Catalog maintenance with non-cooperative maneuvering space objects

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Abstract

This paper presents the capabilities BaSSTDa, a low-level astrodynamics library used by the European Union Space Surveillance and Tracking (EU SST), for effectively cataloging non-cooperative space objects. The library's methodologies for maneuver detection and estimation are outlined, illustrating their impact on catalog accuracy through a Sentinel-3B case study with actual maneuver data. The study emphasizes the vital role of including maneuvers in operational catalog maintenance to ensure precise, reliable and timely tracking of space objects.

1 Introduction

In the current era of space exploration and utilization, the increasing congestion in Earth's orbit presents significant challenges for Space Situational Awareness (SSA) and operational safety. The estimated trackable population of space debris, comprising objects larger than 10 cm, currently stands at approximately 36,500 [1]. The European Union Space Surveillance and Tracking (EU SST) initiative is at the forefront of efforts to mitigate these risks, providing critical services such as collision avoidance alerts, fragmentation and reentry analyses to European space operators and institutions [3]. At the heart of these efforts is the imperative to maintain an accurate and up-to-date catalog of space objects. This task is made increasingly complex by the presence of non-cooperative space objects that undergo maneuvers without prior notification, thereby complicating the catalog maintenance process. The partnership within EU SST, involving 15 countries with Germany responsible for the processing of measurement data, as well as the build-up and maintenance of the space object catalog, underscores the collaborative approach to this challenge. The "Basisalgorithmen für SST-Datenverarbeitung" (BaSSTDa; basic algorithms for SST data processing) library, developed by GMV for the German Space Situational Awareness Center (GSSAC) of the German Space Agency within the German Aerospace Center (DLR), represents a significant advancement in addressing these challenges [7].

The operational maintenance of a space object catalog in the presence of non-cooperative maneuvering objects poses a significant challenge for robust and automated operations. The primary aim is not merely the characterization of the maneuver, i.e., the estimation of its parameters, but the achievement of successful and reliable orbit determination for all cataloged objects, including those that have executed maneuvers. This goal is vital for ensuring the operational integrity of the catalog and the safety of space operations. Besides the enhancement of orbit determination timeliness and accuracy, incorporating maneuvers improves collision risk assessments by providing reliable data on the post-maneuver trajectories of space objects, enabling more precise predictions of potential conjunctions. Moreover, the likelihood of false positives in object identification can be reduced, thereby streamlining the tracking process and enhancing the overall management of space traffic.

To address this challenge, we present a comprehensive methodology, implemented with the BaSSTDa library, that spans the whole processing chain from reception of observations, over maneuver detection and estimation to orbit determination. This method emphasizes simplicity and resource efficiency, allowing for seamless integration into operational catalog maintenance systems without imposing significant computational demands.

This paper leverages simulated observations for a case study based on real maneuvers of a Sentinel satellite, obtained from publicly available maneuver plans. This approach validates the effectiveness of the proposed method in a controlled environment and also underscores its applicability to real-world SSA operations. This case study is not just illustrating the theoretical capabilities of BaSSTDa but, more crucially, its suitability when applied to real-life scenarios mirrored through high-fidelity simulation. This study contributes to the broader discourse on enhancing space safety and sustainability, showcasing how advanced algorithms and collaborative efforts can mitigate the challenges posed by non-cooperative space objects in an increasingly crowded orbital environment.

This paper is structured in four different sections: Section 1 introduces the challenges of maintaining a catalog with maneuvering objects and outlines the motivation behind this research. Section 2 provides an overview of the methodologies for maneuver detection and estimation in the context of catalog maintenance. Section 3 details the setup and findings from the Sentinel case study that was carried out. Finally, Section 4 summarizes the key insights and conclusions derived from the study.

2 Methodology

In this section, a brief overview of the BaSSTDa library is presented, highlighting its primary features and processes. Following this introduction, a more detailed description of the maneuver detection and estimation methodology is provided.

2.1 Cataloging chain

The BaSSTDa library provides a framework entailing all components required for the maintenance of a space objects catalog. The library, developed in C++ and designed with an object-oriented approach, emphasizes modularity and performance to manage the computational demands of catalog maintenance processes. The BaSSTDa library provides the tools needed to perform the orbit maintenance process in a robust and automated way. This process encompasses all processing steps from observation ingestion, detection, estimation and refinement of maneuvers, orbit determinations to the final update of the catalog. Each of the key steps of the methodology are briefly summarized below. For a more detailed overview of BaSSTDa's architecture and its capabilities refer to [7].

1. *Observation acquisition*: the process begins with acquiring observations of space objects, which are collected using various types of sensors, such as radars and optical telescopes. These observations are provided as tracks, where each track is expected to contain observations originated from the same object collected by a single sensor.

2. *Track processing and correlation*: each new track received by the system is correlated against existing objects in the catalog. This involves a track-to-orbit correlation algorithm, which attempts to match the new observations with the predicted positions of cataloged objects. The goal here is to identify whether the observed track belongs to a known object or if it indicates the presence of a potentially new object.

3. *Maneuver detection*: a critical part of maintaining the catalog involves detecting maneuvers conducted by operational satellites, especially those that are non-cooperative, i.e., those which do not disclose any maneuver information. The BaSSTDa library employs a maneuver detection algorithm that analyzes the residuals between actual observations and those inferred from the predicted positions.

4. *Maneuver estimation*: once a maneuver is detected, the library engages in an estimation process to determine the parameters of the maneuver, such as its magnitude and direction as well as the time at which the maneuver was conducted. This is achieved by fitting the post-maneuver observations to the object's pre-maneuver orbit, using an iterative process to refine these estimates until they align closely to the observed data.

5. *Confirmation step*: to improve computational efficiency, the initial maneuver estimation of the previous step is done by utilizing a linear propagator. Due to potential loss of accuracy caused by this linearization, the maneuver parameters are now refined by re-estimating them using a high fidelity numerical propagator during the non-linear Weighted-Least-Squares (WLS).

6. *Orbit determination*: once the maneuver parameters are estimated, BaSSTDa proceeds to update the orbit of the maneuvering object.

This involves incorporating the estimated and refined maneuver into the object's state vector to refine and propagate its orbit. By considering maneuvers in the orbit update process, the orbit determination framework is able to utilize both pre-maneuver and post-maneuver observations to refine state vector estimates.

7. *Catalog update*: finally, the space object catalog is updated with the new orbit information for the maneuvering object.

Each time new observations are received by the system, the outlined procedure is reapplied. This update process ensures that the catalog reflects the most recent and accurate information on the positions and velocities of all tracked objects, maintaining the integrity and reliability of the space surveillance system.

2.2 Maneuver detection

The maneuver detection algorithm within the BaSSTDa library identifies maneuvers of space objects by analyzing discrepancies between predicted and observed tracks. Initially, observational data is collected and pre-processed, to filter out noise and correct systematic biases, ensuring the integrity of the input data. The core of the maneuver detection process involves comparing these refined observations against the predicted positions of space objects, derived from their known orbits, to calculate residuals. The reference orbit used here is usually obtained from available Two-Line Element (TLE) data or a successful instance of a previous orbit determination. However, it must be noted that the orbit is of major importance for the detection process. Utilizing an outdated orbit can result in high residuals with respect to the available observations, potentially leading to incorrect maneuver detections. Conversely, overly recent state vectors risk incorporating the effects of maneuvers into the estimated states prematurely, before their detection. To find a reasonable balance, the current strategy adopts the nearest state vector at the 75% mark of the Orbit Determination (OD) interval, optimizing the timeliness and accuracy of the maneuver detection process.

The diagram shown in Figure 1 outlines the procedure for maneuver detection in more detail. However, this paper primarily concentrates on high-level processes, specifically strategies for managing uncooperative maneuvering objects, and therefore does not delve into the details of the algorithms. For a more comprehensive examination of these algorithms, please refer to [5]. As mentioned before, the residuals, representing the differences between observed and expected positions, are the key to identifying deviations that could indicate maneuvers. The Weighted Root Mean Square (WRMS) can be determined as,

$$WRMS_i = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(\frac{\rho_{i,n}}{\sigma_i}\right)^2}, \tag{1}$$

where N refers to the number of observations, σ_i to the standard deviation of the expected sensor noise of the measurement type i and $\rho_{i,n}$ to the residual between actual and predicted measurement.

To ensure comparability, tracks are then grouped according to their sensor and measurement type. This classification is crucial as maneuvers may affect various types of observations in distinct manners, requiring a tailored approach to analysis.

Outlier rejection of the resulting groups is the next critical step of the maneuver detection process. The algorithm incorporates statistical methods to identify and discard outliers in the observational data, which could skew the analysis and lead to erroneous maneuver detection. This outlier rejection mechanism ensures that the maneuver detection is based on reliable data, reducing the risk of false detections. One of the methods to detect and discard outliers is by examining the statistical dispersion by using the interquartile range, as well as comparing the median WRMS of a series of tracks with predefined thresholds.

After rejecting outliers additional requirements must be fulfilled to trigger the maneuver detection for a group of tracks k. These requirements ensure that the available observations are of sufficient quantity and accuracy and are:

- Exceed minimum number of tracks.
- $\rho_{thres,1}$ must be larger than the median of the residuals.
- Do not exceed maximum percentage of outliers.

Once observations are pre-processed and the requirements are fulfilled, each of the remaining tracks' WRMS behavior is analyzed over time.

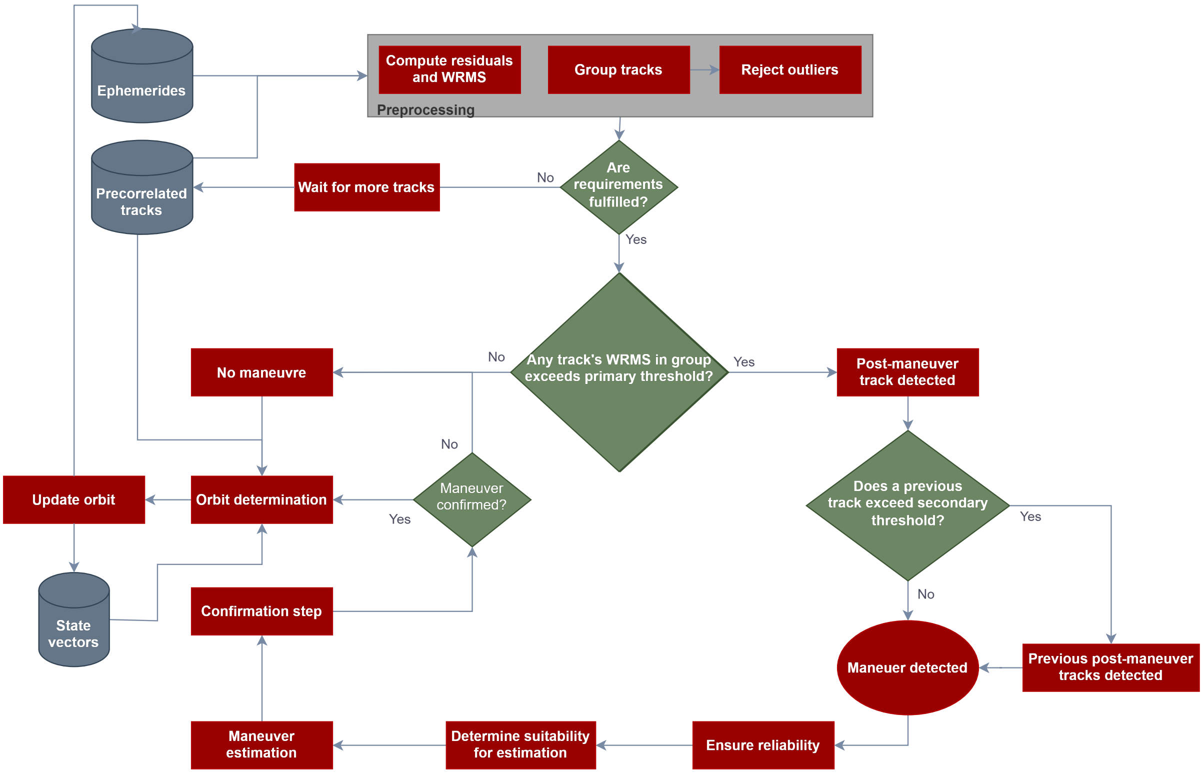

Figure 1: Complete orbit maintenance process.

This temporal analysis plays a crucial role in this detection framework. By examining the pattern of residuals over time, the algorithm can identify sustained deviations from predicted trajectories, indicative of maneuvers, as opposed to transient spikes often attributed to outliers. This temporal approach allows for a more nuanced detection of maneuvers, acknowledging uncertainties in both measurement and dynamic models.

To identify such deviations, the algorithm employs predefined thresholds in the residual analysis. A primary threshold is set based on historical data and expected sensor accuracy, serving as a benchmark for flagging significant deviations as potential maneuvers. Once the primary threshold is surpassed, indicating a significant deviation consistent with a maneuver, the secondary threshold is used to hone in on the precise timing of the maneuver, enhancing the accuracy of the detection. Figure 2 exemplary illustrates both of these thresholds, where the primary threshold is set to $\rho_{thres,1} = 5$ and the secondary one to $\rho_{thres,2} = 2.5$. As can be seen, shortly after the maneuver takes place, the primary threshold is exceeded, which in turn triggers the search for post maneuver tracks within previous tracks. Once a track k falls below $\rho_{thres,2}$ the backwards search is interrupted and the end time of this track is used as the start time for the maneuver detection interval. The end of the detection interval is set to the start time of the following track $k+1$. However, if k ends after the start of $k+1$, the backwards search continues to prevent overlapping and ensure a sufficiently large detection interval.

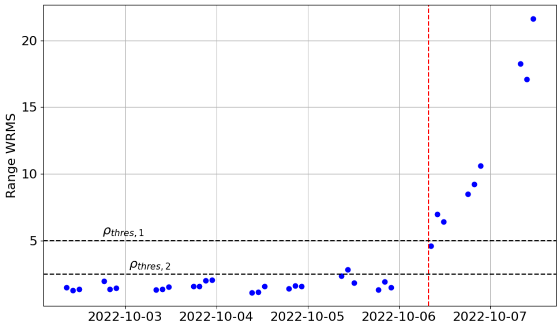

Figure 2: Weighted residuals pre- and post-maneuver. Each point corresponds to the WRMS of a single track for the range measurement component. The maneuver epoch is marked by a vertical dashed red line.

Acknowledging that not all deviations are indicative of maneuvers, further checks are added designed to distinguish actual maneuvers from minor anomalies, which might otherwise lead to false positives. This added layer of verification ensures that only those deviations which pass these tests are classified as reliable maneuver detections:

- Less than a predefined percentage of the post-maneuver tracks are below all secondary thresholds.
- Exceed the minimum number of post-maneuver tracks.

Upon successfully identifying a maneuver, the algorithm triggers a sequence of actions to integrate this maneuver information into the maneuver estimation process. However, even though all criteria for reliably detecting a maneuver might be satisfied, the available observations may still fall short for precise maneuver estimation. Consequently, the following thresholds must be exceeded to assess the suitability of the observations for maneuver estimation:

- Minimum length of the post-maneuver tracks duration.
- Minimum number of measurements in the post-maneuver tracks.
- Minimum number of tracks after the time interval.

2.3 Maneuver estimation

The maneuver estimation algorithm within the BaSSTDa library is a component that follows the detection of a maneuver. Its primary function is to estimate the parameters of the maneuver, such as the change in velocity Δv and the time at which the maneuver occurred t_m, using the available observational data. The modeled maneuvers are assumed to be impulsive, i.e., the Δv is applied instantaneously. The algorithm starts by generating hypotheses for the maneuver based on post-maneuver observations. These hypotheses include different possible times and magnitudes for the maneuver. For each hypothesis, the algorithm defines a set of parameters to be estimated. These typically include the magnitude, direction, and epoch of the maneuver. Using the pre-maneuver orbit as a reference for linearization, the algorithm attempts to fit the post-maneuver observations to the orbit. This is done by adjusting the parameters of the maneuver using WLS until the residuals between the predicted post-maneuver positions, derived from the adjusted orbit, and the actual observations are minimized [5].

During this iterative process multiple hypotheses are evaluated, where the WRMS acts as a benchmark, allowing the algorithm to eliminate those hypotheses that yield a WRMS above a certain threshold, indicating a poor fit. The remaining hypotheses are then ranked based on their WRMS scores. Once the ranking is complete, the algorithm selects the top hypothesis, the one with the lowest WRMS, as the most likely representation of the maneuver. However, additional criteria may be employed to further discern the most plausible maneuver scenario, for instance whether the estimated Δv has a distinct minimum and is of reasonable magnitude. For a more exhaustive description of the maneuver estimation algorithm, refer to [4].

As mentioned before, the initial estimation of the maneuver parameters is then re-estimated by incorporating a high fidelity numerical propagator. This refinement during the *confirmation step* prevents a potential loss of accuracy due to linearization in the initial estimation. The estimated and refined maneuver is used to adjust the space object's state vector. Here, the Δv from the estimated maneuver is applied to the velocity components of the object's pre-maneuver state vector at the estimated time of the maneuver, resulting in a new post-maneuver state. The updated orbit may also serve as a feedback mechanism. If subsequent observations suggest discrepancies, the system can loop back to adjust the maneuver parameters or re-evaluate the orbit determination, ensuring continuous refinement and accuracy. Finally, after converging the updated state is then used to conduct an orbit determination to estimate the full state of the object's state and update the catalog with the newly determined orbit.

3 Sentinel-3B case study

To assess the performance of the BaSSTDa library and underscore the significance of integrating maneuver detection in catalog maintenance, a case study was conducted focusing on the Sentinel-3B satellite. This satellite was selected for its active status and the availability of real maneuver data, providing an opportunity to observe the impact of maneuver handling on the fidelity of the satellite catalog.

The Sentinel-3B maneuvers considered in this study are based on actual maneuvers, accessible from [2]. The selected maneuver for this case study

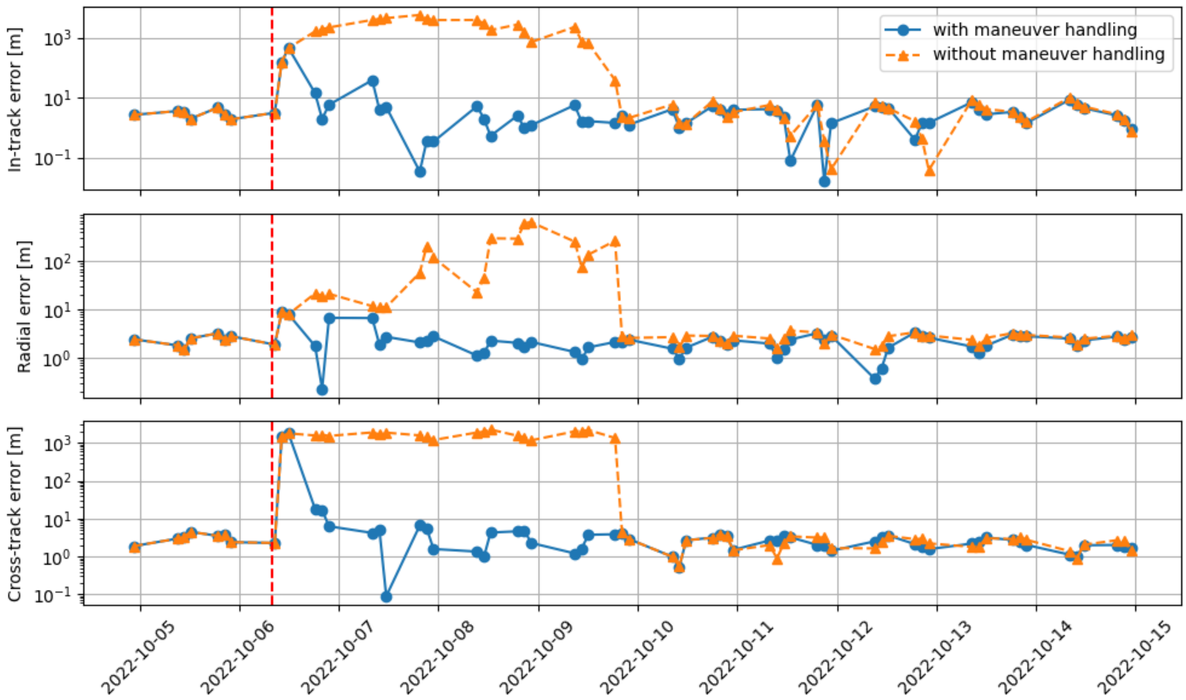

Figure 3: Position errors of estimated states in all axes of local frame, over a series of orbit determination epochs, for both cases: with and without maneuver detection and estimation. The maneuver epoch is marked by a vertical red line.

was conducted on the 6^{th} of October 2022, with $\Delta v \approx (-0.0015, 0.016, 2.10507)\frac{m}{s}$, defined in the QSW frame (radial, along-track, and cross-track directions), which corresponds to a maneuver in predominantly cross-track direction.

Radar observations were simulated to mirror realistic satellite tracking conditions. The radar system used for this case is located in Darmstadt and the observations have been simulated with a zero mean Gaussian noise of 400 mdeg, 13 m, and 550 mm/s for the angles (azimuth and elevation), range, and range-rate, respectively, typical values found for state of the art radars [6]. The conditions for the simulation were chosen to emulate real-world scenarios as closely as possible, including measurement noise, actual visibilities (minimum elevation constraint) between radar and target as well as observation frequency (one every 10 s).

An interval of 10 days was selected for simulation, providing a comprehensive data set that captures the satellite's behavior before, during, and after the execution of a maneuver. These simulated observations were then processed through the catalog maintenance chain. It must be noted, that the process encompasses every step described in 2 and shown in Figure 1 of the cataloging chain, with the exception of track-to-orbit association, as the simulated tracks are assumed to be pre-correlated. This means that the incoming tracks are known to be originated from the specific target, without conducting an additional correlation process.

To distinctly showcase the benefits of maneuver consideration, two separate cases were computed: one with maneuver handling enabled, where the system detects and estimates the maneuvers, and one without maneuver handling, where the system processes the observations without accounting for any maneuvers.

Figure 3 is divided into three panels, each corresponding to a different component of the satellite's orbital error: in-track, radial, and cross-track. Each marker in the plots corresponds to an orbit determination epoch, aligned with the reception of a new track by the system. The state estimates from these epochs are compared against the true reference orbit to determine the accuracy for both cases.

For the simulation with maneuver detection and estimation, depicted in blue, the results demonstrate a rapid recovery of the satellite's orbit following the maneuver, evidenced by the swift decrease of error values across all three components. Within less than 12 hours post-maneuver, the errors are minimized, indicating that the orbit has been successfully recovered and closely aligns with the true orbit.

Conversely, the simulation without maneuver detection and estimation, shown in orange, reveals a very different scenario. Post-maneuver, the errors in all components surge, reflecting the system's loss of track of the satellite. The errors persist at elevated levels, signifying that the object's orbit cannot be accurately determined from the available observations alone. It is only after more than three days, with the assistance of available TLE data and orbit fitting techniques, that the object is re-initialized and brought back into the catalog. This recovery, however, occurs with considerable delay and highlights the risk of losing track of the satellite without maneuver consideration.

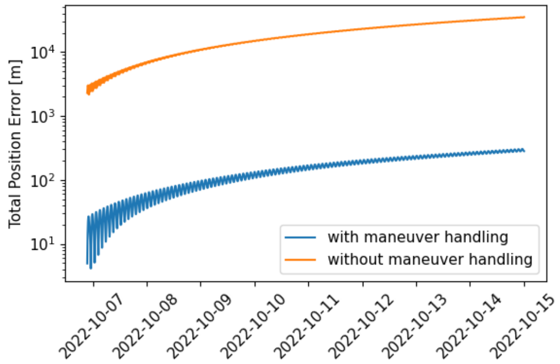

Figure 4: Propagation of two distinct state estimates from approximately 12h post maneuver for both cases: with and without maneuver detection and estimation. Total position errors of the propagations with respect to the ground truth.

The impact of neglecting maneuver handling become particularly evident when the post-maneuver state is used for subsequent orbit propagation. The errors depicted in Figure 4 are the deviations between the propagated estimate of the satellite's state approximately 12 hours after a maneuver and its true orbit. The graph illustrates a severe contrast in total position error between the cases with and without maneuver detection and estimation. In the case with maneuver estimation and detection, shown in blue, the error remains relatively low since the first preliminary maneuver estimation is included in the propagated state vector, indicating a successful adjustment and more reliable orbit tracking. On the other hand, the case without maneuver detection and estimation, represented in orange, exhibits errors several orders of magnitude higher, illustrating that the failure to account for maneuvers leads to a rapidly increasing divergence from the true orbit. This large error results in the orbit being unsuitable for catalog maintenance, rendering the object virtually not trackable for more than three days until the orbit can be reinitialized.

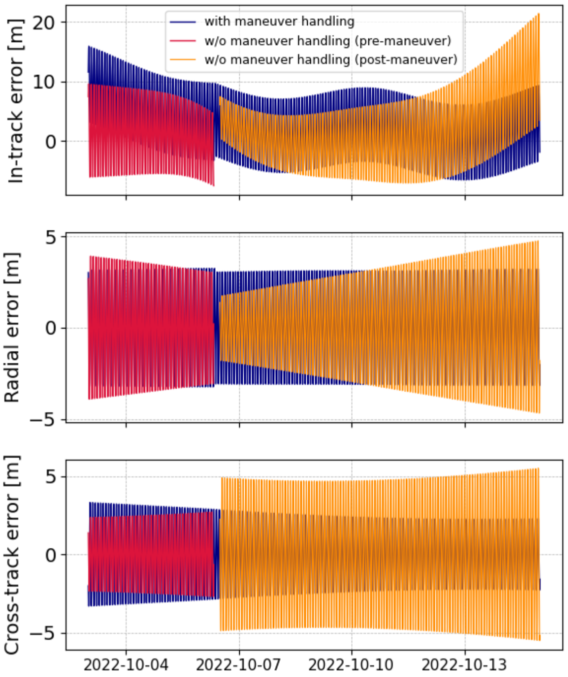

Figure 5: Propagation of state estimates. In blue, propagation of single state vector accounting for maneuvers. In red and orange, propagation of pre-maneuver and post-maneuver states respectively (without maneuver detection and estimation).

Similarly, Figure 5 depicts the outcomes following the propagation for both scenarios: with and without maneuver detection and estimation. The blue lines indicate the deviations when a single state vector, which accounts for the estimated maneuver, is propagated backwards over a 12-day interval. This demonstrates a stable and accurate propagation, seamlessly reconstructing the orbit while ensuring the continuity of the orbital path throughout the maneuver.

Whereas for the cases without maneuver handling, the red lines show the backwards propagation of the last estimated state before the maneuver took place. The orange lines represent the propagation of the first initialized state after the maneuver, which requires more than three days after the maneuver to be obtained. This post-maneuver state is propagated backwards to shortly after the maneuver and forward. Besides the three day interval where no usable orbit data is accessible, this case illustrates the discontinuity between the backward and forward propagation and the consistent increase in deviations as time progresses. This case study underscores how the incorporation of maneuvers into the catalog maintenance workflow enhances the accuracy of orbit predictions and ensures the integrity and reliability of the space object catalog.

4 Conclusions

Within the scope of this paper, BaSSTDa's methodologies for catalog maintenance and build-up were outlined with a particular focus on maneuver handling of uncooperative objects. The presented maneuver detection algorithm of the BaSSTDa library represents a comprehensive and detailed approach to identifying space object maneuvers, incorporating data processing, dual-threshold analysis, temporal pattern recognition, and outlier rejection. This approach ensures that maneuvers are accurately detected and integrated into the orbit determination procedure. The case study based on a Sentinel satellite is showing the BaSSTDa library's robust capability for maneuver detection and estimation as a vital component in maintaining an accurate and reliable space object catalog. The contrast between the two scenarios, considering and disregarding maneuvers, highlights the indispensable role of accurate maneuver accounting in sustaining the utility and safety of space situational awareness frameworks.

The development team is currently working on the track-to-orbit correlation process to address the problem arising from the ingestion of uncorrelated tracks after maneuvers. The ongoing research is exploring the use of this present work on a multi hypothesis framework considering maneuvring targets.

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