EUSST sensor calibration procedure

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ABSTRACT

European Space Surveillance and Tracking (EUSST) services rely on a worldwide network of sensors capable to follow Resident Space Objects (RSOs) in all orbital regimes. The network is composed by ranging lasers, radars, and optical telescopes (with tracking and surveillance capabilities). However, the data provided by this network must be accurate to ensure the best possible provision of the EUSST services (collision avoidance, reentry, and fragmentation). To assess properly the performance of all sensors, EUSST has established a mandatory calibration procedure for all sensors within the network, both for new sensors and those already operational. The performance revealed during the calibration process is used to determine the operational status of each sensor involved and, hence, its usefulness for the provision of data to EUSST.

During the period available to submit calibration observations (so called calibration campaigns), the sensors must observe a list of well-defined RSOs with accurate orbits. Depending on the operational regime of the sensor, the observed objects are either GNSS satellites (usually Galileo) or LEO satellites suitable for calibration. Only the data obtained during the calibration campaigns (and labelled for calibration) are currently used to calibrate the sensors.

Once the calibration observations are provided, they are processed by two independent national centers (S3TOC and COO). The calibration procedure evaluates the measurement accuracy provided by the sensors by comparing the provided observations with the well-known position of the objects selected for calibration. During the comparison process, the data provided by some of the sensors need to be corrected by relativistic effects (annual and diurnal aberration). In addition, using state of the art observation measurement models, the reference orbits are used to compute the signal travel time, the tropospheric influence, and the ionospheric effect (for ranging related measurements). The residuals with respect to the reference positions are then computed, and the process is iterated using a weighted sigma-clipping rejection algorithm to remove any possible outliers. The results of the calibration are finally compared between the two independent national centers and, in those rare occasions when results differ, the underlying causes are investigated and resolved.

The resulting biases (e.g., time bias or range bias) and RMS (Root Mean Squared) of the data are then evaluated and compared with previously determined thresholds. The threshold values are set according to the service provision needs. Only those sensors providing data within the thresholds for a certain period (at least two calibration campaigns) are categorized as operational and considered suitable for the provision of data to EUSST. New sensors fulfilling all the calibration thresholds in a calibration campaign are considered temporarily operational and also allowed to provide data to the EUSST.

The calibration procedure provides a robust method to categorize the sensor capability to provide quality data to the EUSST. This procedure is continuously reviewed and improved when possible. For example, the calibration thresholds may be evaluated and updated between consecutive calibration campaigns, if considered necessary. In some specific cases, the sensors are allowed to provide calibration data to perform a fast calibration and change its operational status without the need to wait for a new calibration campaign. Finally, several additional studies are undergoing to further improve the EUSST calibration procedure. The possibility to use GEO satellites for calibration may provide a better characterization of the sensors observing these RSOs. Another possibility would be to continuously monitor the performance of the sensors between two calibration campaigns using a near-real time

calibration process, allowing the fast detection any possible deviations due to maintenance operations, or degradation of the sensor capabilities. In this sense, a preliminary near-real time continuous calibration tool is being implemented, and qualification tests are on-going.

To summarize, the EUSST sensor calibration procedure provides a well-tested method to evaluate and ensure the quality of the data provided by the global network of sensors. This method has already been applied in nine calibration campaigns, proving to be a valuable tool to ensure the quality of the provided EUSST services.

1. INTRODUCTION

The EUSST (European Union Space Surveillance and Tracking) system is a network of ground-based and space-based sensors capable of surveying and tracking space objects, together with processing capabilities aiming to provide data, information and services on space objects that orbit around the Earth. For the implementation of the EUSST, established in 2021 as a fully-fledged security subcomponent of the EU Space Program[1], the SST Partnership of 15 EU Member States (Austria, Czech Republic, Denmark, Finland, France, Germany, Greece, Italy, Latvia, the Netherlands, Poland, Portugal, Romania, Spain and Sweden) together with the European Union Agency for the Space Program (EUSPA[2]) acting as the EU SST Front Desk form the SST Cooperation.

Previously, EUSST was established as a Support Framework by the SST Decision (2014)[3], which foresaw the creation of an SST Consortium of EU Member States. The Consortium and the European Union Satellite Centre (SatCen) cooperated to gradually develop the SST capability with the support of the EU under different funding lines (i.e. H2020, Galileo & Copernicus programs). EUSST is now funded by the EU through the EU Space Program and the Horizon Europe programs.

The SST capability consists of three main functions: sensor, processing, and service provision (Fig. *1*). Sensors from Member States contribute data that is analyzed in the processing function and feeds a joint database and ultimately a catalogue; from this, products are derived for three services, generated by the Operations Centers (OCs) and delivered to users via the SST Service Provision Portal (SST Portal).

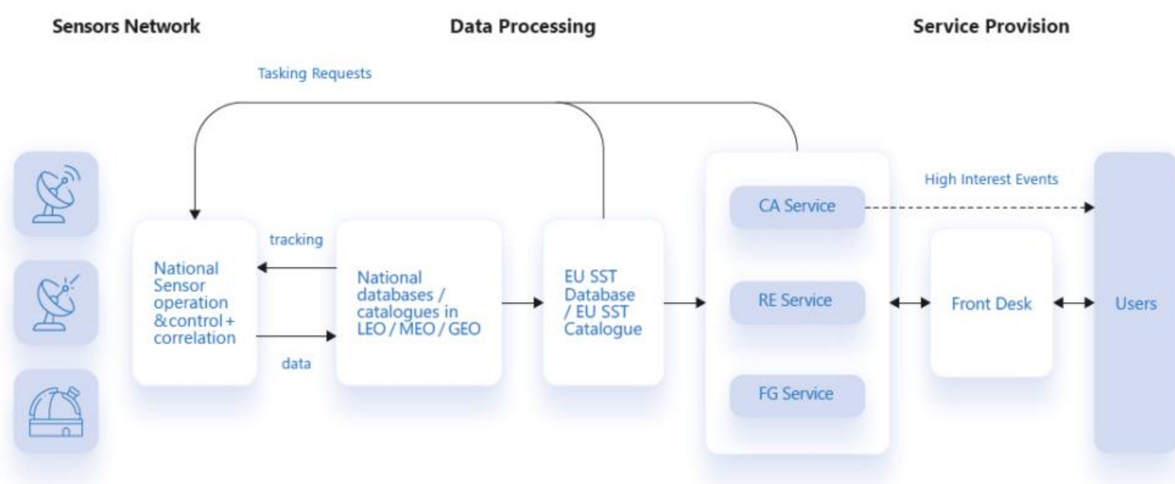

Fig. 1. EUSST Architecture. © SST Cooperation 2023

[1] Regulation (EU) 2021/696 of the European Parliament and of the Council of 28 April 2021 establishing the Union Space Programme and the European Union Agency for the Space Programme and repealing Regulations (EU) No 912/2010, (EU) No 1285/2013 and (EU) No 377/2014 and Decision No 541/2014/EU.
[2] https://www.euspa.europa.eu/newsroom/news/euspa-grows-further-support-eu-space-traffic-management
[3] Decision No 541/2014/EU of the European Parliament and of the Council of 16 April 2014 establishing a Framework for Space Surveillance and Tracking Support.

The **Sensor function** consists of a network of sensors to survey and track space objects in all orbital regimes (LEO, MEO, HEO and GEO). The network (initially described in [1]) currently comprises over 40 sensors of the member states (incl. radars, telescopes and laser ranging stations, Fig. *2*).

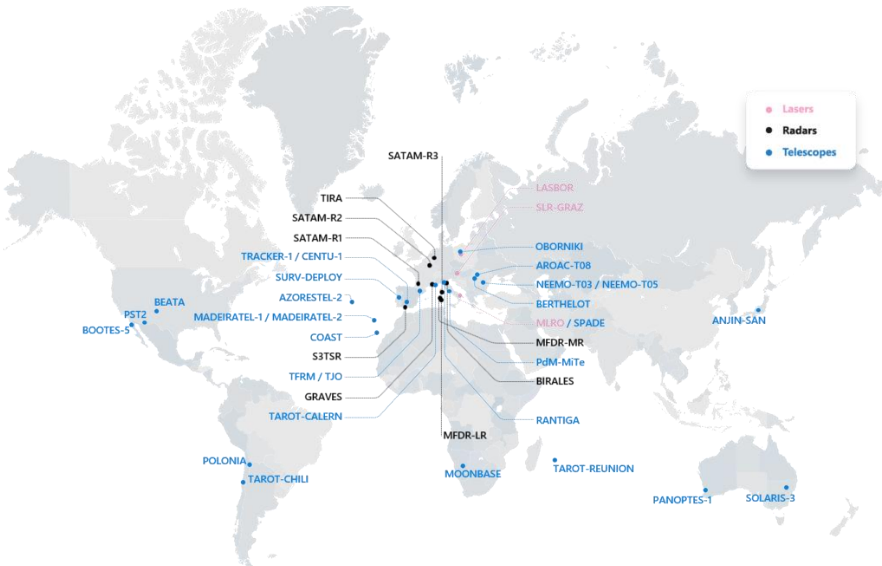

Fig. 2. EUSST sensor network (July 2022). © SST Cooperation 2023.

The **Processing function** aims to coordinate the data-sharing between the different OCs via a common database and to process thousands of daily measurements from the sensors contributing to EUSST. These data constitute the basis for a future EUSST Catalogue that will be used for the SST services. Germany is responsible for hosting the EUSST Database and generating the future EUSST Catalogue.

The **Service Provision** function provides three SST services – Collision Avoidance (CA), Re-entry Analysis (RE) and Fragmentation Analysis (FG) – to entitled users through a secure portal, the SST Service Provision Portal[4], managed by EUSPA, which acts as Front Desk. More than 190 organizations are receiving these services and more than 400 satellites are safeguarded from the risk of collision. Currently, the French and Spanish OCs are responsible for the CA service, while the Italian OC is in charge of the RE and FG services.

2. CALIBRATION CAMPAIGNS

An important aspect of the sensor function is to ensure the quality of the data provided by the different sensors in the network. Several Key Performance Indicators (KPIs) are evaluated for each sensor in the network, but the quality of their data is mainly evaluated through the calibration campaigns. The calibration campaigns are executed twice per year, or every six months, following a similar approach to the one used for the US Air Force Space Command Space Surveillance Network (SSN) calibration [2].

During the calibration campaigns, the sensors in the EUSST network must observe a list of Resident Space Objects (RSOs) with accurate orbits. The list of objects to be observed depend on the capabilities of each sensor and, specially, on the orbital regime that they can observe. For those sensors observing MEO and GEO objects, Galileo satellites are used for calibration. For those sensors observing LEO objects, satellites with publicly available precise ephemerides are used (e.g., Table *1*). Precise ephemerides are usually provided by DORIS[5] or ILRS[6] services. The list of LEO objects is reviewed and updated before starting a new calibration campaign.

[4] https://portal.eusst.eu/
[5] ftp://doris.ign.fr/pub/doris/products/orbits/ssa
[6] ftp://cddis.nasa.gov/slr/products/orbits/

Table 1. List of RSOs used during CC9 to calibrate sensors in the LEO regime.

COSPAR ID	NORAD ID	OBJECT NAME
2016-011A	41335	SENTINEL-3A
2018-039A	43437	SENTINEL-3B
2020-086A	46984	SENTINEL-6
2010-013A	36508	CRYOSAT 2
2016-002A	41240	JASON-3
2013-009A	39086	SARAL
2020-066A	46469	HAIYIANG-2C
2021-043A	48621	HAIYIANG-2D
2003-042F	27944	LARETS
2012-006A	38077	LARES
1975-010A	7646	STARLETTE
1993-061B	22824	STELLA
1976-039A	8820	LAGEOS 1
1992-070B	22195	LAGEOS 2
1989-001C	19751	ETALON 1
1989-039C	20026	ETALON 2

The EUSST calibration campaigns have been scheduled consecutively since the second half of 2020, with the latest fully completed calibration campaign being CC9 (CC10 is currently ongoing). The participation of each sensor in a particular calibration campaign depends on the type of sensor. Telescopes are required to participate in all the calibration campaigns, whereas radars and lasers are required to participate in one calibration campaign per year (Fig. *2*). The participation requirements were defined as a compromise between the expected (and later confirmed) stability of the sensors, the need to have a clear monitoring of their operational parameters and the goal to dedicate most of the sensor time to operational activities.

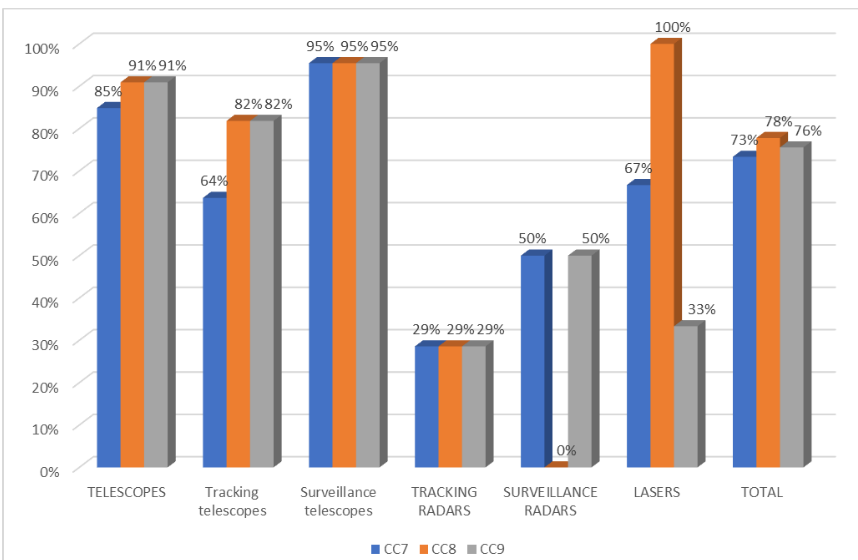

Fig. 3. Fraction of sensors participating in the last three calibration campaigns.

The requirements on the characteristics of the observations provided by each sensor are adapted to the observables that each sensor can provide (e.g., Table *2*). They are defined to minimize the impact of calibrations on the sensor operations and to ensure that results are statistically significative. When a calibration observation is obtained, it is marked as such and uploaded to the EUSST database to be processed.

Table 2. Minimum number of observations required for each sensor during CC9.

TELESCOPES	
Duration	14 days. Maximum difference between first and last measurement
Minimum number of objects with at least 50 measurements (35 LEO telescopes)	3
Minimum number of total measurements belonging to all the objects usable	200 (130 LEO)
RADARS	
Duration	14 days Maximum difference between first and last measurement
different passes of the agreed objects	5
Minimum total tracks duration	6 minutes
LASERS	
Duration	14 days: Maximum difference between first and last measurement
Number of tracks belonging to different passes	3
Minimum number of total measurements	25 Normal points

3. CALIBRATION DATA PROCESSING

Once the period to submit calibration observations is concluded, all the calibration data is processed independently by Spain and France National Operation Centers (NOCs, S3TOC and CCO, respectively). The purpose of this independent calibration is to crosscheck the estimated measurements quality of each sensor.

The calibration data processing compares the data provided by the EUSST sensors with the precise ephemerides of the calibration RSOs obtained from public archives (in SP3 form). For each sensor, any possible biases in the observables provided are also computed. Since each sensor obtains different observables, the parameters to be calibrated are adapted to the provided data (Table *3*). Unless that sensor measurements already include them, several effects are included in the calibration processing:

- Relativistic effects of annual and diurnal aberration.
- Signal travel time.
- Atmospheric modeling, including both tropospheric and ionospheric effects.

The processing uses a weighted sigma-clipping rejection algorithm to both consider any possible biases and reject any possible outliers. In addition to the biases, the Root-Mean Squared (RMS) of the fit and the percentage of rejected measurements are also considered in the evaluated results.

The results of the calibration are compared between the two NOCs and, in those rare occasions when results differ, the underlying causes are investigated and resolved. Once the results agree for all the sensors, the obtained parameters for each sensor are submitted to the EUSST calibration approval commission, composed by all member states. The commission evaluates the resulting parameters according to a list of thresholds (e.g., Table *4*). Only those sensors fulfilling the measurements quality thresholds are considered operational and allowed to continue providing data to the EUSST (among other KPIs). The same process is applied to new sensors that provide data to the EUSST for the first time. They are only considered operational and allowed to provide data once they fulfill the expected thresholds.

Table 3. Parameters considered for all the different EUSST sensors during the calibration campaigns.

SENSOR MEASUREMENT	SENSOR TYPE	EVALUATED PARAMETER
Time	Telescopes	Bias drift
	Radars	-
	Lasers	-
Right Ascension	Telescopes	Angular RMS
Declination	Telescopes	
Azimuth	Radars	-
Elevation	Radars	-
Range	Radars	Range RMS
	Lasers	Range RMS
Doppler	Radars	Range rate RMS

Table 4. Thresholds that EUSST sensors had to fulfill at CC9.

SENSOR TYPE	RMS THRESHOLDS	BIAS DRIFT	REJECTED OUTLIERS
MEO, GEO telescopes	Angular RMS ≤ 2 arcsec	≤ 70 ms	≤ 5%
LEO tracking telescopes	Angular RMS ≤ 30 arcsec		
Surveillance radars	Range RMS ≤ 100 m Range rate RMS ≤ 4 m/s	NA	
Tracking radars	Range RMS ≤ 50 m Range rate RMS ≤ 2 m/s		
Tracking lasers	Range RMS ≤ 5 m		

The thresholds shown in Table *4* are determined as a compromise between the cataloguing requirements and the sensor operational capabilities. The results obtained for the previous calibration campaigns (Fig. *4*) reveal that most sensors clearly fulfill the requested thresholds. The current network of EUSST sensors include over 40 sensors fulfilling the calibration thresholds.

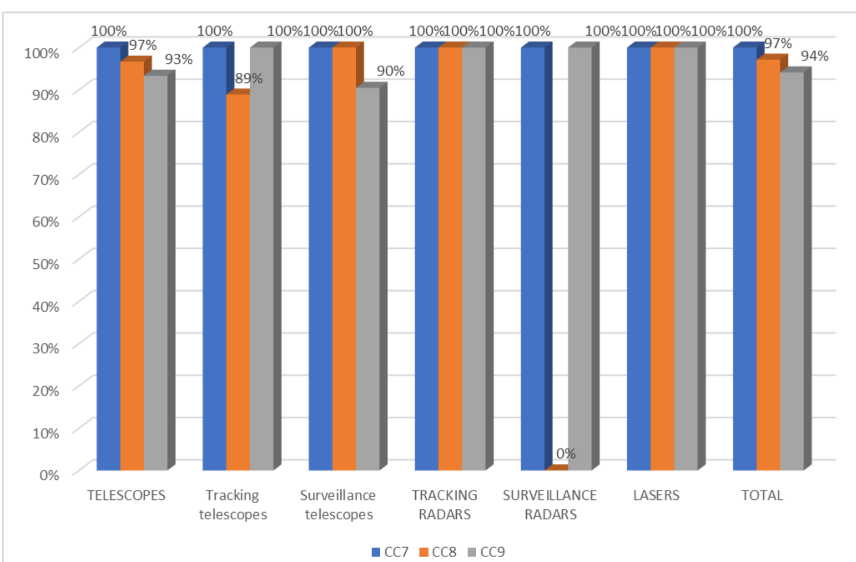

Fig. 4. Fraction of sensors fulfilling the thresholds the last three calibration campaigns.

4. FURTHER IMPROVEMENTS

The calibration campaigns provide an accurate view of the measurement accuracy of the sensors in the EUSST network. However, there is still room from improvement in three specific aspects:

- **Responsiveness.** The definitive ephemerides for many of the calibration RSOs are usually published within two weeks after the epoch of the orbit. This makes that the processing of the calibration data is delayed until the precise ephemerides are obtained.
- **Operational evaluation.** The current calibration campaigns periodically evaluate the data accuracy provided by a sensor during only two weeks every six months. This could raise potential issues in the cataloguing chain if a sensor starts to deviate from its calibration parameters.
- **Reactivity.** Having a calibration campaign every six months makes that a new sensor cannot be made operational for a long time, even when it could be able to provide data with the required quality.

To overcome the limitations of the current calibration campaigns, two different approaches are being implemented: the fast calibration and the continuous calibration.

4.1. Fast calibration

To improve the calibration reactivity, the fast calibration campaigns were introduced at the end of 2022. The fast calibration procedure allows either a new sensor, or a sensor that did not pass the previous calibration campaign by a tolerance factor (currently, 5% in RMS), to request a specific calibration. The fast calibration is also useful to confirm the quality of the measurements for an operational sensor after a maintenance period. The process is identical to the calibration campaigns, with the only exception that the calibration data is processed as soon as the definitive ephemerides are available. The fast calibration has the potential to allow a sensor to become operational within few weeks, instead of having to wait for several months.

4.2. Continuous calibration

To further improve the operational evaluation and the calibration processing responsiveness, a new calibration system is currently being defined by the EUSST calibration team. The continuous calibration aims at obtaining observations in a routinely manner by all the sensors in the network. Once the calibration observations are obtained by a particular sensor, they would be immediately processed using preliminary ephemerides or using RSOs with a fast publication of their ephemerides. The process would be continuously repeated for each sensor in the network, so that the operational parameters of all the sensors in the network could be determined with a short delay, ensuring a high quality of the data provided by all sensors involved in EUSST.

5. CONCLUSIONS

The calibration process described above has been applied to the EUSST sensor network for three consecutive years and has proven its capacity to accurately assess the data quality provided by its sensors. The double independent calibration performed by two NOCs (S3TOC and COO) has proven to be extremely valuable to justify when a sensor fulfills the calibration thresholds. In addition, the dynamic nature of the calibration process, where the RSOs suitable for calibration as well as the thresholds are continuously evaluated provides a very robust calibration method. It also provides the capability to use the most up to date RSOs and to evolve with the EUSST sensor network characteristics. In the future, the calibration process is expected to be even more robust, with the implementation of the continuous calibration, since all the benefits of the calibration campaigns will be used in quasi-real time for all sensors in the network.

6. REFERENCES

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7. ACKNOWLEDGEMENTS

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