Europe's total of 487 satellites.

Thus, from a European perspective and given the profile of European LEO satellites >50Kg mass by type of usage can be asserted that laser tracking services are in principle of interest to European users for civil (including institutional and university) as well as military and commercial purposes.

It should also be recalled that the potential addressable market of a laser tracking network based on ESA laser technology would in principle not be limited to European users as it could also serve non-European satellite operators broadening its user base to global.

Finally, the above figure of the global and European addressable market for laser tracking can be viewed as conservative for 2 main reasons: i) trends suggest that in the coming years there will be more satellites orbiting in LEO than there are currently and ii) also LEO nano-micro satellites (10-50Kg) will progressively have a propulsion system on board powerful enough to perform a CAM and therefore will become potential users of laser tracking services in the future.

Laser tracking services and willingness to pay

Future, ESA laser tracking is expected to reach a level of performance (accuracy inflight direction of few tens of meters and false alerts of ~10%) that can, in principle, enable the provision of complementary services so much better compared to current CSpOC basic services (~20 times better accuracy in-flight direction and ~9 times less false alerts) that can trigger the willingness to pay of LEO satellite operators in Europe for SST tracking services.

Interviews with LEO satellite operators in Europe suggest that their willingness to pay zone starts at the point when SST systems' performance generate services with an accuracy in-flight direction on the order of 500m (at 3 days prior to the conjunction event) and the percentage of false alerts drop to about 20%, which are performances that ESA laser tracking is expected not only to meet but exceed. Thus, ESA laser tracking capabilities are expected to fit within the characterised willingness to pay zone as illustrated in the figure below.

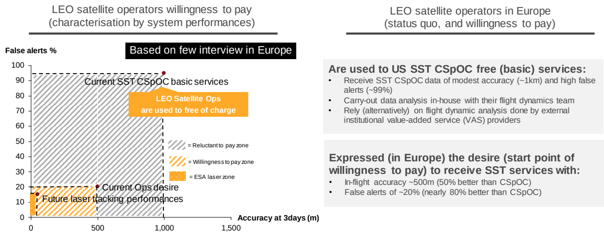


Figure 8: Characterisation of LEO satellite operator willingness to pay by SST service performance [4]

Traditionally, and currently, LEO satellite operators in Europe are used to utilise US SST CSpOC (formerly JSpOC) basic services (about 1km accuracy inflight direction and 99% of false alerts), which are provided to operators from allied Countries on a free-of-charge basis, and task their in-house flight dynamic team to carry out SST data and conjunction assessment analysis,

Commercial tracking as a service for LEO satellite operators is not an established market yet. However, it is pioneered (worldwide) by US company LeoLabs (whose radar performances are not plotted on the above figure), and LEO satellite operators have started to shift mindset towards SST commercial tracking services and have begun to sign-up to LeoLabs (for a fee) to receive enhanced cataloguing services and dedicated tracking measures (on customer request) to get more accurate CAM data and more reliable alerts.

Looking forward to laser tracking services, when we prompted questions to LEO satellite operators in Europe to characterise their willingness to pay, it become clear (based on few interviews made with operators that have not yet used commercial tracking services) that they are willing to pay for SST tracking services if there is a significant performance improvement compared to current CSpOC basic services.

More specifically, LEO satellite operators expressed their desire to receive SST services with an in-flight direction accuracy on the order of 500m at 3 days before event (50% better than CSpOC) and a rate of false alerts on the order of 20% (almost 80% better than CSpOC) and indicated that such level of performance coincide with the point where their willingness to pay would start.

Thus, ESA laser tracking is expected to well fit within LEO European satellite operator's willingness to pay zone, because is expected to provide an accuracy in flight direction of few tens of meters at 3 days before the conjunction event (much better than the desired 500m) and 20% or less false alerts (on par or better than the operators' desired performance).

In other words, although from a price perspective it remains to be seen what the cost of ESA laser technology enabled tracking services will be, from a performance perspective ESA laser tracking capability is expected to be able to trigger the willingness to pay of LEO satellite operators in Europe.

3 CONCLUDING REMARK

The paper has presented the main results of the ex-ante impact assessment of the envisaged ESA SST laser tracking, which (based on expected performances) has grossly estimated its potential benefits in terms of:

- Innovation (e.g., technology gap shortening from a service perspective)
- Industry/service competitiveness (e.g., cost savings for LEO satellite operators)
- Market opportunities (e.g., addressable market and willingness to pay).

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The PwC study analysis reported in this paper have been carried out in the context of a broader PwC assignment for ESA on 'Socio-economic impact assessment of ESA's ground systems engineering and operations activities, and Space Safety Programme', which was completed in July 2022.

5 REFERENCES

[1] ESA Space Debris Master Model

[2] Seradata Space Track satellite database

[3] GMV expert judgment

[4] LEO satellite operators stakeholder consultation

[5] US national defence magazine, article on US strengthening space defence awareness

[6] ESA LARAMOTIONS: a conceptual study on laser networks for near-term collision avoidance for space debris in the low Earth orbit

[7] ESA SST/space debris expert consultation

[8] LeoLabs website

[9] SST operators stakeholder consultation

[10] Spaceflight 101 website, Sentinel 3 webpages

[11] Spaceflight now website, article on Rockot launch clears way for long-delayed ESA mission