Conceptual Design for Expert Centres Supporting Optical and Laser Observations in an Space Surveillance and Tracking System

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Abstract

One of the goals of ESA's SSA Programme for Space Surveillance and Tracking (SST) is the successful establishment of expert centres for supporting optical and laser observations. These centres will serve as the focal point for interfacing with segment-external sensors and assets, provide feedback on the data and will be able to request and manage observations. Benefits are expected in the coordination and monitoring of sensors and data providers, as well as through the expert support provision to the SST segment, such as for sensor qualification and calibration. The establishment of the expert centres will have a strong technological focus on the complex networking and integration of heterogeneous sensors in a coherent SST segment, for which the enormous expertise available in Europe will be used. The motivation and requirements analysis for the establishment of the centre, expected to start in 2015, are presented.

1. **Introduction**

1.1 ESA's SSA program and the SST segment

The objective of ESA's Space Situational Awareness (SSA) programme is "to support the European independent utilization of and access to space for research or services, through providing timely and quality data, information, services and knowledge regarding the environment, the threats, and the sustainable exploitation of the outer space"[1].

The high-level users' needs for the European SSA system, expressed by an SSA user group during its meetings in 2006-2008, can be summarised as [1]:

- support safe and secure operation of space assets and related services
- support risk management (on orbit and during re-entry)
- assess the status and basic characteristics of space objects (both human-made and natural)
- support the assessment of compliance with applicable international treaties and recommendations
- enable the allocation of responsibility for space objects to organisations (ESA, Member States, etc.), and support confidence building measures (identification of owner and/or operator).

Hence, ESA's SSA System comprises three segments:

- Space Surveillance and Tracking (SST) of man-made space objects
- Space Weather (SWE) monitoring and forecast
- Near-Earth Objects (NEO) surveillance and tracking

Space Surveillance and Tracking is required to maintain awareness of the population of man-made space objects. The SST segment is to provide high-level services to users: object cataloguing, conjunction risk analysis, re-entry prediction analysis, fragmentation analysis, special mission support, sub-catalogue characterization and mission characterization [2]. Today, ESA and European national space agencies are dependent on surveillance data from non-European (mainly US sources) for several applications.

During a first period (2009-2012), SST activities focused on developing the system architecture and core technology (radars and the data centre), and the evaluation of precursor systems by reusing and federating existing assets. The latter activities' results were fed back into development. A top-down approach established the customer and system requirements, and defined two parallel sensor and data centre architectures. These architectures represent also the first iteration of the design definition of the final Space Surveillance and Tracking Segment. The architecture already distinguishes between internal and external sensors: internal sensors are owned, operated and fully controlled by the SST segment, while external sensors are only governed (or not) by a certain agreement with varying levels of service depending on each specific sensor.

During a second period (2013-2016) ESA continues developing, prototyping and integrating an SST segment that provides applications (objects catalogue, conjunction and re-entry prediction, fragmentation detection and analysis) to European end users. In general, period 1 developments are enhanced and the activities' focus is on successfully integrating the available SST sensors and simulators with the data processing system and SST applications. Research and development are the core goals, while end-to-end functionality demonstrations bring in another strong technological aspect: networking and integrating a complex system in a coherent SST segment covering sensors, data processing and applications. ESA aims to establish an expert centre for supporting optical and laser observations during period 2.

The SST activities in research and development are planned to continue in period 3 (2017-2020), subject to adequate funding. It is understood that complementing and coordinating with the various other SST activities in Europe will have priority. The coordination must be based on the period 1 and 2 results, e.g. defining and developing a common SSA/SST data processing core.

The SST Segment consists of the following systems: Conjunction Prediction System (CPS), Re-entry Prediction System (RPS), Fragmentation Analysis System (FAS), Catalogue Query System (CQS), Data Processing Chain (DPC), Sensor Simulator (SSIM) and Sensor Planning System (SPS).

The SST segment will be able to use various data sources, but sensors (radar systems, and optical systems such as telescopes) will be the main data providers. One alternative to the use of radar for tracking in the LEO regime is satellite laser ranging (SLR). During periods 1 and 2 SST has already worked with several sensors during test campaigns. Widely, the contributing sensors are operated independently, and are not owned by ESA. Further, extension of these activities to new sensors, such as ESA's robotic telescopes in Cebreros and a location in South America, are planned.

1.2 Expert centres in ESA's SSA

ESA's SSA programme has already set-up coordination or expert centres for the Space Weather and NEO segments.

The SSA Space Weather Coordination Centre (SSCC) is located at the Space Pole in Belgium. It provides a Space Weather Helpdesk and coordinates the overall provision of SSA Space Weather services. These services are accessed via a central web portal hosted at the SWE Data Centre in Redu and are provided by a network of five federated Expert Service Centres addressing complementary SWE themes. The SSCC monitors the overall service network, and provides scientific expert support with input from the Expert Service Centres which are themselves federated groups of European entities providing access to a wide range of key space weather data, products and expertise.

ESA's NEO Coordination Centre (NEOCC) serves as the central access point to a network of European NEO data sources and information providers. As for the SSCC, the NEOCC provides and integrates expert support in the field by federating new and existing European assets, systems and sensors into a future NEO system. Further, it is the focus point for scientific studies on NEO warning services, provides near-real-time data and coordinates with European national and international customers.

1.3 Motivation for SST expert centres

In SST a certain overhead in coordinating observations requests can be expected from an architecture that is incorporating to a larger extend existing sensors under external control. This is mainly due to very practical aspects, such as adopted data formats and general interfaces, and due to the usually very different sensor capabilities and availability schemes. Installing a proxy between the backend SST system and the sensors can solve such practical questions, if the proxy entity is established with proper authority to deal with both sides. In addition that entity may be also an optimal place for providing support services, to support research on observations, and for technology development.

In ESA’s SST topology external sensors play a fundamental role. In addition, for the SSA programme establishing expert centres is obviously possible. It can be concluded that these centres would be the obvious choice to improve and optimise the input/output functions and products of a federated European SST system, by working closely (assuming a proxy role) with the data centres and the individual external sensors.

ESA has already studied working with external sensor data to a larger extend in the SST segment. Test campaigns using radars (Chilbolton CAMRa, EISCAT, Monge), optical telescopes (Zimmerwald telescopes, ESA’s Optical Ground Station (OGS), La Sagra Sky Survey observatory operated by the Observatorio Astronómico de Mallorca (OAM), Starbrook, Telescope Fabra ROA Montsec (TFRM)) and laser ranging (SLR station in Graz) have been conducted.

The first two observation campaigns with radar were performed in 2010 and 2011. With optical sensors, three different optical observation campaigns, each consisting of a 7-day interval, have been executed in 2010 and 2011 (see, e.g. [3,4,5]). The emphasis during the first campaigns was on gathering enough calibration observations so as to characterise the sensors and to identify possible biases and astrometric reference system issues. For the third campaign also efficient collaborative tracking of a drifting object in GEO was studied. For all campaigns it was important to verify that the data meets appropriate CCSDS (Consultative Committee for Space Data Systems) formats, and that the results from orbit determination tests are obtained.

Based on these preliminary test campaigns sensors at Zimmerwald, OAM, and TFRM executed larger coordinated optical GEO-campaigns during the year 2013 (see, e.g., [6]). During these tests studying in detail the networking of the external sensors became a key topic. Figure 1 gives as an example a resulting sensor availability chart. Obviously, staying aware of the sensor availability in that dynamical network is a crucial and cumbersome task that needs to be automated as far as possible. The second key topic that was studied in this campaign was tracklet formation and catalogue correlation.

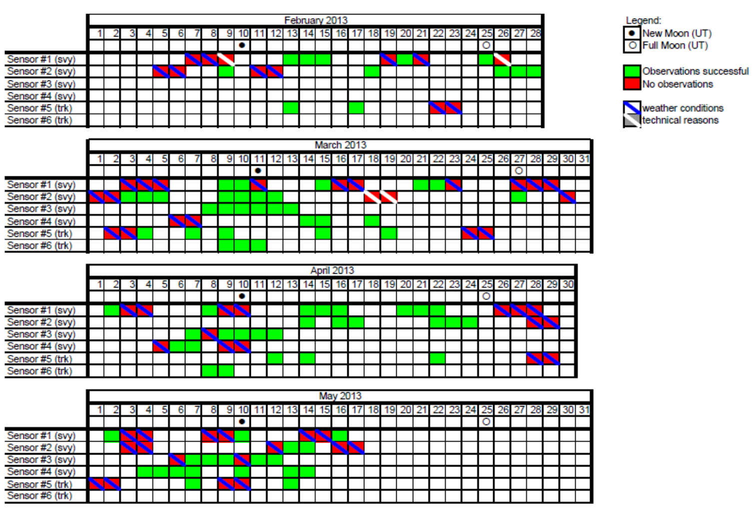

Fig. 1. Example availability chart from a collaborative optical test campaign executed in 2013 [6].

Finally, the Austrian Academy of Sciences in Graz performed a laser ranging and tracking experiment together with three other stations: Zimmerwald, Wettzell and Herstmonceux, which covered around 60 objects and aimed at understanding the general capabilities of that observation technique and to learn about data formats and interfaces.

2. Identified objectives and tasks of a SST expert centre

In the following sections we investigate the suitability, objectives and expected benefits, system requirements and derived architecture, and expected operations model of an SST expert centre. The subsequent detailed design and establishment of the centre are on-going activities and are not covered here.

Grouped by the level of interaction, three different types of external sensors can be identified from ESA's SSA/SST system architecture:

- Sensors providing data without any kind of control by the SST system.
- Sensors providing data upon request from the SST system (under certain co-operation scheme) on a best effort basis.
- Sensors providing data to the SSA system based on a certain service level agreements (SLA) but without committed availability

The expert centres are the obvious choice to interface between a SST system and the heterogeneous national sensor infrastructure. Benefits (in costs, functionality increases, performance gains) are expected by making expert support to the external sensors providers available, by increasing the efficiency of SST orbit determination process using data quality checks and applying consistent modelling, by implementing a centralized scheduler that best addresses the backend SST needs and the status of the external sensor network, by contributing to standardisation of data exchanges, and by establishing a test environment for advanced SST data processing techniques.

The following top-level use cases for an expert centre have been identified for the ESA SST system:

- A potential Expert Centre shall be external to the SST System,
- A potential Expert Centre shall interact with external (federated) optical sensors and laser sensors,
- A potential Expert Centre shall interact with the SST System but will not replace any of its functionalities,
- A potential Expert Centre shall coordinate the sensors for tracking and surveillance tasks,
- A potential Expert Centre shall support the calibration of sensors (support internal sensors, and responsible for quality control of external sensor data),
- A potential Expert Centre shall qualify external data sources,
- A potential Expert Centre shall monitor the compliance of the external sources with the SLAs in place.

From that two functional blocks can be identified, an operations function and a support function.

2.1 <u>Operations function</u>

The system architecture studies of SSA concluded that a future SST System will have to manage a large variety of different, external, federated sensors with different operators. Given the very different nature of external, federated sensors with different operators, a main objective for the expert centre shall be the coordination of all the External Sensors with the SSA/SST Segment. Beyond that, the operations support needs to include the qualification of external data and the monitoring of SLAs. That set-up will enable quick interactions with the SST backend and sensors: the SST segment does not have to deal with adapting to specific interfaces (ICDs) and monitoring the data quality, the sensors will benefit from a clear interface and receiving pre-filtered, moderated, coordinated, and tailored observation requests.

2.2 <u>Support function</u>

The support functions are: sensor calibration, evaluation of observation and processing techniques, data quality control, as well as expert support and research and development in these domains.

The calibration of sensors should be available not only to external, but, potentially, also to SST-internal sensors on request, given the clustering of expertise and support options at the expert centre. For the external sensors the calibration task is also linked to sensor qualification and evaluation. The qualification of external data sources is not only a crucial topic for the SST system itself, to precisely understand what is delivered, but also a request by sensors. The SSA system is responsible for using or not using the data from external sensors, and it must ensure that the data from external sources do not poison the results provided by the system. For the sensor operators and member states, a qualified feedback of the sensor data quality, reports on calibration of these assets, and expert proposals on potential improvements sets a use case.

Of course, the evaluation of data processing techniques must consider all aspects, starting from data acquisition and related hardware aspects, image or raw data processing, tracklet extraction, and, potentially, correlation and orbit determination and improvement. The latter very much depends on the sensor capabilities and on the requests placed by the SST backend system.

The related research and development shall be best organized through making expert support available in the form of *ad-hoc* off-site expertise, and through resident staff. The main areas to cover are: the calibration and sensor evaluation topics, such as image and data processing, sensor performance modelling, monitoring and control and software engineering), advanced technology for observation scheduling, image processing, and astrometric reduction. The experts' support could be organized in so-called Quality Working Groups, or in the form of a test centre, to validate and test newly developed SST technologies and methodologies with real data.

2.3 Specific considerations on laser observations

The analyses of operations and support functionalities become a specific relevance if we consider the potential use of Satellite Laser Ranging (SLR) of uncooperative objects for SST. Such approaches are actively studied, and have gained increasing interest (see, e.g., [7,8]). SLR activities are, in general, coordinated under the International Laser Ranging Service (ILRS) [9]. The ILRS is responsible for providing the global satellite and Lunar laser ranging data and several data products to support research activities. The ILRS Networks and Engineering Working Group (NEWG) seeks to improve and optimize the input-output functions and products of the ILRS network by working closely with the data analysis community and the individual laser ranging stations. Its primary responsibility is to facilitate the generation, collection and distribution of data in a timely and efficient manner to the user community while meeting the data quality and quantity requirements. In October 2014 the ILRS, on request of Georg Kirchner (IWF), established the Space Debris Study Group (SDSG).

The ILRS defined several primary tasks for the SDSG, including sensor calibration. It will be the task of the SDSG to define, establish and test calibration procedures for SLR stations for space debris measurements. In this case the planning and data provision of the SLR stations to a SST system will best be performed trough an expert centre interacting with or inside the SDSG.

3. System requirements and proposed system architecture

The following system requirements at functional, interface, and performance level for an optical/laser expert centre are applicable for the further establishment of the centre. While these requirements are fully sufficient to derive a system architecture, it is important to note that during the built-up of centre functionality a higher degree of detail is still needed. This applies in particular to the performance requirements, such as on response time, accuracy, availability, coverage for surveys, etc. That next step of analysis needs to be part of the detailed design of the centre, and is also subject to the available external sensor infrastructure and available SST data processing capabilities.

3.1 Functional requirements

At functional level, the coordination of the external sensors must be precisely described through linked standards. This implies specifying the implementation of sensor ICDs, the collection of aggregated sensor data, and delivery to the SST segment back-end. The retrieval of unclassified data from the SST back-end for offline calibration and qualification of internal sensors is another requirement. As output the expert centre shall deliver calibrated, validated and quality controlled data, as well as sensor status and qualification analyses.

Further, the monitoring of SLAs and of non-formal agreements must be described. The qualification approach for external data sources and external sensors, data quality control and consistency checks, and the calibration support to internal sensors and the calibration of external sensors must be addressed. Hence, sufficient processing and testing capabilities have to be established at the expert centre. It seems feasible to consider independent software for this function, which is made available under consultancy agreements with domain specialists. The requirements must also specify how the research and development capabilities of the expert centre are to be set-up, as, e.g., through allowing roles of visiting and resident researchers.

3.2 Interface Requirements

Needed interfaces only exist between the expert centre and the SST-SSA back-end, the external sensors, the ILRS/SDSG. Other entities will be covered on demand (e.g. Quality Working Group, external off-site experts).

These interfaces exist at several levels and are of very different complexity. The interfaces with the SST segment are following CCSDS standards. The interfaces with the sensors are likely to remain in proprietary formats, despite some sensors are moving towards CCSDS compliance in their data. For raw data the FITS format is the choice for optical data, while Consolidated Laser Ranging Data (CRDs) are for the laser observations. Parallel and still on-going work addresses appropriate equivalents for tracking and scheduling requests [10].

3.3 Performance Requirements

A typical way to group performance requirements in SST is per availability, data coverage and timeliness. This allows distinguishing between regular operations (as per SST system requirements) and individual request from the SST segments (e.g. within 24h).

The SST System shall be allowed to request special support in certain scenarios (e.g. foreseen re-entry objects, predicted potential collision, etc.) within a certain period (24 hours).

For the remaining top-level performance needs, where the existing SST segment system requirements can be directly converted into expert centre requirements, only the specification of the notification delays is needed for planned and unplanned unavailability periods and the availability of sensors and processing capabilities (e.g. 6 hours before starting operations). Of course, the data from the expert centre shall not deteriorate the data quality provided by the external sensors. Finally, the expert support can be specified to provide initial sensor calibration within a certain timeframe (such as 6 months).

3.4 System architecture proposal

Several architecture options can be derived from the system requirements. By weighing security, cost, task coverage, accessibility to expertise, operability, efficiency, robustness, complexity, scalability and maintainability, a temporary merging of all functionalities into one combined expert centre was identified as the best option. This will make the build-up and testing of the functions easier for the early operation phases. However, a modular design should be considered due to a possible future separation into two different expert centres, one for optical and the other for SLR data.

Figure 2 presents the high level interactions between the expert centre, the external sensors and the internal sensors (within the SST segment). The expert centre acts as the interface between the SST segment (on the left) and the external sensors (bottom), the ILRS SDSG (right) and external experts. It receives tracking and status requests (from the SDSG, right) and data for qualification from the SST segment. These requests are processed and, if needed, sent to the appropriate external entity (tasking request to sensors, etc.). The data returned by sensors is processed and sent to the SST segment, as are other products, such as data qualification results.

The experts and the Quality Working Group may not need to be collocated, and they do not need to be reside in the expert centre, too. They are represented as light orange boxes in Figure 2 to show their functional dependency with the expert centre.

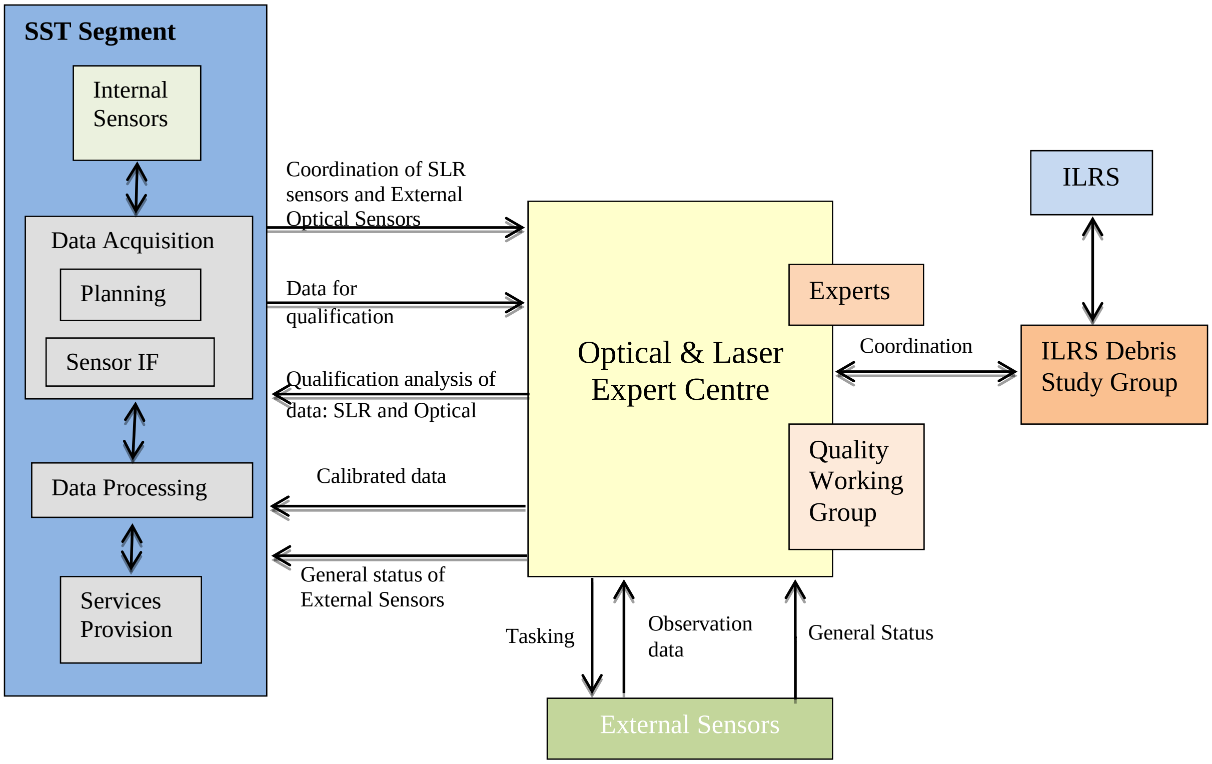

Fig. 2. Possible concept for the combined optical and laser SST expert centre

4. Summary

ESA's SSA Programme is progressing during period 2. In the Space Surveillance and Tracking (SST) segment the successful establishment of expert centres for optical and laser observations is planned. While there have been successful data exchanges with national sensors through test campaigns in the first period of the program, the evaluation and qualification of national assets has started in period 2.

One of the identified core tasks of such an expert centre is the coordination of a loose sensor network under external control, acting as the sole access point for the backend SST processing of that network, and the monitoring of the underlying agreements with the external sensors. Furthermore, the expert centre was found to be optimal for providing support, such as calibration and sensor evaluation, and for collecting and providing related expertise. This shall be used to provide feedback on the provided data. National actors have already expressed interest in using the sensor qualification function. Establishing a closer link with international forums, e.g. the ILRS Space Debris Study Group driving the development and evaluation of new technologies, is considered by ESA’s SSA programme.

ESA has derived a set of draft requirements for an expert centre on optical and laser observations. As a temporary step a derived hybrid architecture combining both technologies in the same centre will be implemented. Work on establishing the centre is about to start.

The final establishment and full testing and validation of the expert centre is proposed for the program period 3, with a strong technological focus on the complex networking and integration of heterogeneous sensors in a coherent SST segment, for which the enormous expertise that is available in Europe will be used.

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