The GSSAC Mission System: a new solution for space objects cataloguing from DLR

A. Sancho, A. Bialkowski, A. Pastor
GMV, Europaplatz 2, 64293 Darmstadt, Germany
C. Kronjäger, J. Nicolai, A. Bachlechner
DLR, German Space Situation Awareness Centre, Muehlenstraße 89, 47589 Uedem, Germany

ABSTRACT

The civil section of the German Space Situational Awareness Center (GSSAC), operated by the German Space Agency within the Deutsche Zentrum für Luft- und Raumfahrt (DLR), has been working with GMV since 2021 to upgrade and enhance the GSSAC Mission System (GMS). One goal of the GMS is to build-up and maintain a space objects catalogue by processing Space Surveillance and Tracking (SST) data, focusing on automation, reliability, and robustness.

This paper introduces the system architecture, details the cataloguing service, an essential part of the GMS, and presents the monitoring of the system. The GMS encompasses not only the essential software components for SST data processing but also includes databases, archiving systems, system interfaces, and a dedicated framework designed to streamline the cataloguing process. It features an Application Programming Interface (API) gateway to input and output data. This development-friendly interface allows operators to easily navigate through the system, enhancing their productivity and efficiency. Moreover, the GMS provides software components responsible for creating valuable products and a product submission module that facilitates the distribution of these products to both internal and external stakeholders. The data generated by the GMS is readily available and easily accessible, promoting reliability and timeliness.

1. INTRODUCTION

To address the growing problem of the near-Earth space environment, the European Union (EU) has proposed a joint approach on Space Traffic Management (STM) to ensure a safe, sustainable, and secure use of space. The increasing congestion in Earth's orbit, with an estimated trackable population of space debris that can be regularly tracked by space surveillance networks and maintained in space objects catalogue of about 36,090 [1], presents significant challenges for Space Situational Awareness (SSA) and space sustainability.

The European Union Space Surveillance and Tracking (EU SST) initiative is a partnership involving 15 countries [2]. The Space Surveillance and Tracking (SST) capabilities of EU SST consists of three pillars (see Fig. 1): sensors from the member states, processing of this data, and service provision [3]. Among the member states, Germany contributes by providing the EU SST database and catalogue. The German Space Situational Awareness Center (GSSAC) is responsible for the processing of observations, as well as the build-up and maintenance of the space objects catalogue. The space objects catalogue is a robust, automated, and reliable database containing information of detected and maintained space objects, built-up and maintained through a set of processing techniques. It is a key enabler for space environment sustainability and contains information on the objects' characteristics (e.g., mass, size, object identifiers) and about their orbital state, in the form of ephemeris, state vectors, mean elements and even maneuvers. The basic algorithms behind these processing techniques have been developed in "Basisalgorithmen für SST Datenverarbeitung" (BaSSTDa; basic algorithms for SST data processing), the astrodynamics library used within the GMS [4] [5].

This paper is organized as follows. In Section 2, the system architecture is introduced, including the design principles, microservices approach and their communication. In Section 3, the cataloguing service is detailed. In Section 4, the monitoring system is presented. Finally, in Section 5, the conclusions and future of the system are discussed.

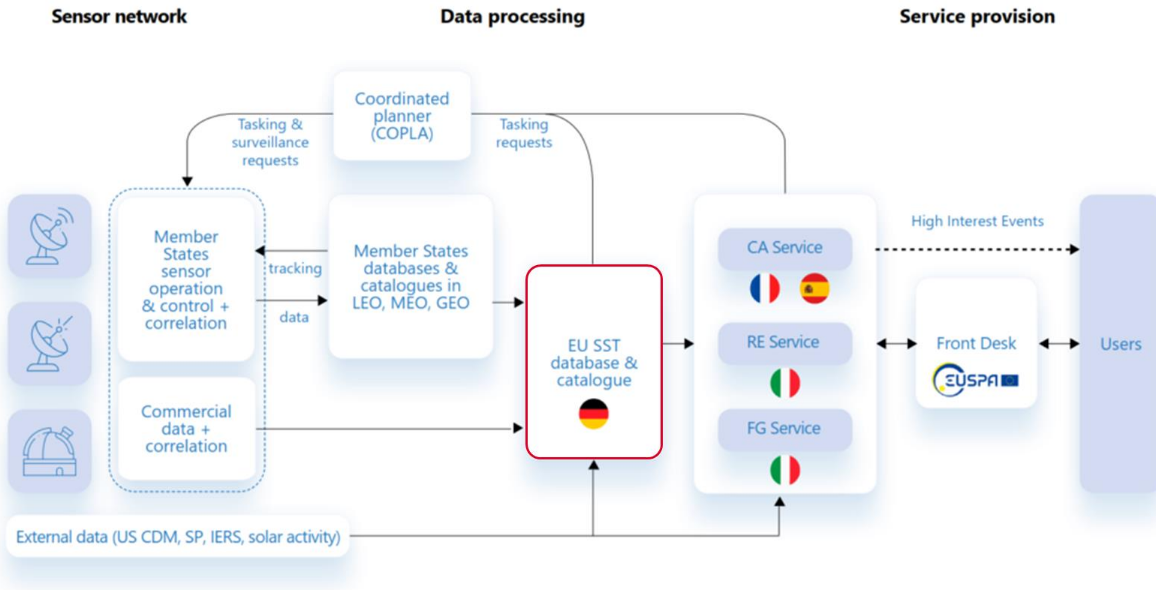

Fig. 1. EU SST architecture [3]

2. SYSTEM ARCHITECTURE

The GMS architecture is built on the principles of microservices. This microservices architecture features a collection of loosely coupled and highly cohesive services that collaborate to provide the necessary functionality to users. Each microservice is fine-grained, and communication protocols between them are lightweight, reducing overhead. The design adheres to the principle of **Separation of Concerns (SoC)** and the single-responsibility principle, separating software into distinct components, each addressing a different functionality. This modular approach allows functionalities to be encapsulated into different microservices, exposing them through well-defined interfaces. Microservices are organized by functionality and cover all layers needed to implement a given functionality, from the user interface to data persistence. This vertical integration facilitates parallel development and deployment, enabling independent maintenance and evolution.

The microservices are deployed in separate **Docker containers**, ensuring consistency across environments and simplifying deployment. They are designed to scale horizontally, ensuring that system performance is maintained as the population of space objects grows and sensor tracking and surveillance capabilities improve.

The GMS system uses two types of internal communication: **synchronous** and **asynchronous**. Synchronous communication involves direct interaction between services, using **Representational State Transfer Application Programming Interfaces (REST APIs)** implemented according to the OpenAPI standard. This type of communication is suitable for immediate information exchange, often requiring only an acknowledgment. An example is the LogService, where various services send log information directly to the LogService, which stores these messages in its database. Asynchronous communication employs a **Kafka-based message broker** to handle inter-service communication. Services publish messages to Kafka topics, and other services subscribe to these topics to consume messages as needed. This method is used to trigger events and actions, decoupling the services and allowing for flexible and scalable communication. The combination of synchronous and asynchronous communication provides the system with the flexibility to handle different types of interactions efficiently. Synchronous communication ensures real-time interactions for scenarios like logging, while asynchronous communication via Kafka enables the system to manage workloads and scalability effectively. This mixed communication model enhances the system's flexibility, performance, and scalability.

Concerning deployment, currently, each service within the GMS system runs individually in Docker containers. However, as part of the project roadmap, there are plans to migrate to **Kubernetes** to leverage the capabilities of a system composed of multiple nodes. This transition will enable the implementation of service replicas, improving system performance and facilitating task distribution. With Kubernetes, the system will be able to manage scalability and resilience more efficiently, ensuring superior performance and a greater ability to adapt to growing demand.

Fig. 2 describes the main components of the GMS architecture: A **Health Monitor + Resources** handler that provides the functionality to monitor the system, an **Admin Web Portal** that provides administrators the tools and features to manage various aspects of the application, an **API Gateway** which acts as the single entry point for all client requests, the **File Transfer Service** that is in charge of handling the transfer of files within the system and from/to the external system and users, a **Password Service** that stores credentials, an **Archive Service** that handles the storage of the relevant archives of the system, a **Catalogue Database Service** that stores the different elements of the catalogue such as space object, state vectors and ephemeris information, among others, a **Sensor Configuration Service** that manages the information about the sensors, a **Log Service** that is in charge of handling the log messages from different services, storing them in a homogeneous way and finally the **Cataloguing Service**, which provides the cataloguing functionalities such as orbit determination, track-to-orbit correlation, etc., as described in the following section. The **Message Broker** service is the component that facilitates asynchronous, real-time communication between all the services by enabling them to publish and subscribe to data messages that describe actions to be triggered by those services.

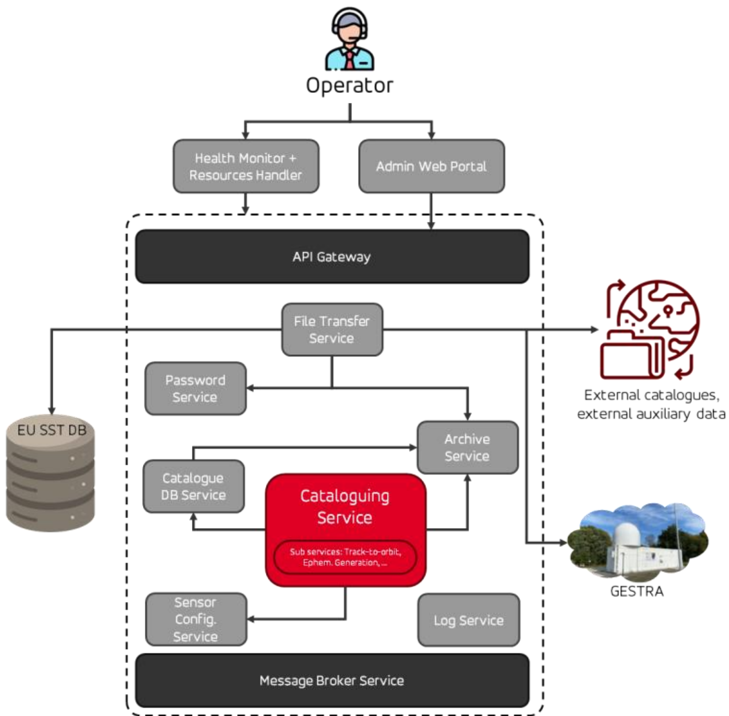

Fig. 2. System architecture design

3. CATALOGUING SERVICE

A strong focus of the GMS is set on the cataloguing service, an essential part of the system that is responsible for the catalogue maintenance and build-up activities. On the **catalogue maintenance** side, for the ingested tracks that can be correlated to already catalogued objects, the cataloguing service handles the Orbit Determination (OD) process [5], which updates the main cataloguing products, such as state vectors, ephemerides, visibilities or mean elements. Concerning the **catalogue build-up**, the cataloguing service is also responsible for the execution of the track-to-track association [6], which groups uncorrelated tracks (UCTs) to create a potential new object and derive the initial orbit estimate for that object using initial orbit determination (IOD) methods. Moreover, for potential new objects, the service can try and correlate their orbits with those of the other objects of the catalogue, to look for possible duplications.
These processes are automatically triggered, either on schedule or in an event-based manner (for instance, when a new track enters the system). The service includes other advanced capabilities like state-of-the-art methods for maneuver detection and estimation [7] [8]. Fig. 3 shows the processing chain that is implemented in the cataloguing service of GMS, depicting the main data flows and steps that are followed. The next subsections contain a more detailed description of each one of those processes, which are implemented using BaSSTDa.

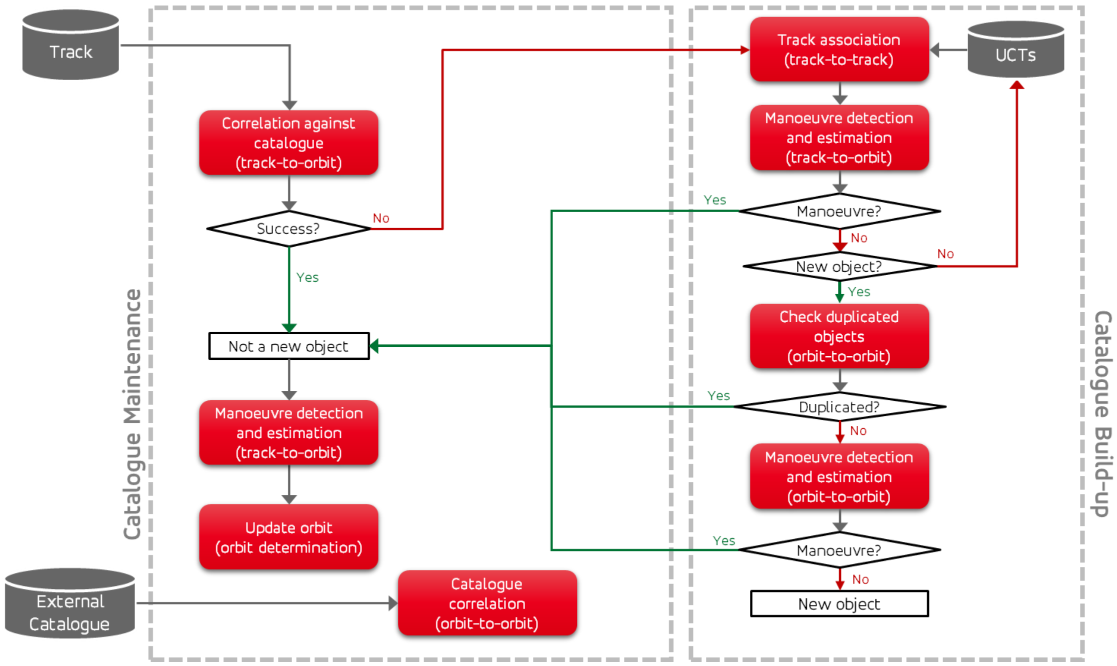

Fig. 3. Cataloguing processing chain

3.1 TRACK-TO-ORBIT CORRELATION

The cataloguing processing chain is dynamically started with different triggers, e.g., new track ingested in the system, considering a track as a set of observations taken by a single sensor during a period of time of continuous observation of an object. GMS can handle the most common file formats, like the Tracking Data Message (TDM) from the Consultative Committee for Space Data Systems (CCSDS) [9] and Consolidated Laser Ranging Data Format (CRD) from the International Laser Ranging Service (ILRS) [10], via parsers that transform the information included in the input file into the defined data model used within the system. Hence, it can be easily evolved to treat other formats by just implementing new parsers, while the rest of the processing chain would remain the same.

The first step is then trying to correlate the new track with one of the objects in the catalogue, i.e., track-to-orbit correlation (T2O). GMS cataloguing service allows the selection of the source of orbital information that will be used for T2O, either ephemeris generated by the system itself (see Section 3.4) or ephemeris coming from external sources, like the Special Perturbations (SP) ephemerides [11] from the 18th Space Defense Squadron (SDS) (see Section 3.7). The system also allows the operator to select between doing just a pre-correlation check or a full correlation. Indeed, in certain cases, the input track may already contain information on the space object for which the observations have been taken (e.g., sensor operating in tracking mode). For those cases, the **pre-correlation check** verifies if the observations belong to the space object identified in the input track. To do so, the T2O process verifies if that object is visible from the sensor that has performed the observations during the time interval of the track and if that condition is fulfilled, then it verifies that the observations in the track match the latest available ephemeris of the object. This verification is based on an analysis of the residuals. The T2O process simulates the measurements at each observation epoch using the ephemeris information (i.e., predicted measurements) and compares them with the actual measurements. If residuals-related metrics are below the thresholds configured by the operator, then the T2O correlation process is deemed successful. Otherwise, or if the operator has selected to do a **full correlation** (e.g., ignoring the object that the input track refers to), then a one-vs-all correlation process is triggered: the correlation of the input track is analyzed against all the objects in the catalogue. For performance purposes, this one-vs-all process has several filters.

The first filter is the **visibility check**, which selects only the objects visible from the sensor. If a space object was not visible from the sensor during the track time interval, it is ruled out since the sensor could not have generated observations for that object. The second filter is the **coarse filter**, based on a residuals analysis but using quick but less accurate information: the mean elements set of each object. The first step of this filter is generating the hypotheses, i.e., pairs of input track and object. Then, an observation is simulated at the middle epoch of the actual track, compared to the one interpolated from the actual track, and weighted with the expected sensor measurement noise, to obtain the

Weighted Root Mean Square (WRMS). The hypotheses whose WRMS is above a given configurable threshold are pruned. The last filter is the **fine filter**, whose process is similar to the coarse filter, but it uses higher accuracy ephemeris information instead of mean elements sets for the prediction of the measurements. Moreover, the configured thresholds are more restrictive in this filter, to ensure - as much as possible - that the retained solution is not a false positive. After pruning, the remaining hypotheses are sorted according to their figure of merit (based on the WRMS) and the best one, if any, is selected for promotion, leading to a track correlation.

Finally, if the T2O process is successful, the system is capable of generating a TDM file that is uploaded to the EU SST database. If the T2O is not successful, meaning that the track couldn't be correlated to an existing object, the track is marked as UCT, and continues through the association process described in Section 3.5.

3.2 MANEUVER DETECTION AND ESTIMATION

To improve the accuracy and convergence of the OD process (see Section 3.3), it is crucial to properly characterize the dynamics of the space object. One of the main uncertainties in this regard are the maneuvers that the object may perform and which, in most cases, usually are not known beforehand by the system. Therefore, a necessary step is detecting and estimating maneuvers from the available information. To do so, the GMS cataloguing service includes a **maneuver detection process** that is based on the identification of outliers in the residuals of incoming observations and a well-established orbit before the maneuver. The execution of this maneuver detection and estimation process can be enabled or disabled by the operator and, in any case, is only executed for those objects that are classified as active or for which the operational status is unknown to avoid false positives. When a potential new maneuver is detected, the **estimation process** is triggered. It uses a linearization (state transition matrix) of the high-fidelity numerical propagator to perform an estimation of the maneuver, placed at different epochs along the identified time interval [7], that best fits the observations. The best solution is then selected based on a trade-off between the estimated delta-v (optimal control assumption) and on post-fit WRMS (goodness-of-fit). If the maneuver estimation process succeeds, the new maneuver is included in the GMS for the space object and will be used from then on in the processing chain. However, since usually only a limited number of observations after the maneuver is available, and due to the simplified dynamics used in this initial maneuver estimation, this first maneuver estimation is refined during the nominal OD cycle or ignored if not identified reliable (see Section 3.3).

3.3 ORBIT DETERMINATION

The OD process is responsible for the update of the orbital state of the space objects based on new available information. This includes mainly newly received tracks from the sensor network, e.g., radar, optical, and Satellite Laser Ranging (SLR). Within the cataloguing service of GMS, the OD process is triggered based on a **schedule** defined by the operator via a crontab-like expression: an OD process cycle is executed with a certain configurable frequency. The process loops over all the catalogued space objects that are not decayed and executes the OD process for each one of them, parallelizing the computations via a thread pool executor.

For each object, the process first **prepares the inputs** of the OD. This step verified the OD needs to be executed. Several conditions have been implemented, among others: 1) the last available OD for the object is older than a configurable threshold (otherwise, there is no need to update it again); 2) there is an initial solution, either state vector or mean element set, available close enough to the OD epoch; 3) there are new tracks available for the object ; 4) the available tracks are not too old; 5) the tracks cover an interval long enough; 6) the number of tracks is above a given threshold (otherwise the OD results are not expected to be reliable). This input preparation also includes a smart selection of the dynamical model to be used along the OD, depending mainly on the orbital regime of the space object. Besides, catalogued maneuvers are also included here (see Section 3.2), to be refined or assumed constant depending on the total number of maneuvers and their age with respect to the OD epoch. For instance, in the case of a maneuver that has already been estimated several times or which is far away in the past, its components are no longer estimated, but assumed fixed. Once the inputs are ready, the OD is **launched**. The GMS cataloguing service implements a non-linear weighted least squares algorithm [5] for the estimation of the full state (i.e., position, velocity, dynamical parameters, and maneuvers, if any). Once the OD computation is finished, its status is verified. Several **acceptance criteria** are considered: percentage of rejected observations, final WRMS, or the number of used tracks, among others. If the OD result is accepted, a new state vector is generated and stored in the GMS for the object, as well as the eventual maneuver parameters, which will trigger the next step in the chain (see Section 3.4). If the OD is not accepted, no state vector is stored in the system database and the eventual newly detected maneuvers (coming from the process described in Section 3.2) are removed from the database since they are considered as false positives. Note that if there was a maneuver detected and estimated for the first time, it is expected to be detected again in the next OD cycle, when more information is available, leading to a more reliable estimation.

3.4 EPHEMERIS GENERATION

The ephemeris generation process is triggered whenever a new state vector for a given object is available in the system, either because a new OD has been successfully executed (see Section 3.3) or the orbit fitting of an external ephemeris has been performed (see Section 3.7). The service recovers the input state vector, as well as the different configuration parameters, required for the propagation, including the dynamical models to be used or the time span that the ephemeris needs to cover, and updated ancillary files needed (e.g., space weather). These parameters are configurable by the user, and they are dependent on the orbital regime of the space object, since the dynamical models that need to be considered, for instance, for Low Earth Orbit (LEO) are different from the ones in case of Geostationary Earth Orbit (GEO). The maneuvers associated to the object are also considered. Once all the inputs are recovered, the state is **propagated** using a high-fidelity numerical propagator, and if the computation is successful, the new **ephemeris** is stored in the GMS.

Apart from the ephemeris itself, this process can also generate two other products. Using the computed ephemeris for the given object, the **visibility periods** for that object from all the defined sensors in the system can be computed. Amongst other purposes, these visibilities can be used for the T2O process, as explained in Section 3.1. Moreover, the system is also capable of producing a set of **mean element sets** using the computed ephemeris. In this case, the trajectory is considered as observations and a fitting process based on SGP4 is performed [12]. If there are maneuvers in the propagation interval, several mean element sets are computed, one per ballistic trajectory between maneuvers.

3.5 TRACK-TO-TRACK ASSOCIATION

In the catalogue build-up part of the cataloguing service, the system associates UCTs (e.g., tracks from sensors operating in survey mode). This is the goal of the track-to-track (T2T) association process implemented in GMS. As for the OD, the T2T association process is triggered on a scheduled basis, depending on a crontab-like expression that can be configured by the operator. This T2T process tries to associate UCTs to create **hypotheses**, i.e., groups of tracks that belong to the same object, to then provide a reliable initial estimation of the object state. In this process, there are two categories of tracks: the ones that have never been used in a T2T process before (i.e., newly received UCTs) and those that have already been processed. This classification is done required by the algorithm as it tries to associate new tracks with new tracks and with historic tracks, but not historic tracks between them. In the T2T process, the first step is the generation of hypotheses (i.e., couples, triplets, etc.) of UCTs, and for each one a set of IOD and OD processes are performed. For the ODs that are accepted, a goodness-of-fit metric based on the WRMS of the residuals is computed and the hypotheses whose metric is above a certain threshold are pruned. Finally, as in the T2O process, the hypotheses that remain are kept as candidates and a figure of merit is computed. Those hypotheses whose figure of merit is above the quality threshold defined by the operator are promoted and considered as belonging to the same space object. The details of the algorithm can be found in [6].

As a result, for each promoted hypothesis the T2T association process will create a **potential new space object** in the catalogue with default values, it will associate the tracks to that new object and will also store in the system database the state vector coming from the OD performed during the T2T. With this state vector, the ephemeris generation process is then triggered. Once the ephemeris is computed for this newly created object, the orbit-to-orbit correlation process (see Section 3.6) is triggered for the sake of robustness.

3.6 ORBIT-TO-ORBIT CORRELATION

The orbit-to-orbit (O2O) correlation process closes the catalogue build-up chain, and it tries to ensure that there are no **duplicated objects** in the catalogue and that an existing space object has not been **wrongly labelled as new**. This O2O process is triggered on event when a new object is created after T2T (see Section 3.5) and can also executed on a scheduled basis according to a configurable crontab-like expression. In the latter case, the process is executed over all the objects in the catalogue that do not have any International Designator (COSPAR ID) or Satellite Catalog Number (NORAD) assigned. The process in both cases is the same: pairs of hypotheses involving two orbits are created to which filters like those used in Conjunction Detection process (i.e. Smart-Sieve, see [13]) are applied. For those hypotheses passing the filters, the differences in position and velocity between both orbits are computed and a figure of merit (which can be chosen to be based on the Mahalanobis distance if covariance information is available) is used to score them. A promotion process follows, and the best solution remains. As in the case of the T2O correlation and for performance reasons, the O2O correlation is split in two steps: coarse, in which the mean elements information is used, and a fine, applied to the pairs promoted in the coarse step, in which ephemeris information is considered. Finally, when a duplication is detected, the elements of the system (tracks, ephemeris, state vectors and mean elements) that were initially associated to the new object are transferred to the object already existing in the catalogue and the new object is deleted from the catalogue.

3.7 ORBIT FITTING

The GMS cataloguing chain also allows the ingestion of ephemerides provided by external sources, such as the 18th SDS SP catalogue [11] to integrate them in the catalogue, so that they can then be used, for instance in the T2O process (see Section 3.1). This process is triggered whenever new external ephemeris data are ingested by the system and has two different flavors. The first, **orbit fitting** of the ephemeris via OD using a high-fidelity numerical propagator to estimate the full state of the object at a given epoch using the inertial positions of the ephemeris as observations. If the process finishes correctly, the new state vector of the object is stored in the system database and the ephemeris generation process is triggered. The second flavor, which is the one recommended, is a simpler one: a **reference frame transformation** to transform the ephemeris to Geocentric Celestial Reference Frame (GCRF), the default inertial frame used all along the cataloguing chain. Note that the SP catalogue ephemerides are expressed in True Equator Mean Equinox frame (TEME). Once finished, the original ephemeris is removed from the system and replaced with the new transformed one. Moreover, if configured so by the operator, this can also trigger the computation of visibilities (as described in Section 3.4), using the transformed ephemeris in GCRF as input.

4. SYSTEM MONITORING

Due to the significant amount of data that is processed by the GMS, the monitoring is an essential part to keep track of all tasks that are performed **automatically**, and to give an overview of the **performance and computational workload**. In addition, it can also be used to verify the correct behaviour of a **new GMS version** before releasing it to the operational instances. The monitoring system is responsible of illustrating the status of the system in a user-friendly way. This includes the performance of the different processes such as T2O and OD, as well as the resources that are consumed. The performance of the system can be assessed by evaluating the number of tracks that are processed and the number of products that are generated by the system during a specific time as well as the number of processes that are successfully executed. The monitoring system illustrates the system's performance using several dashboards. Some of these panels are shown in Fig. 4.

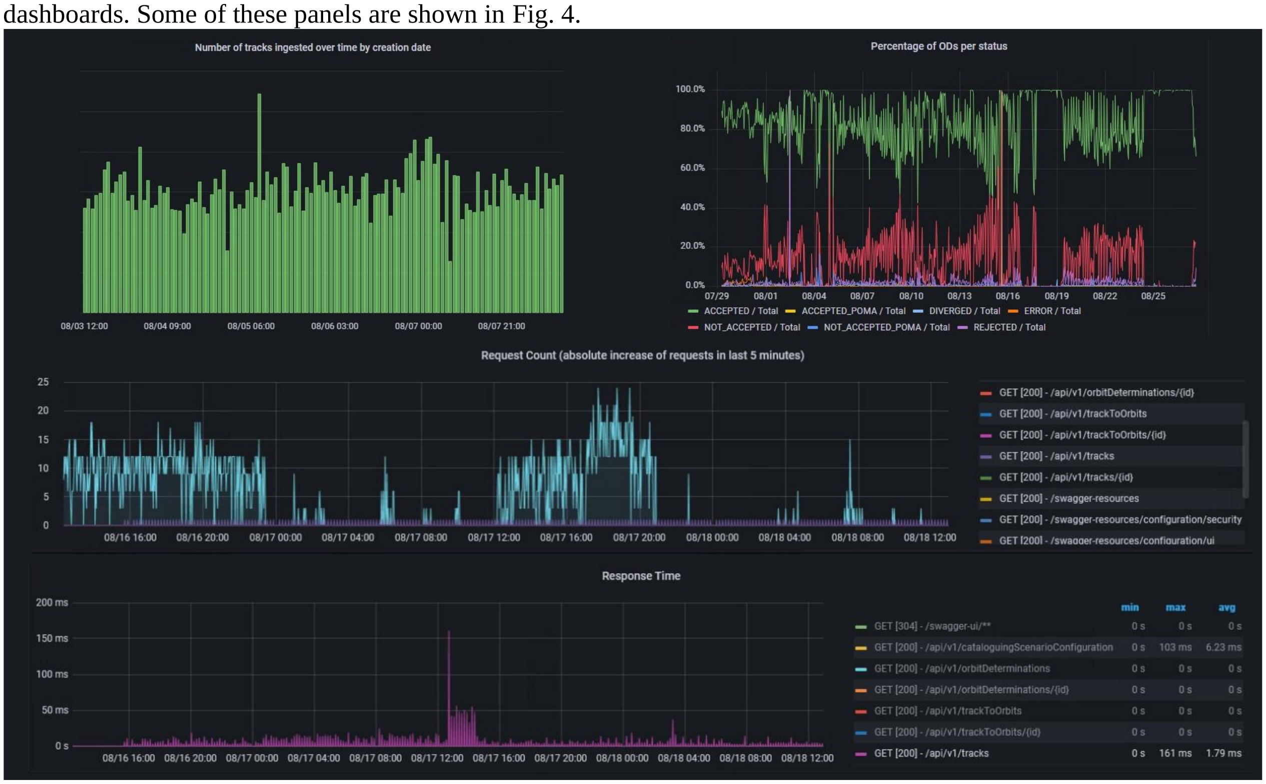

Fig. 4. Performance monitoring with simulated data

The two plots in Fig. 4 (top) depict the panels with the number of processed tracks and executed ODs. The information is presented in clear **graphs** or **histograms** that can easily be analysed. The chosen time period and the **step size** of the data points can be configured by the user. Hence, it can be assessed how many ODs were accepted based on configurable acceptance criteria.

Due to the enormous amount of data that is processed, it is also necessary to analyse the consumed system resources which is also provided by the monitoring system. This includes the **computational resources** such as disk space, memory, or CPU usage. Again, the monitoring system allows to see the evolution of the considered metrics over time. On the other hand, due to the API based approach, the number of requests sent between the different services and the corresponding response times must also be monitored. Suitable dashboards are provided by the monitoring system which are also shown in Fig. 4 (bottom). Here, the number of requests that are sent to a specific endpoint can be assessed in combination with the corresponding response time. The user can easily switch between the available endpoints to check the performance for each endpoint individually.
The performance check of the system also includes the achieved results from the **T2O processes**. For that, the number of successfully correlated tracks are illustrated using eye-catching panels as shown in Fig. 5. This dashboard shows the number of successfully executed T2O processes compared to the total number of executed processes. This is also represented as a percentage value. Striking colours illustrate the success rate immediately. In addition, the figure of merit is given to show the outcome of the process and the quality of the input data. The dashboard also allows to show the evolution of the T2O results and the correlation rate for a specific sensor. All these panels can be created for the coarse and the fine correlation process (see Section 3.5).

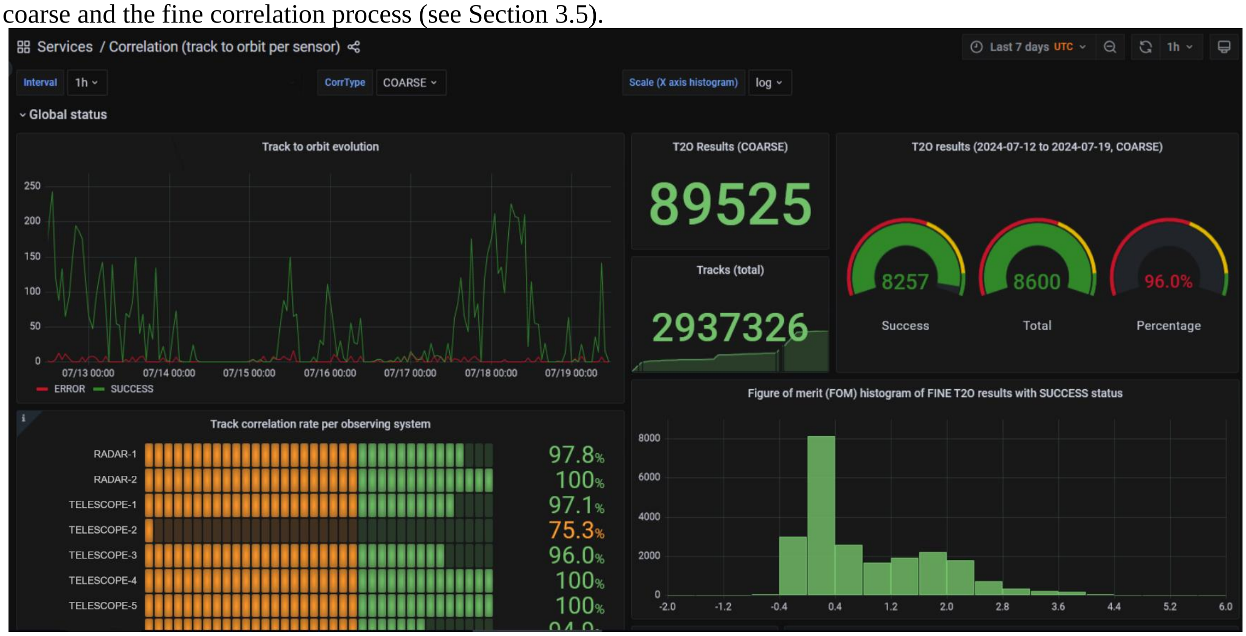

Fig. 5. Correlation monitoring system with simulated data

Additional dashboards show the performance of the database, the files that are ingested by the system, or additional spring boot statistics. Furthermore, it is possible to monitor a specific space object. This involves the status and type of the object and the change of the Keplerian elements and the update of its state vector. A main dashboard gives an overview of the entire system.

5. CONCLUSIONS

The development and implementation of the GMS mark a significant achievement in SST capabilities. The GMS along with its components, is engineered to effortlessly adapt to changing needs and requirements. Enhancements, such as cataloguing workflow improvements, or data acquisition from new sources, require minimal development effort. The microservices architecture has enabled the GMS achieving a high degree of automation, reliability, and robustness, essential requirements for a comprehensive space object catalogue. The modular design, with its development-friendly API gateway has facilitated seamless interaction between the system services. This is expected to improve the operator operations and to ensure the reliability and timeliness of the data products generated by the GMS. This strategy not only renders the system flexible and capable of adapting to upcoming needs, but also facilitates the exploration of new methodologies at a reduced cost.

ACKNOWLEDGMENTS

This project has received funding from the European Union within the European Union Space Surveillance and Tracking (EU SST) framework.
The authors would like to acknowledge M. Eickmans, S. Hesselbach,, D. Stelmecke, and D. Thesing from DLR for their constant and active support, as well as to the GMS development team and people from GMV boosting the project: I. Llamas de la Sierra, J. Tirado, M. Casado-Martín, R. Ströbel, M. Wegner, P. Sazawal, Z. H. Khan, D. López-García-Ripoll, M. Callejón-Cantero, O. I. García-Lobo, M. Torras-Ribell, N. Semprini, M. A. Iova.

REFERENCES

[1] ESA's Space Debris Office, *Space Environment Statistics*, 2024.

[2] R. Peldszus and P. Faucher, "European Union Space Surveillance & Tracking (EU SST): State of Play and Perspectives," *Space Policy,* vol. 62, p. 101503, November 2022.

[3] EU SST, *About us*, 2024.

[4] J. Velasco, C. Fernández, A. Pastor, S. Hesselbach, J. Nicolai and M. Eickmans, "Generic Orbit Determination Routine to Support Space Object Catalogue Maintenance," *2nd Orbital Debris Conference,* December 2023.

[5] F. Stechowsky, J. R. García-Espinosa, A. Pastor, C. Kronjaeger, S. Hesselbach and A. Bachlechner, "Catalog maintenance with non-cooperative maneuvering space objects," *29th International Symposium on Space Flight Dynamics*, December 2024.

[6] A. Pastor, M. Sanjurjo-Rivo and D. Escobar, "Track-to-track association methodology for operational surveillance scenarios with radar observations," *CEAS Space Journal,* vol. 15, p. 535–551, July 2022.

[7] A. Pastor, G. Escribano, M. Sanjurjo-Rivo and D. Escobar, "Satellite maneuver detection and estimation with optical survey observations," *The Journal of the Astronautical Sciences,* vol. 69, p. 879–917, June 2022.

[8] L. Porcelli, A. Pastor, A. Cano, G. Escribano, M. Sanjurjo-Rivo, D. Escobar and P. Di Lizia, "Satellite maneuver detection and estimation with radar survey observations," *Acta Astronautica,* vol. 201, p. 274–287, December 2022.

[9] Consultative Committee for Space Data Systems, "Recommendation for Space Data System Standards, Tracking Data Message, Recommended Standard, CCSDS 503.0-B-2, Blue Book," 2020.

[10] ILRS Prediction Format Study Groupof the ILRS Data Format and Procedures Working Group, "Consolidated Laser Ranging Data Format, Version 2.01," 2019.

[11] 18th & 19th Space Defense Squadron, "Spaceflight Safety Handbook For Satellite Operators, Version 1.7," 2024.

[12] D. Vallado, P. Crawford, R. Hujsak and T. S. Kelso, "Revisiting Spacetrack Report #3," in *AIAA/AAS Astrodynamics Specialist Conference and Exhibit*, 2006.

[13] J. R. Alarcón Rodríguez, F. Martínez Fadrique and H. Klinkrad, "Collision Risk Assessment with a `Smart Sieve' Method," in *Joint ESA-NASA Space-Flight Safety Conference*, 2002.