# Generic Orbit Determination Routine to Support Space Object Catalogue Maintenance

**J. Velasco(1), C. Fernández(1), A. Pastor(1), S. Hesselbach(2), J. Nicolai(2), M. Eickmans(2)**

(1) GMV GmbH, Zeppelinstraße 16, 82205 Gilching, Germany,
juan.velasco.mariscal@gmv.com, cfernandez@gmv.com, apastor@gmv.com
(2) DLR, German Space Situation Awareness Centre, Muehlenstraße 89, 47589 Uedem, Germany,
sebastian.hesselbach@dlr.de, jonathan.nicolai@dlr.de, marius.eickmans@dlr.de

## Abstract

The European Union Space Surveillance and Tracking (EU SST) provides essential services to European space operators and institutions to mitigate risks, through maintaining a catalogue of space objects. Within EU SST, Germany is responsible for data processing which also includes the maintenance of the object and orbital data catalogue. GMV is building a low-level astrodynamics library to support EUSST through German Space Situational Awareness Center (GSSAC), under Deutsche Zentrum für Luft- und Raumfahrt (DLR). The library, "Basisalgorithmen für SST Datenverarbeitung" (BaSSTDa; basic algorithms for SST data processing), provides a wide set of algorithms to be used for cataloguing purposes in Space Surveillance and Tracking (SST).

The Orbit Determination (OD) routine within the library is based on non-linear weighted least squares estimator, with the capability to estimate "any" given orbital, model, or spacecraft parameter including uncertainty information. Different forms of SST observations from radars, passive optical telescopes, Satellite Laser Ranging (SLR), Space Debris Laser Ranging (SDLR), and passive ranging stations are incorporated in a modular and fully scalable fashion.

The developed OD routine is incorporated within most of the other functionalities required within a cataloguing system. Within the scope of this paper, we present the added value of a generic OD within cataloguing activities. The same OD supporting processing of large volume of observational data in an automated fashion is presented while discussing the simulation results. Besides, it has been employed within maneuver detection and maneuver estimation routines. The flexibility this OD offers to estimate and refine maneuvers with ease and simplicity is discussed – supporting both Space Situational Awareness (SSA), Space Traffic Management (STM) and flight dynamics needs.

## 1 Introduction

The European Union (EU) has proposed a joint approach on Space Traffic Management (STM) for a safe, sustainable, and secure use of the space [1]. The current space debris population of objects greater than 10 cm is estimated to be around 36,500, which is the usual size threshold above which space surveillance networks can detect and track on a regular basis [2]. In the past few years, the proliferation of satellite constellations has increased the number of close approaches, threatening the sustainability of the space environment. SpaceX reported to have performed more than 25,000 maneuvers from December 2022 to May 2023, corresponding to collision events with probability greater than 1e-5 of the more than 4,200 operational Starlink satellites at that time [3].

Space Situational Awareness (SSA) is one of the essentials components of the EU Space Program, under the responsibility of the European Union Agency for the Space Programme (EUSPA) [4]. The three areas covered by EUSPA on SSA are Space Surveillance and Tracking (SST), Space Weather (SWE) monitoring, and Near-Earth Objects (NEO) monitoring [5]. The EU founded the European Union Space Surveillance and Tracking (EU SST) consortium in 2014, which has been extended to a partnership of up to 15 member states in 2022. Its general objective is the arrangement of a support framework which ensures the long-term availability of European and national space infrastructure, facilities, and services essential for safety and security, prevent the proliferation of space debris and preserve the orbital environment [6]. Germany, as part of the consortium has a key role in the provision of services as maintainer of the European database through German Space Situational Awareness Center (GSSAC). Such activity consists of receiving the data coming from the available sensors, processing it, and providing it to the different services: collision avoidance, reentry, and fragmentation analysis [7].

In this scenario, the space objects catalogue is conceived as the cornerstone of the space environment sustainability. 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. "Basisalgorithmen für SST Datenverarbeitung" (BaSSTDa; basic algorithms for SST data processing) is conceived as a library to provide all the tools required to meet those requirements.

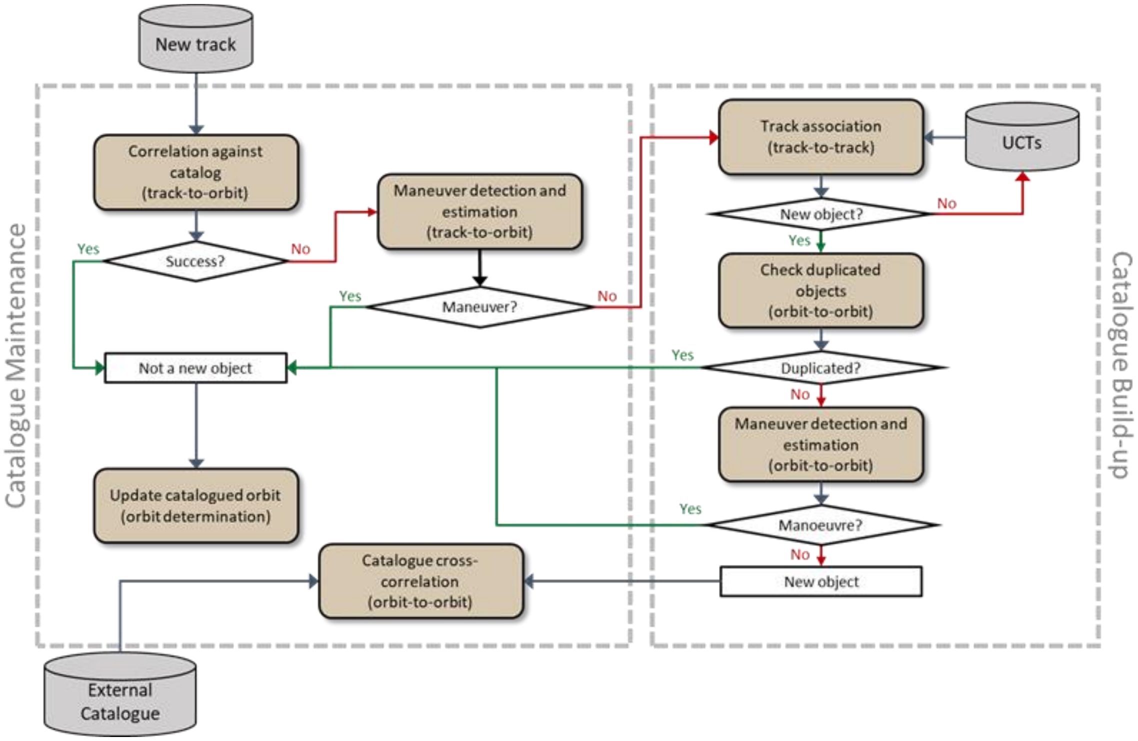

Fig. 1. Simplified sketch of a general cataloguing process.

Different strategies can be followed to build-up and maintain a space objects catalogue, but a simplified approach is depicted in Fig. 1. When a new track, i.e., batch of observations generated when a space object passes over a sensor, is received, this is correlated against the available catalogue. If the correlation is successful, the track is used for the update of the orbit of the corresponding object. Otherwise, it may belong to a maneuvering target or to a new object. Different algorithms are included in the catalogue build-up methodology. First, this new track is injected into the track association algorithm, which tries to set up groups of tracks belonging to the same object. It is possible that there are not enough tracks to confirm a new orbit in the system. Then, these are stored in an "uncorrelated tracks" (UCTs) database until a new object is detected. Once this happens, it is necessary to ensure that the new orbit does not correspond to an existing body that has been wrongfully labelled as new. To this end, orbits are correlated against the current catalogue and checked for duplicates. As a way of verifying the quality of the maintained catalogue, the cataloguing chain includes a correlation step against external catalogues.

As part of the GSSAC Mission System, the BaSSTDa library has already been successfully used in the test phase for catalogue operations since the end of 2022. With the start of the transition phase to an operational object and orbit data catalogue in 2024, DLR plans to deploy the latest version of the BaSSTDa as the main library for their cataloguing system. The system will also be finally used for the generation of the EU SST Catalogue, whose operational status is targeted for the 2nd quarter in 2024.

This paper is organized as follows. In Section 1, the context in which the BaSSTDa library was conceived is presented. In Section 2, the architecture of the library is introduced. In Section 3, the orbit determination component is detailed. In Section 4, several use cases of the orbit determination component to cataloguing techniques are reviewed. Finally, in Section 5, the conclusions and future work are discussed.

## 2 Library Architecture

BaSSTDa library is being developed in C++ following an object-oriented programming paradigm. The software design is driven by four principles: modularity, understood as writing simple parts connected with clear interfaces; composition, understood as developing components capable of connecting with other components; separation, to split data from algorithms using a clear data model; and performance, considering the heavy computational load of some processes from the onset. A diagram describing the included modules and how these are grouped and interact between each other is shown in Fig. 2.

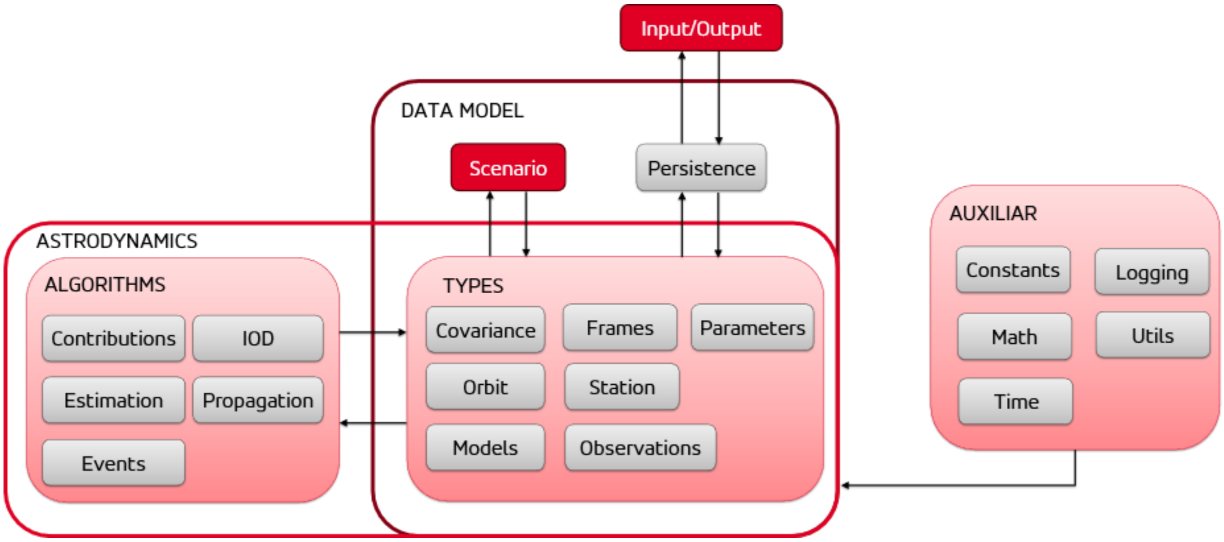

Fig. 2. Architecture of BaSSTDa library.

An independent data model has several benefits, including the possibility to develop a relational model on which different elements (e.g., satellites, orbits, measurements, or events) are related to each other either directly (e.g., pointers) or through simple mechanisms that implement efficient searches. Additionally, an independent data model keeps the data on multiple formats apart from in memory during execution, or a database, or a file, which can be exchanged through a network. Designing the software as a library interacting with the data model, enables the change and evolution of the algorithms without the need to modify the data model. The data model represents the core for information management, both inside the library and between software and user. It is also used as a database including all the information needed for running computations. The main content of this group is two modules: scenario and persistence. The scenario is a stand-alone component whose main purpose is to serve as a receptacle of all the data necessary for the calculation processes, as well as to store the results of the computations in an ordered and accessible manner. All the information that should persist is saved in a scenario instance and accessed during any astrodynamics process. Examples of input data include satellite and station properties, space weather data, geopotential coefficients, state vectors, and observations, among others. As a result of the different processes several products as ephemeris, state vectors and parameters are also loaded into the scenario, with the final purpose of being exported or persisted to take part in other processes. This class is filled and managed using the persistence module, which represents the Input/Output interface for external files reading and writing.

Astrodynamics features inside the library can be classified into two categories: types and algorithms. The first one comprises all the classes specific of astrodynamics applications such as orbits, frames, stations, models, covariance, or observations. All these models include not only the classes themselves, but also the methods used for their definition and their basic operations. All these types are used by the algorithms modules to compute all the astrodynamics operations covered by the library. The result of these are also instances of those astrodynamics types involved in the processes, which are loaded into the scenario.

In addition to the previous functionalities, auxiliary methods and classes are included to support the algorithms. This includes constants, time, math, logging and utils (generic module for routine tasks and common utilities). BaSSTDa also makes use of external libraries including several functionalities. Examples of this include Standards of Fundamental Astronomy (SOFA), Simplified General Perturbations (SGP), planetary ephemeris, or atmospheric models.

For each of the required processes of a general cataloguing chain, several modules and applications have been developed and included in the library for user usage. Tab. 1 present main BaSSTDa functionalities and how these relate to cataloguing chain steps.

Tab. 1. Catalogue build-up and maintenance needs and corresponding BaSSTDa functionality.

| **Catalogue need** | **BaSSTDa functionality** |
|---|---|
| Observation correlation | Orbit propagation<br>Observations simulation<br>Residuals computation<br>Track-to-orbit correlation |
| Catalogue cross-correlation | Ephemeris interpolation<br>Orbit fitting<br>Orbit comparison<br>Orbit-to-orbit correlation |
| Duplicated object management | Orbit-to-orbit self-correlation |
| Orbit update and maintenance | Orbit propagation<br>Orbit determination<br>Maneuver detection and estimation with observations<br>TLE fitting |
| Track association | Orbit Determination<br>Track-to-Track association |
| New object generation | Track-to-Track association<br>Maneuver detection and estimation with orbits<br>Orbit-to-Orbit self-correlation |

## 3 Orbit Determination Component

OD component is the core of the estimation module. BaSSTDa applies the concept of inheritance to establish a general abstract estimator class, from which all the usual estimation algorithms are derived. This way, generic estimation procedures can be reused or adapted in different flavors depending on the algorithm to be implemented. From them, the Weighted Least Squares (WLS) [8] is usually the common choice for parameter estimation in space surveillance operational environments. Although both WLS and sequential estimators [9] have been implemented in BaSSTDa, only the first one is detailed here.

First, the user defines a list of parameters to be estimated and defines their a-priori values and uncertainty. The variety of the parameters covered in the library ranges from the usual inertial position and velocity in an inertial frame, to dynamical parameters, sensor parameters, or TLE parameters [10]. Observations required by the estimator in BaSSTDa shall be present in the data model. BaSSTDa supports radar, optical, Satellite Laser Ranging (SLR), Passive Ranging (PR), and inertial position observations to perform orbit determination, the main observation types in SST. Furthermore, the modularity of the library allows to expand the available o*bservation* classes and adapt the library to the user requirements. The propagator provides the dynamical model connecting the estimated parameters and observations manifolds. Several propagators have been implemented in BaSSTDa: high-fidelity numerical integrator with most usual contributions (geopotential, third bodies, drag, solar radiation pressure, among others), two-body problem analytical and SGP4 [8]. In the same fashion, all propagators derive from a common abstract class, and in consequence, new propagators covering user needs can be implemented. The last input required by the WLS component is the observation simulator. This class simulates the observations and computes the partials of the observations, which are needed for parameter estimation. Several corrections are available: tropospheric and ionospheric corrections to angular and radar measurements, aberration, bias, flight time corrections and delays. As a result of this process, the predicted observations are obtained, with which the residuals needed for the estimation are computed via comparison with the actual observations.

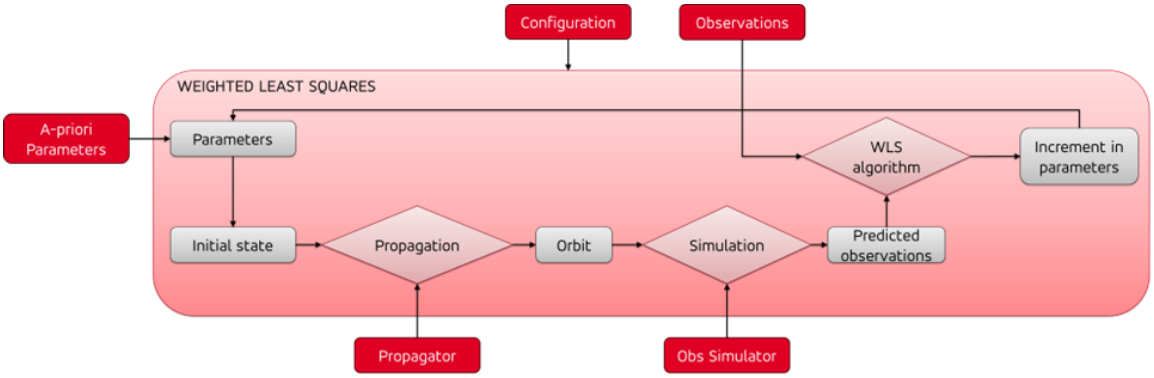

Fig. 3. WLS component data flow.

The iterative process starts using the configuration provided by the user. Starting from the a-priori parameters, an initial state vector is set. The latter is used to propagate an orbit to be fitted with the observations. Once the ephemeris for the desired interval is generated, it is used to simulate the observations at the epochs of the real ones. The required partial derivatives for the WLS algorithm are computed, along with residuals of the measurements. With all these inputs, the WLS component estimates the change in the parameter values leading to the minimization of the residuals. This process is repeated iteratively, linearizing the system on each iteration, until the convergence criteria is met.

Maximum value of the Weighted Root Mean Square (WRMS) and maximum change between iterations are the most relevant criterion. The system also accounts for the presence of outliers in the observations, rejecting them so the estimated state is not polluted by wrongly generated measurements. All the metrics, statistics and residuals computations are stored in the scenario, and are exportable for expert analysis.

## 4 Application to Cataloguing Techniques

The power of the WLS lies on its versatility:  the fitting and residuals minimization can be applied to different problems, just adapting the inputs with the available observations, dynamical model, and estimated parameters. This flexibility of the estimation component has allowed to establish the WLS algorithm as the key methodology of the cataloguing chain in GSSAC-Mission System. From diverse settings of the algorithms, several applications have been derived to meet the requirements of such system. A summary of the main functionalities and their configuration in terms of chosen propagator, observations and estimated parameters can is compiled in Tab. 2. In this section, some applications are detailed and selected use cases presented to showcase the cataloguing features.

Tab. 2. Applications of the WLS component.

| Application | Propagator | Observations | Estimated parameters |
|---|---|---|---|
| Orbit determination | Numerical | Radar and optical | Inertial position and velocity, and dynamic parameters |
| Orbit fitting | Numerical | Inertial positions | Inertial position and velocity |
| TLE fitting | SGP4 | Inertial positions | TLE parameters |
| Maneuver estimation | Numerical (linearized) | Radar and optical | Maneuver components |
| Maneuver refinement | Numerical | Radar and optical | Maneuver component and time corrections |
| Track-to-track association | Numerical + SGP4 | Radar and optical | Inertial position and velocity, and dynamic parameters |

### 4.1 Orbit and TLE fitting

BaSSTDa can ingest ephemerides provided by external sources to perform an orbit fitting. This consists in using the WLS component with the high-fidelity numerical propagator to estimate a full state vector at a certain epoch as parameters (e. g., inertial position and velocity, drag, and solar radiation pressure coefficients). The inertial positions in the ephemeris to be fitted are then considered as observations. As a result, BaSSTDa provides the estimated parameters through the data model. Several tests have been performed fitting the 18th Space Defense Squadron (SDS) Special Perturbations (SP) catalogue [11]. The fitting process can be successfully completed for most of the objects with residuals of the order of meters. This fitting method can also be applied to the generation of TLEs by using SGP4 and TLE parameters as estimated parameters, allowing the library to generate TLEs after a nominal OD process or as an alternative product to ephemerides from the numerical propagator.

## 4.2 Maneuver Detection, Estimation and Refinement

BaSSTDa implements a maneuver detection algorithm based on the identification of outliers in the residuals of incoming observations and a well-established pre-maneuver orbit. A divergence in the residuals, i.e., potential maneuver, is identified when the residuals surpass a certain threshold, and a time interval where it is suspected that the maneuver may have occurred is provided. To mitigate the number of false positives, the algorithm accounts for outliers and removes them from the analysis.

Once detected, the maneuver is estimated by using a linearization of the high-fidelity numerical propagator, i.e., use of the state transition matrix, to perform an estimation of the maneuver that best fits the observations at each epoch given on the identified time window. The goodness of the estimation is based on the delta-v of the estimated maneuver and the resulting WRMS. The solver includes a reliability check to avoid considering new maneuvers that are not properly estimated. The details of the methodology can be found in [12] and [13]. However, because of the limited number of observations and the assumptions on the dynamics, the accuracy of this initial estimation is limited. That is why BaSSTDa includes a method to refine a-priori maneuvers via WLS. To do so, corrections to the magnitudes of the three maneuver components and epoch are defined as estimable parameters, and the high-fidelity numerical propagator selected. As new observations are received, this refinement makes the estimated maneuver converge.

To illustrate this application, Fig. 4 represents the evolution of maneuver estimation and refinement for an out of plane simulated maneuver of a Low Earth Orbit (LEO) satellite, with properties similar to Sentinel 3A (Semi-major axis: 7180 km, eccentricity: 1.12e-4, inclination: 98 deg). The tracks were simulated assuming a radar sensor located in Spain mainland. The estimated maneuver converges to the reference values (black dashed lines) after three days of tracks from the maneuver epoch. The greater changes in the maneuver magnitude are found at the beginning of the refinement process, as the solution is far from the true maneuver.

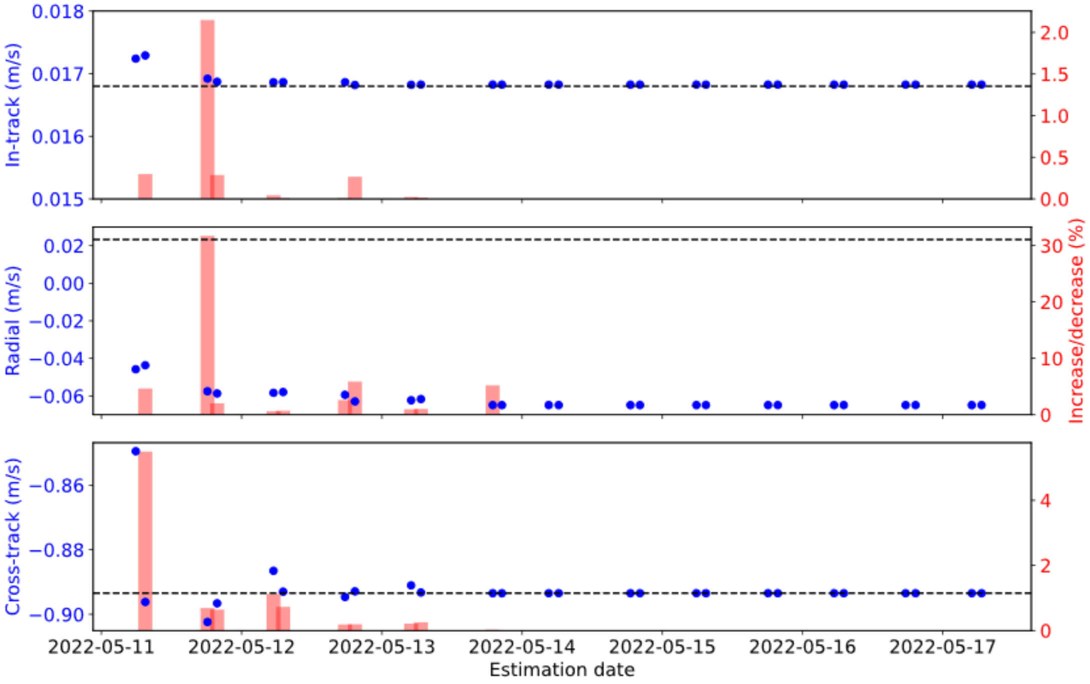

Fig. 4. Evolution of a refined estimated maneuver with successive OD processes.

### 4.3 Orbit Maintenance

BaSSTDa has been used to arrange a pipeline that automate the orbit maintenance process considering the received observations and potential maneuvers. For now, the orbit maintenance chain includes OD, maneuver detection, maneuver estimation and refinement. The strategy considers a continuous flow of pre-correlated observations from maintained objects already present in the catalogue. First, the maneuver detection algorithm is used to identify for potential maneuvers. If this is the case, then the maneuver estimation algorithm is triggered, and the resulting maneuver is included in the data model only if identified as reliable. Finally, WLS estimates not only the state vector and dynamical parameters, but also corrections to the maneuver epoch and components magnitude.

Fig. 5 shows a time series of the errors between the estimated state and the ground truth of a simulated test case, with and without (i.e., only OD) the strategy presented before. This test case uses the same object as in Section 0. The first benefit is the availability of state vectors soon after the maneuver. The time for recovery of the object is near to four days when not estimating the maneuver, while it is reduced to one day when it is considered. Enough post-maneuver observations are required to get a successful OD if the maneuver is ignored. In addition, the accuracy of the retrieved state vectors is higher when accounting for maneuvers. The time required to achieve an error in the order of meters when applying the strategy is around 3 days, while when disabled might reach 1 week. These results prove the goodness of the integration of maneuver detection, maneuver estimation and OD, and its suitability for preserving the quality and maximizing availability of the catalogue.

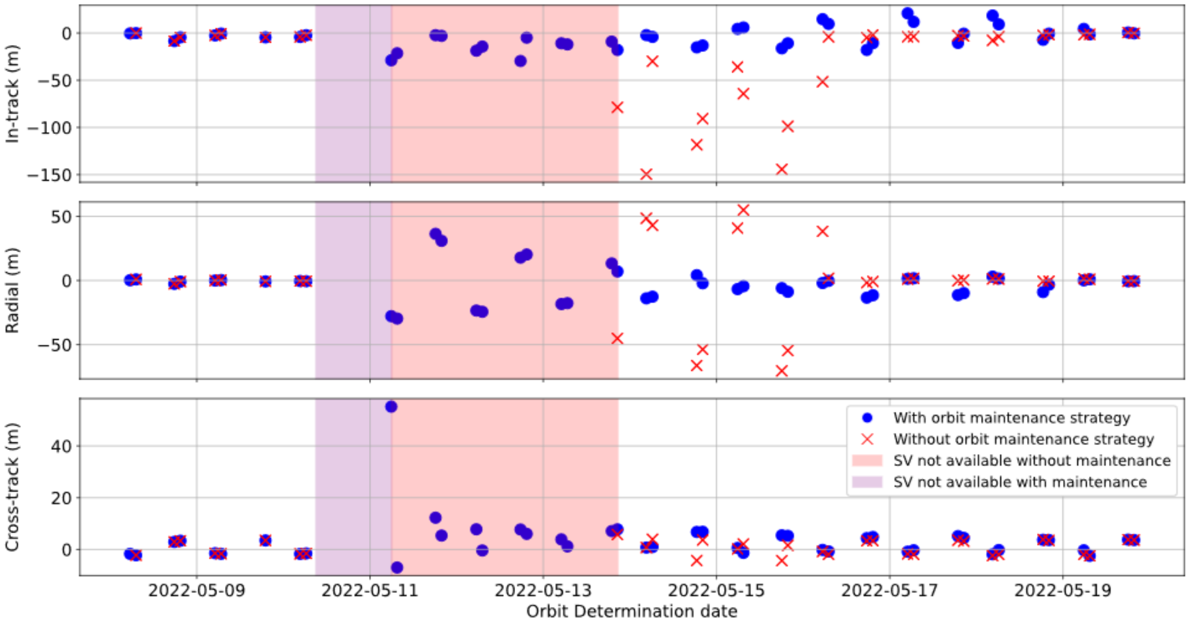

Fig. 5. Error of estimated state vectors with respect to reference orbit. Blue dots represent solutions with maneuver estimation. Red crosses represent solutions without maneuver estimation.

### 4.4 Track-To-Track Association

The previous strategy covered the catalogue maintenance activities. However, during catalogue build-up, the incoming tracks are uncorrelated, i.e., the object they belong to is unknown. To that end, BaSSTDa includes a track-to-track association algorithm that allows the system to group tracks belonging to the same object. The methodology exploits the versatility on the WLS component to compute multi-fidelity ODs between candidate tracks, with which the likelihood of an association of tracks, or hypothesis, is evaluated [14]. It begins relying on initial orbit determination methods that although not accurate enough to provide a well-established orbit, enables the use of complexity reduction techniques and gating processes to prune false hypotheses. First, some of the initial orbit determination method use low-fidelity analytical propagators because of their low computational cost, as well as SGP4 for medium-fidelity, and finally the high-fidelity numerical propagator, only for the final confirmation step. BaSSTDa architecture has enabled the use of the same component for all the OD processes involved, with minor configuration changes on each step, thus optimizing the performance of the track-to-track association.

## 5 Conclusions

This paper has presented BaSSTDa: a new astrodynamics library providing the basic algorithms for building-up and maintaining the future space objects catalogue of EU SST. Within this scope, a generic and versatile orbit determination component has been developed with the purpose of covering essential cataloguing chain needs. Its application on the fundamental cataloguing activities has been presented, as well as the flexibility of its configuration for the different strategies and processes.

The next steps focus on the continuous optimization of algorithm usage in the catalogue generation processes of the final system in an operational sense. Furthermore, investigations of an input-specific approach for the use of different algorithms are pushed. The objective is to achieve the most optimal processing of data from heterogeneous sensor networks, such as the EU SST Sensor Network, to allow the generation of products and services within the EU SST Framework in the same way. For this purpose, a continuous as well as holistic evaluation is also performed, which in combination with the modular framework of the BaSSTDa library allows a proactive and fast reactivity to e.g. new data sources as well as their processing in the future.

## 6 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 A. Bachlechner, C. Kronjaeger, D. Stelmecke, and D. Thesing from DLR for their constant and active support, as well as to the BaSSTDa development team and people from GMV boosting the project: D. Escobar- Antón, J. Fernández-Sánchez, I. Llamas de la Sierra, J. Berzosa-Molina, L. Bao, M. A. Muñoz de la Torre, R. Pastor-Muela, M. Fernández-Usón, S. Lara-Espinosa, M. Salas-Lasala, S. Setty, R. Ströbel, S. Metz, J. R. García-Espinosa, F. Gámez-Losada, B. Bija, K. Stock, F. Stechowsky, M. Callejón-Cantero, O. I. García-Lobo, and D. Skoulidou.

## 7 References

[1] High Representative of the Union Forforeign Affairs and Security Policy, "Joint Communication To The European Parliament And The Council," 2022.

[2] Space Debris Office, "Space Environment Statistics," ESA, 12 09 2023. [Online]. [Accessed 10 2023].

[3] D. Goldman, "SpaceX constellation status report," 2023.

[4] European Union Agency for the Space Programme, "EUSPA takes on the Space Surveillance and Tracking helpdesk as of 2023," 06 2022. [Online]. Available: https://www.euspa.europa.eu/newsroom/news/euspa-takes-space-surveillance-and-tracking-helpdesk-2023. [Accessed 10 2023].

[5] European Union Agency for the Space Programme, "Space Situational Awareness," 2023. [Online]. Available: https://www.euspa.europa.eu/european-space/space-situational-awareness. [Accessed 10 2023].

[6] P. Faucher, R. Peldszus and A. Gravier, "Operational space surveillance and tracking in Europe," *Journal of Space Safety Engineering,* 2020.

[7] 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.

[8] D. Vallado, P. Crawford, R. Hujsak and T. S. Kelso, "Revisiting spacetrack report #3: Rev 2," in *AIAA/AAS Astrodynamics Specialist Conference and Exhibit*, 2006.

[9] B. D. Tapley, "Orbit determination in the presence of unmodeled accelerations," 1975.

[10] D. Oltrogge and J. Ramrath, "Parametric characterization of SGP4 theory and TLE positional accuracy," in *Advanced Maui Optical and Space Surveillance Technologies Conference*, 2014.

[11] 18th Space Control Squadron, *Space-Track,* 2020.

[12] A. Pastor, G. Escribano, M. Sanjurjo-Rivo and D. Escobar, "Satellite maneuver detection with optical survey observations," *The Journal of the Astronautical Sciences,* 2022.

[13] L. Porcelli, A. Pastor, A. Cano, G. Escribano, M. Sanjurjo-Rivo, D. Escobar and P. D. Lizia, "Satellite maneuver detection and estimation with radar survey observations," *Acta Astronautica,* August 2022.

[14] A. Pastor, M. Sanjurjo-Rivo and D. Escobar, "Track-to-track association methodology for operational surveillance scenarios with radar observations," *CEAS Space Journal,* 2022.