MANOEUVRE DETECTION AND ESTIMATION BASED ON SENSOR AND ORBITAL DATA

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ABSTRACT

This paper presents two methodologies for manoeuvre detection and estimation of Resident Space Objects (RSOs). The first, based on orbital data, represents the natural evolution of previous works with Two Line Elements (TLEs) catalogue and has been applied to the Special Perturbations (SP) catalogue. The second, uses optical observations to detect and estimate manoeuvres using a low number of observations, a track-to-orbit for single burn manoeuvres and an orbit-to-orbit one for multiple burns. Results include manoeuvre detection between subsequent catalogue issues and determination of typical manoeuvre frequencies with the orbital data methodology. Besides, real observations from the Spanish Space Surveillance Sensor Network (S3TSN) have been used to study the performance under typical operational environments.

Keywords: manoeuvre detection; manoeuvre estimation; track association; track correlation; pattern of life.

1. INTRODUCTION

The increasing number of Resident Space Objects (RSOs) and the congestion of the orbital debris environment makes satellite operation activities more challenging year after year. There are more than 500 operational satellites only in Geostationary Earth Orbit (GEO), most of which perform manoeuvres every one or two weeks. Meanwhile, satellite mega-constellations, with manoeuvring capabilities, are gaining momentum in low altitude orbits. These orbit control manoeuvres have an impact on the provision of Collision Avoidance (CA) services. First, manoeuvres are a source of false negatives and false positives collision warnings in case those are not taken into account. Second, manoeuvres are also used to lower the risk of potential collision events. And third, manoeuvres are also used for orbit control as part of the station-keeping, but can also be modified for collision avoidance purposes. Hence, detecting those manoeuvres and characterising their frequency is crucial for Space Situational Awareness (SSA) service provision. Besides, for the robust and reliable provision of CA services, a challenging trade-off between detection time and manoeuvre characterisation accuracy should be performed. The main problem associated with the execution of manoeuvres by satellites for Space Surveillance and Tracking (SST) systems is the difficulty in correlating the observations. In the case of surveillance sensors, the correlation is made by comparing the actual measurements with the synthetic measurements generated from the predicted orbits. Unless the predicted orbits contain the information of the manoeuvre plan (provided directly by the satellite operators), correlations will fail. Even for tracking sensors this can pose a problem, since it is possible that the object is not located where expected, and is not observed. Moreover, if it is observed, it may not be known to which object the observations really correspond, in case there are several satellites in the sensor's field of view. If one does know which object they correspond to, it is necessary to detect the manoeuvre, otherwise the orbit determination will fail.

Manoeuvre detection of a satellite using Two Line Elements (TLEs) has been studied for several years and various approaches have been successfully proposed so far. One of such approaches is based on a trial and error method, aimed at finding anomalous differences in the subsequent observation of the orbital elements. To do so, a threshold filter is set for a first-order polynomial with a window length between the successive data points of a satellite's TLE data [1]. This work claims a 95% detection rate of all the manoeuvres down to change in velocity at magnitudes less than 1 cm/s and that is why it was selected as the starting point of our methodology based on orbital data. The methodology consists in detecting significant changes in the orbital parameters by evaluating the difference between the orbital parameters of consecutive TLEs propagated with the Simplified General Perturbations (SGP) theory to the same epoch. The orbital differences are filtered before and after the time at which differences are to be computed. On the one hand, the so-called trailing filter consist in an offset that is used for mitigating the noise of the states before the manoeuvre. On the other hand, the leading filter is a

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linear function that fits the states after the manoeuvre. Finally, the orbital elements difference is evaluated by comparing the value extrapolated from the leading and the trailing filters.

The High Accuracy Catalog (HAC), also known as Special Perturbations (SP) catalogue [2] is built-up and maintained by the 18th Space Control Squadron (SPCS) [2] with the sensing data of the United States Space Surveillance Network (SSN) and contains the ephemerides of every catalogued RSO. Compared to TLEs [3], these ephemerides provide an enhanced precision and are updated or propagated on a daily basis. In fact, TLEs are nowadays the outcome of a fitting process performed on the SP catalogue ephemerides [4] and therefore, the use of the SP catalogued is preferred. However, the SP catalogue ephemerides only contain position and velocity information, being then not possible to directly perform further propagation nor data gaps fillings. To overcome these limitations, the ephemerides are first processed with an orbital fitting to ensure dynamical model matching between the SP catalogue and in-house propagation. Regarding satellite manoeuvres, it is important to note that SP catalogue published ephemerides are continuous and internal analyses have shown us that they are propagated without considering manoeuvres. There is no overlapping between consecutive issues of the orbits and as a consequence, it is not possible to directly infer manoeuvres by locating intercepting trajectories.

In this paper, we tackle the GEO satellites manoeuvres detection. Two novel methodologies for the detection of manoeuvres are applied, one based on orbital information from SP catalogue, and another [5] based on optical observations.

This paper is organised as follows. In Section 1, we review the rationale behind this work and present the problem. In Section 2, we briefly describe the two manoeuvre detection and estimation methodologies. In Section 3, we present and discuss results of the analyses performed with the two methodologies. Finally, in Section 4, we highlight the conclusions of this paper and envision the guidelines for analyses and research to be followed in the near future.

2. METHODOLOGIES

This section presents the two methodologies proposed for the manoeuvres detection and estimation based on orbital and sensor data. The main focus of the first is to detect manoeuvres using only ephemerides from a catalogue of RSOs to distinguish manoeuvrable (active payloads) from non-manoeuvrable objects and assess the most typical manoeuvre frequencies. Regarding the second, the main objective is to detect and estimate single burn and multiple burns manoeuvres using pre-manoeuvre orbits and optical observations.

2.1. Methodology based on orbital data

This methodology is based on an orbital comparison of ephemerides from subsequent catalogue issues. The approach is similar to [1], although it does not require access to the dynamical model used to generate the ephemerides. Accordingly, it is not limited to ephemerides from SP catalogue but suitable for any catalogue or orbits source that provides ephemerides periodically. For this purpose, the Root Mean Square (RMS) of the position differences between each pair of ephemerides in the local TNW frame (along-track, normal and cross-track) is used as manoeuvre detection metric, defined as:

$$RMS_k^2 = \frac{1}{N}\sum_{i=1}^{i=N}(x_{2,k,i} - x_{1,k,i})^2 \tag{1}$$

being $x_{j,k,i}$ the kth component of the position from the jth ephemerides at the ith common epoch and N the total number of considered common epochs to perform the comparison. A relative threshold value of 3 times the mean of the RMS series was found to be a good compromise to detect the actual manoeuvres discarding outliers. Moreover, to avoid false manoeuvre detections when dealing with non-active RSOs, an absolute threshold of 1.5 km is set for the in-track and cross-track RMS for East-West (EW) and North-South (NS) burns, respectively, to account for model mismatch and outliers. Besides, by analysing the orbital differences of the components between consecutive orbits, it is possible to distinguish between EW (in-plane) and NS (out-of-plane) manoeuvres, allowing their individual detection if a sufficient number of days have passed between them, as will be further discussed.

A manoeuvre consists in a sudden change in velocity that propagates through time and deviates the position from a nominal ballistic trajectory. In other words, a noticeable increase on the RMS is expected when comparing two ephemerides estimated only with observations before and after the manoeuvre. The existence of this footprint of the manoeuvre on the RMS is the cornerstone of the methodology. Therefore, by comparing ephemerides from certain catalogue issue, hereinafter referred to as orbit, with the subsequent one on the available overlapping time span, it is possible to detect the existence of a manoeuvre by setting proper criterion on the RMS.

If we assume that only well-established orbits are included in the catalogue, the post-manoeuvre orbit would not be available until enough observations are received by the sensor network to perform the estimation of the orbit. The duration of this *cataloguing delay* is unknown, unless sensing data is available, since it strongly depends on the revisit time and the performance of the cataloguing process. Therefore, a manoeuvre detected with this methodology should not be assumed to have been performed the exact day the RMS increase is monitored, but earlier. For that reason, a *calibration process* is included for the estimation of a typical value of cataloguing delay, to be subtracted to the RMS increase date. In the case of SP catalogue, this average delay was found to 2.54 days. It is important to remark that this date shift depends on the RSO and many other factors, being the use of a typical value the only option due to the lack of additional information. Moreover, the detected manoeuvre epochs cannot be estimated with a precision lower than the time between consecutive catalogue issues (orbit updates), since the manoeuvres are assumed as not considered during the estimation of the orbits, as it happens with SP catalogue.

2.2. Methodology based on sensor data

Manoeuvre detection with optical observations can be understood as an association/correlation problem and should be integrated within the cataloguing chain used in this work, as depicted in Fig. 1, which shows a view of the different processes involved. The very first uncorrelated tracks (UCTs), also known as uncorrelated optical observations (UCOs) for optical observations, received after a manoeuvre will most likely not be reliably correlated against any RSO in the catalogue due to the velocity change and its effects on the dynamics, so it enters into the track-to-track association algorithm, intended for the detection of new objects.

Initially, this first post-manoeuvre UCT cannot be associated to any other track in the track-to-track process. As more post-manoeuvre UCTs are obtained, these can be associated. If nothing is done to detect the manoeuvres, this would give rise to a new object at the end. In order to prevent this, depending on the complexity of the manoeuvre, there are two possibilities (branches 1 and 2 in Fig. 1).

On the one hand, the new UCT is first associated with the corresponding orbit of the RSO via track-to-orbit correlation considering a *single-burn* manoeuvre (branch 1 in Fig. 1). This allows to establish a first and preliminary link (association or hypothesis in the Multi Hypothesis Tracking framework) between an orbit and a single UCT, although the manoeuvre cannot be yet confirmed nor estimated reliably due to the scarce information available. As more UCTs after the manoeuvre arrive to the system, new associations of more tracks arise until there is enough information to promote, i.e. confirm, the hypothesised manoeuvre. The number of tracks for the association required to properly confirm and estimate a single burn manoeuvre (i.e., promote hypotheses) is expected to be around two or three, less than the four required for a full and nominal RSO initialisation in the catalogue ([6] and [7]). The track-to-orbit methodology proposed is able to detect manoeuvres based on residuals between the estimated orbit before the manoeuvre and observations afterwards. The more time after the manoeuvre is elapsed, the greater the divergence of the residuals becomes. This is an indication of the footprint of the manoeuvre on the residuals of the post-manoeuvre tracks with respect to the pre-manoeuvre orbit.

On the other hand, the information contained on a single track might not be enough to estimate the parameters characterising a manoeuvre of *multiple burns*, since the track-to-orbit correlation algorithm including manoeuvres as described above (branch 1 in Fig. 1) would not be able to link the orbit with the post-manoeuvre UCTs. Therefore, it is required to associate a higher number of post-manoeuvre tracks to obtain a new and reliable orbit estimation without the use of prior information, i.e. perform a potential new RSO detection, by means of track-to-track correlation. The number of tracks required is higher than in the previous situation, since a full RSO initialisation is performed, although initial estimates of the post-manoeuvre orbit can be derived allowing an early detection of the manoeuvre. Once accurate post-manoeuvre orbital information is available, the manoeuvre detection and estimation can be done in the orbit space by means of an orbit-to-orbit correlation considering manoeuvres (branch 2 in Fig. 1). This problem corresponds to the estimation of two manoeuvres capable of linking two already well-established orbits. The case of low-thrust manoeuvres is a challenge for this approach, but the method would still be applicable as long as the low-thrust manoeuvre is finished, although the estimated impulsive manoeuvres will not be very representative of the actual low-thrust manoeuvre performed. The two methods proposed for manoeuvre detection and estimation are detailed in [5].

3. RESULTS

This section presents the results of several analyses performed with the two methodologies proposed for the manoeuvre detection and estimation based on orbital and sensor data. The following terms are intensively used during this section:

- *Orbit*: ephemeris from SP catalogue corresponding to certain object. SP catalogue is issued on a daily basis, although gaps (missing orbits from certain objects) are not unusual. We refer to “orbit received on” as the orbit from the SP catalogue issued on certain date.
- *Track*: set of observations received by three optical sensors of the Spanish Space Surveillance Sensor Network (S3TSN). Each track is correlated against SP catalogue during a track-to-orbit pre-processing process. This has allowed us to reduce the complexity of the problem and it is not expected to have a significant impact on the results but on the computational burden.

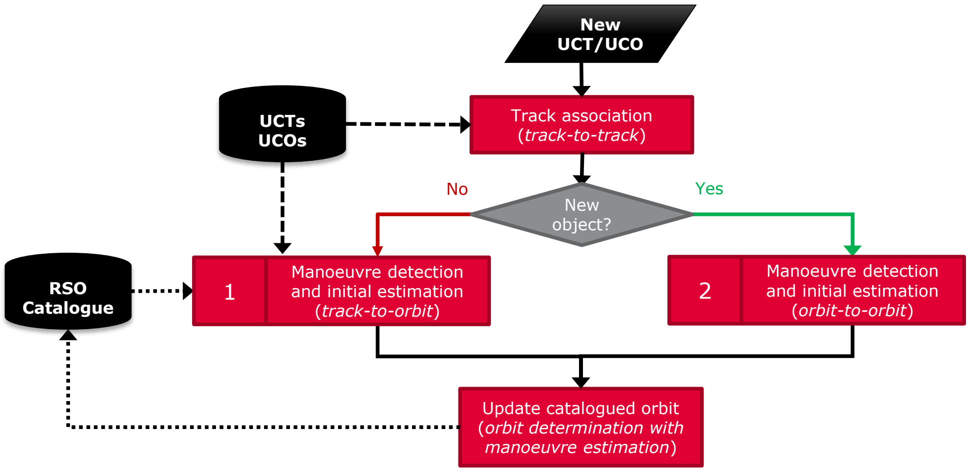

Figure 1. Manoeuvre detection and estimation role in the cataloguing chain.

- *Reference manoeuvre*: manoeuvre as reported by the satellite operator.
- *Estimated manoeuvre*: manoeuvre detected and estimated, depending on the matching with respect to reference manoeuvres, it is classified as *true positive* (TP): correctly estimated manoeuvre, i.e. there is one matching reference manoeuvre; or *false positive* (FP): incorrectly estimated manoeuvre, i.e. there is not any matching reference manoeuvre.
- *Non-estimated manoeuvre*: manoeuvre not detected nor estimated. Depending on the detectability of the manoeuvres, it is classified as *false negative* (FN): reference manoeuvre that was not estimated, although it should have been detected and estimated since there was enough data; or *true negative*: reference manoeuvre that was not estimated, since there was not enough data.

3.1. Methodology based on orbital data

The methodology has been applied to the dataset of GEO RSOs with ephemerides available on the SP catalogue from March 2018 to May 2020. In this section, the results from two arbitrary RSOs, active and non-active, are presented first and then the whole GEO catalogue results and manoeuvre frequency analysis discussed.

3.1.1. Example of an active RSO

Firstly, the proposed methodology was applied to a single manoeuvrable RSO, in the complete time-span of available data. Fig. 2 shows the RMS in the along-track direction for each pair of orbit comparisons. The outliers, located above the threshold, correspond to manoeuvres. Both NS and EW manoeuvres are detected on the time interval. Besides, the timeline of events on a shorter time interval is depicted in Fig. 3, where the estimated manoeuvres (red) match the manoeuvres present on the operator manoeuvre plan (green). Dashed lines represent EW manoeuvres and solid lines NS. Finally, blue lines represent the date at which an orbit was available on SP catalogue. Overall, detected manoeuvres match the actual ones. Bear in mind that the detected manoeuvres are set at date with precision of a single day due to the SP catalogue publication rate, whereas the ones coming from the operator information are set at its exact epoch, causing slight time differences in Fig. 3.

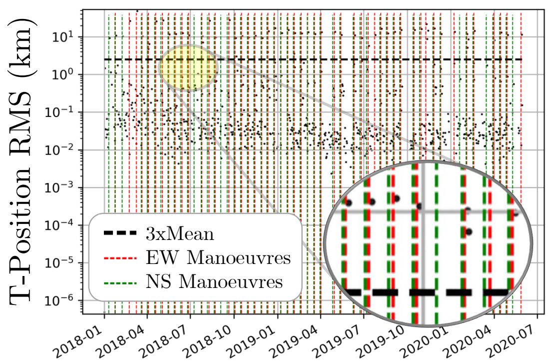

Figure 2. Along-track RMS of an active RSO and detected manoeuvres with methodology based on orbital data.

Moreover, this case is representative of some the issues that need to be considered during the manoeuvre estimation process. On the one hand, there might be cases in which a false manoeuvre is detected, as seen after the second detected NS manoeuvre (on July 2018 in Fig. 3). False positive manoeuvre detections might be triggered by a degradation of the orbit accuracy as a consequence of a poor catalogue maintenance (e.g., lack

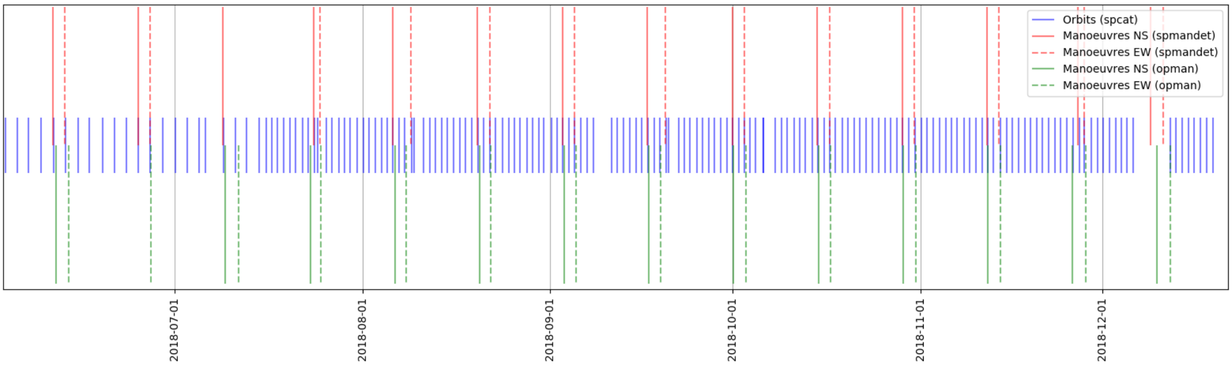

Figure 3. Timeline of available SP catalogue issues (blue); detected (red lines) and planned (green) NS (solid) and EW (dashed) manoeuvres in 2018 with methodology based on orbital data.

of observations to update the orbit) that leads to high RMS during subsequent ephemerides comparisons. Cross tagging may also lead to unexpected increases of RMS and not related to manoeuvres. On the other hand, false negative manoeuvre detections are also expected if the manoeuvre is so small that the effect on the orbit is lower than the accuracy of the catalogued orbit. Under this situation, the manoeuvre will remain undetected unless the precision of the orbits improves, as can be appreciated in the first published EW manoeuvre after July 2018 in Fig. 3. Finally, there are periods in which the SP catalogue does not contain orbits regularly (very likely due to a catalogue maintenance issue triggered by a significant manoeuvre). This makes the detection process more challenging, as observed in the last pair of detected manoeuvres in Fig. 3.

3.1.2. Example of a non-active RSO

Secondly, the proposed methodology was applied to a single non-manoeuvrable RSO. Fig. 4 shows the RMS in the along-track direction for each pair of orbit comparisons. As opposed to Fig. 2, no manoeuvres are detected since all RMS points are below the absolute threshold of 1.5 km. Besides it can be appreciated how some points are located above the 3 RMS mean value. If the absolute threshold was not applied, then a set of false manoeuvres would be identified. This threshold was set as a compromise between pruning most of the false positives while maintaining the capability of detecting low magnitude manoeuvres, such as EW burns.

3.1.3. GEO catalogue analysis

One of the main capabilities to assess regarding the proposed methodology performance is its ability to identify manoeuvrable (active payloads) RSOs in a catalogue. For this purpose, the Satellite Catalogue (SATCAT) provided by CelesTrak [8] has been used to retrieve the type of object for each RSO in the SP

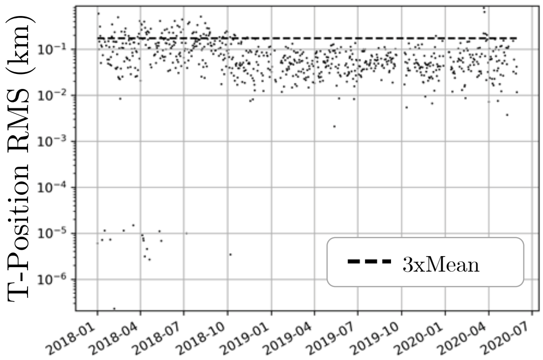

Figure 4. Along-track RMS of a non-active RSO and detected manoeuvres with methodology based on orbital data.

catalogue. The reference population under analysis was obtained by filtering in this catalogue for objects not showing a decayed status and having a semi-major axis greater than 34,000 km. This amounts for a total of 1,707 objects, out of which 1,132 are tagged as manoeuvrable in SATCAT. Tab. 1 shows the results after applying the proposed detection methodology to that same population in all available SP catalogued post-processed orbits from March 2018 to May 2020. Ignoring the few RSOs whose information was not available in the SP catalogue, the proposed methodology is able to detect most (96%) of the manoeuvrable RSOs, according to CelesTrak.

Table 1. Number of manoeuvrable and non-manoeuvrable RSOs detected on SP catalogue and stated as so in CelesTrak [8].

Type	Reference (SATCAT)	Detected (SP catalogue)	
Manoeuvrable	1,132	1,087	96.02%
Non-manoeuvrable	575	538	93.57%
No data	-	82	

3.1.4. Manoeuvre frequency analysis

Using the SP catalogue orbits from the 1,707 objects on the previous time window, the manoeuvre frequency can be inferred. For each RSO, the time period between consecutive manoeuvres, either EW or NS, was aggregated, resulting on the data distribution shown in Fig. 5. The most typical manoeuvre frequency corresponds to 14 days, which is one of the typical frequencies used by most GEO operators. Additionally, it is observed that 13 and 15 days present also a high probability. This can be attributed to small deviations in the operation plans or to the expected methodology precision of 2 days, showing that same dispersion around 14 days. The second most popular frequency is of 7 days, which is also an expected result. Some satellites must be kept under more restrictive pointing budgets and its orbital position must be corrected more regularly. Analogously to the previous case, two smaller peaks are found at 6 or 8 days of frequency presumably for the reasons previously mentioned. Finally, a significant amount of RSO are found to manoeuvre in 3 or 4 weeks periods. The frequencies above one month or even greater than a year that are observed in the figure are caused by the lack of data of some objects during certain periods.

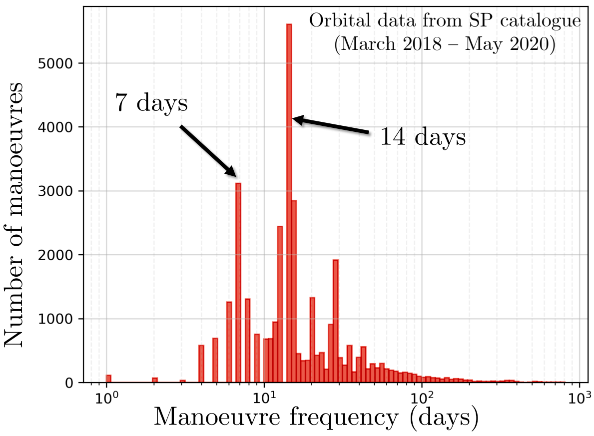

Figure 5. Manoeuvres frequency histogram obtained with methodology based on orbital data.

3.2. Methodology based on optical observations

Impulsive reference manoeuvres from January 2018 to June 2020 of 15 GEO satellites available at Spanish Space Surveillance Operations Centre (S3TOC) have been analysed. The dataset considered for the results presented concern 21,676 optical tracks from three sensors of the S3TSN. The track duration distribution of the dataset is presented in Fig. 6, where a blue dashed vertical line corresponding to 0.2% of the orbital period (around 1 day) has been included, as it is the reference value below which a track is usually considered short [9]. Therefore, more than 62% of the considered tracks can be considered short tracks and the maximum track duration is lower than 12 min (around 0.8% of the orbital period). This complicates the track association that is performed before the manoeuvre estimation, as well as the manoeuvre estimation itself, since the information contained on a single track is reduced.

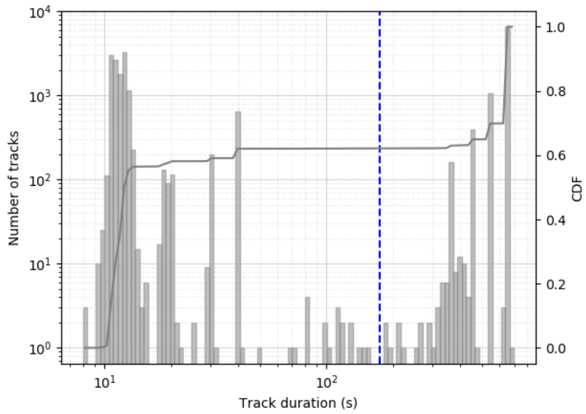

Figure 6. Track duration distribution of the 21,676 optical tracks considered to analyse the methodology based on sensor data.

The matching between estimated and reference manoeuvres is performed by solving an association problem via a nearest neighbour approach. To do so, pairs of reference and estimated manoeuvres whose epochs differ less than five days are evaluated in terms of the following figure of merit:

$$f^2 = w_t^2 \left(t_{ref} - t_{est}\right)^2 + w_{\Delta V}^2 \left(\Delta V_{ref} - \Delta V_{est}\right)^2 \quad (2)$$

where t is the manoeuvre epoch and ΔV is the manoeuvre magnitude. The weight of each difference (epoch and magnitude) is given by w and $w_{\Delta V}$, that have been set at 5 days and 1 m/s, respectively.

Once evaluated the figure of merit of each potential pair, the one with lowest figure of merit is promoted, incompatible potential pairs (those with common estimated or reference manoeuvre) are discarded and so on, until every potential pair has been promoted (i.e. confirmed) or discarded. Accordingly, true positives correspond to estimated manoeuvres that could be associated with a reference manoeuvre, false positives correspond to estimated manoeuvres that could not be associated, while false negatives and true negatives correspond to reference manoeuvres that could not be associated.

The difference between false negatives and true negatives is given by the *detectability conditions*: 1) enough pre-manoeuvre orbits: at least one orbit before the current reference manoeuvre, after the previous reference manoeuvre and not older than five days with respect to the manoeuvre epoch is available; and 2) enough post-manoeuvre tracks: at least three tracks after the current reference manoeuvre, before the next reference manoeuvre, not older than one week with respect to the manoeuvre epoch and separated more than six hours are available.

Finally, note that only correlated tracks have been considered for performing the manoeuvre detection and estimation of each satellite, from the propagation of the pre-manoeuvre orbit, track association, to the manoeuvre estimation. If tracks would not have been correlated during pre-processing, then the dimension of the track association problem would have increased, leading to a significant increase of the computation time. In other words, the pre-processing is only expected to discard tracks and thus speed up the analyses. Fig. 7 shows the methodology followed for the results presented in this section. First, the tracks are correlated by means of track-to-orbit correlation in order to assign each track a set of orbits from the SP catalogue. Secondly, tracks from each of the 15 satellites are input into the track association algorithm, in charge of associating tracks before and/or after the manoeuvre. Then, depending on whether there are enough tracks (4) to estimate an orbit, the manoeuvre estimation is performed with the track-to-orbit or orbit-to-orbit method. They take the pre-manoeuvre information (tracks if track-to-orbit and estimated orbit if orbit-to-orbit) from the optical tracks of the S3TSN and the post-manoeuvre information from the SP catalogue.

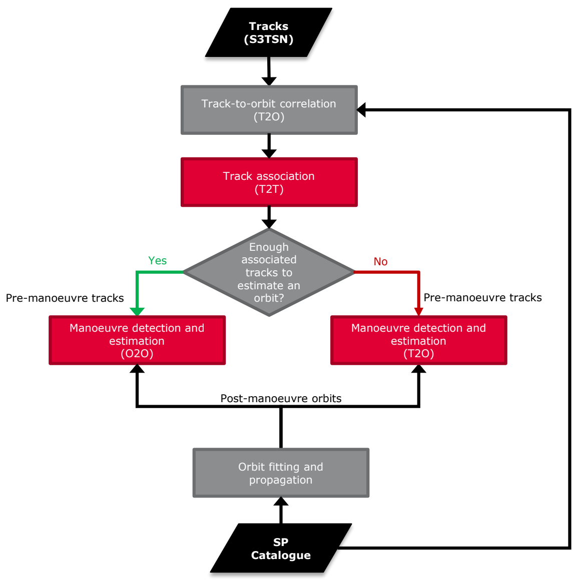

Figure 7. Manoeuvre detection and estimation procedure considered to analyse the methodology based on sensor data.

Three sets of analyses have been conducted to evaluate the performance of the manoeuvre detection and estimation methodology based on optical observations: 1) *isolated analyses*: a detection and estimation problem is built and solved for each reference manoeuvre of each satellite; 2) *preliminary bulk analysis*: first approach to a operational strategy; and 3) *bulk analyses*: a sequential strategy representative of an operational environment

3.2.1. Isolated analyses

The aim of these analyses is to solve a batch of detection and estimation problems, each representing a relatively small and simple scenario to assess and understand the performance of the methodologies. For every single burn reference manoeuvre of each satellite, the following data was retrieved to set up the manoeuvre detection and estimation problems for the track-to-orbit methodology: *pre-manoeuvre orbit*: last orbit available before the manoeuvre; and *post-manoeuvre tracks*: every track available after the manoeuvre up to one week later or the next manoeuvre (whichever is earlier). Regarding the orbit-to-orbit methodology, for each double burn reference manoeuvre (assumed to be consecutive manoeuvres separated less than two days) of each satellite, the following data was retrieved: *pre-manoeuvre orbit*: last orbit available before the first burn; and *post-manoeuvre tracks*: every track available after the second burn and one week later or the next manoeuvre (whichever is earlier).

Results in terms of the metrics discussed above are shown in Tab. 2 and Tab. 3 for the track-to-orbit and orbit-to-orbit methodologies, respectively. Note that in this case there are no false positives since the estimation is only performed in the time vicinity of a reference manoeuvre.

Table 2. Isolated analyses metrics of the track-to-orbit methodology based on sensor data.

Sat.	TP		FN	
#01	12	100.00%	0	0.00%
#02	26	96.30%	1	3.70%
#03	28	100.00%	0	0.00%
#04	27	96.43%	1	3.57%
#05	27	100.00%	0	0.00%
#06	27	93.10%	2	6.90%
#07	33	100.00%	0	0.00%
#08	14	93.33%	1	6.67%
#09	39	95.12%	2	4.88%
#10	31	100.00%	0	0.00%
#11	31	93.94%	2	6.06%
#12	24	85.71%	4	14.29%
#13	34	97.14%	1	2.86%
#14	20	100.00%	0	0.00%
#15	34	100.00%	0	0.00%
all	407	96.67%	14	3.33%

Fig. 8 and Fig. 9 illustrate the accuracy of the estimated manoeuvres, by showing the distribution of the manoeuvre magnitude and epoch error of each estimation with respect to the reference value. In the

Table 3. Isolated analyses metrics of the orbit-to-orbit methodology based on sensor data.

Sat.	TP		FN	
#01	3	100.00%	0	0.00%
#02	8	88.89%	1	11.11%
#04	16	94.12%	1	5.88%
#05	13	92.86%	1	7.14%
#06	11	91.67%	1	8.33%
#07	19	95.00%	1	5.00%
#08	7	70.00%	3	30.00%
#09	1	100.00%	0	0.00%
#12	19	76.00%	6	24.00%
#13	21	95.45%	1	4.55%
#15	23	100.00%	0	0.00%
all	141	90.38%	15	9.62%

case of the orbit-to-orbit methodology (Fig. 9), the two dots connected by the straight line represent each of the burns of the double burn manoeuvre. The manoeuvre magnitude estimation is of the order of the reference manoeuvre, since the relative error is bounded between -100% and 100%. Besides, the median magnitude of the magnitude error (absolute value) is 10% and 15% in the track-to-orbit and orbit-to-orbit methodologies, respectively. On the other hand, the median epoch error (absolute value) is 2h in the track-to-orbit methodology and 36h/24h for the first/second burn in the orbit-to-orbit methodology. The highest error in the epoch estimation of the orbit-to-orbit methodology was expected, since it is based on the use of two orbits (although the second one is estimated with the measurements). This means that the optimal combination of two burns in terms of manoeuvre magnitude is selected from the parameter space, which does not always represent the reality. In fact, 78% of the double burn estimations have a magnitude lower than the reference value, i.e.: estimated manoeuvres tend to be more efficient than reference manoeuvres. However, in absence of further information, these estimations allow to solve the orbit linkage problem and thus maintain orbit traceability.

3.2.2. Preliminary bulk analysis

A preliminary bulk analysis was conducted on a data subset to give a clear insight on the estimation procedure. Accordingly, we performed a track-to-orbit correlation process between the provided tracks and the SP catalogue to assign each track an RSO and therefore alleviate the track-to-track association problem. Then, it was decided to focus on one satellite for which manoeuvre information is available at S3TOC, during the year 2019. Fig. 10 shows a timeline with vertical lines depicting events: tracks (straight black), orbits published on SP catalogue (straight blue), NS manoeuvres (straight green) and EW manoeuvres (dashed green). This satellite performed 11 EW station keeping burns and one attitude slew manoeuvre during

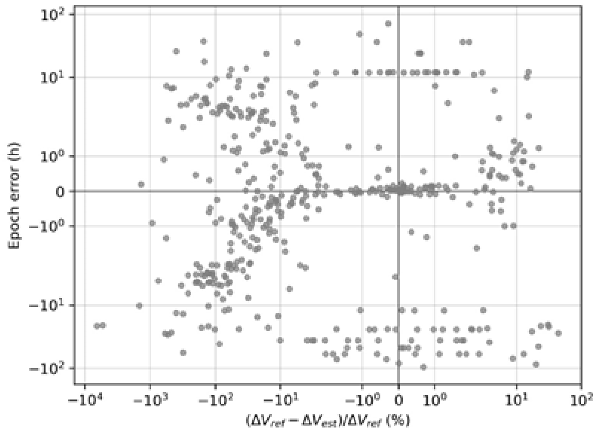

Figure 8. Manoeuvre magnitude and epoch error distribution in the isolated analyses of the track-to-orbit methodology based on sensor data.

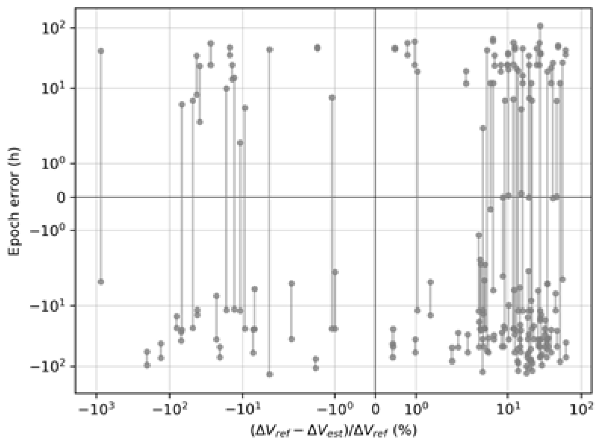

Figure 9. Manoeuvre magnitude and epoch error distribution in the isolated analyses of the orbit-to-orbit methodology based on sensor data.

2019. There are some periods, such as April and May, without any observations and therefore no manoeuvres could be detected there.

For each SP catalogue issue containing the orbit of the RSO of interest and the tracks correlated from two days before the SP catalogue publication date (to account for the typical cataloguing delay) and one week after, the following procedure is performed:

1. *Generation of associations of tracks and orbits*: analogous to an operational track-to-track association process, but ensuring there are no false positives (only correlated tracks are used). Associations of two, three and four tracks are generated and orbits estimated only for promoted associations of four tracks: an orbit is only generated from promoted associations, containing enough information to reliably estimate an orbit.

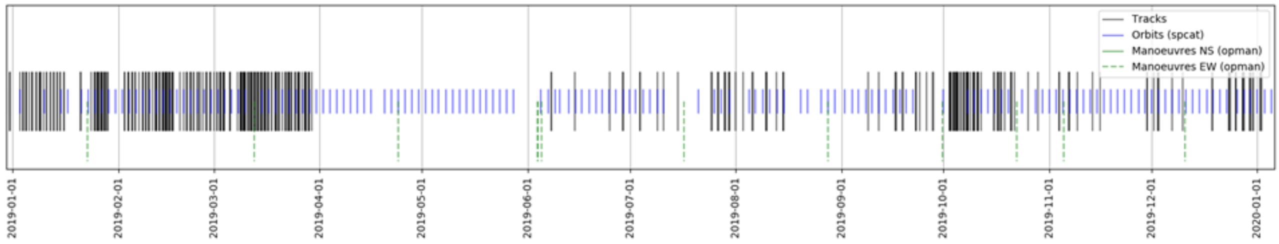

Figure 10. Timeline of tracks, orbits from SP catalogue and manoeuvres on 2019.

2. *Manoeuvre detection*: the residuals of each association against the SP catalogue orbit are computed to detect the existence of the already mentioned footprint. This is a complexity reduction technique that avoids trying to estimate manoeuvres that have not happened or cannot be detected. After this filter, only some associations remain on the manoeuvre estimation loop.

3. *Manoeuvre estimation*: the two methods are applied: 1) track-to-orbit manoeuvre estimation, for each pair of the orbit from SP catalogue and track association; and 2) orbit-to-orbit manoeuvre estimation: for each pair of the orbit from SP catalogue and estimated orbit.

Fig. A.1 shows the set of solutions from the track-to-orbit method found after running this analysis over the whole year 2019. The top plot shows the timeline of events for reference, the middle one shows the distribution of the delta-V corresponding to each solution and the bottom one the corresponding weighted RMS. Each solution is classified as NS (circles) or EW (crosses) manoeuvre and the colour indicates the number of tracks of the association. Note that the minimum number of tracks criteria has been removed to confirm its impact. The existence of many solutions with low weighted RMS, i.e.: good agreement between observations and orbit with the manoeuvre. The overlapping of solutions near to the true manoeuvres epochs. This does not happen with spurious solutions. Although already justified, it is clear that single tracks do not provide reliable solutions. Although the corresponding residuals are low, these solutions concentrate on high values or delta-V. There is not enough information to perform the estimation with less than three tracks. Observation availability after the manoeuvre is crucial to perform the estimation. If more than a week elapses between the manoeuvre and the SP catalogue issue, then the manoeuvre cannot be estimated.

Given the high number of solutions, a promotion algorithm was designed to generate a list of candidate solutions from the whole dataset. To do so, the solutions are sorted by the analysis date (the one of the corresponding SP catalogue issue) and starting from an empty list of candidates, the solutions are promoted as follows:

1. *Track interval overlapping*: group solutions whose track interval overlaps on time.

2. *Delta-V sorting*: for each of the previous groups, the solutions are sorted by ascending delta-V.

3. *Check solution incompatibility*: the solution is promoted if and only if none of the corresponding associated tracks is not included on a previously promoted association.

This iterative promotion algorithm helps to ensure that the solutions correspond to optimal manoeuvres estimated by independent sets of tracks, identify similar manoeuvres and prune spurious solutions. After applying the algorithm to the set of solutions, the number of solutions is reduced drastically, as shown in Fig. A.2, where the distribution of the delta-V of each solution along the manoeuvre epoch is provided. Note that the selected solutions correspond to estimated cases with at least 2 tracks. The next step was to include additional requirements during the promotion algorithm that help us to retain the solutions surrounded by the red dotted circles in Fig. A.2. In terms of the association problem, this is equivalent to the filtering of false positive detections and the results are discussed on the next section.

3.2.3. Bulk analyses

Once concluded and understood the isolated and preliminary bulk analyses, a more complete set of analyses were performed to evaluate the performance of the track-to-orbit methodology under a more operational-like scenario. As opposed to the previous analyses, reference manoeuvres information is not used to filter input data. Isolated analyses were limited in the sense that provided data was restricted to maximum extent. On the contrary bulk analyses are more representative of a daily operational environment, since all incoming data is processed. The manoeuvre detection is triggered whenever a new orbit is available and considering every track between two days before (to account for the previously observed typical manoeuvre detection delay in SP catalogue) and one week after this orbit (typical manoeuvre frequency, to try to focus on single manoeuvre cases). This processing is performed sequentially since track association information history is stored, allowing thus to process only new tracks but enabling new associations arise from combinations of previous associations and new tracks. To illustrate this, if an orbit is received on 2020/01/01 and new tracks arrive from 2020/01/01 to 2020/01/07, when the next orbit received next day (2020/01/02), then only new tracks from 2020/01/07 to 2020/01/08 are going to be processed, although they could be association to those from 2020/01/01 to 2020/01/07 thanks to the association tree history. Results in terms of the metrics discussed above are shown in Tab. 4. Note that, as opposed to the previous cases, there are false positives since the detection and estimation is sequentially performed and not only in the time vicinity of a reference manoeuvre.

Table 4. Bulk analyses metrics of the track-to-orbit methodology based on sensor data.

Sat.	TP		FP		FN	
#01	30	100.00%	8	21.05%	0	0.00%
#02	116	99.15%	4	3.33%	1	0.85%
#03	124	100.00%	18	12.68%	0	0.00%
#04	60	98.36%	5	7.69%	1	1.64%
#05	54	100.00%	5	8.47%	0	0.00%
#06	45	100.00%	3	6.25%	0	0.00%
#07	58	98.31%	3	4.92%	1	1.69%
#08	39	97.50%	3	7.14%	1	2.50%
#09	60	95.24%	6	9.09%	3	4.76%
#10	59	100.00%	4	6.35%	0	0.00%
#11	65	95.59%	3	4.41%	3	4.41%
#12	54	100.00%	4	6.90%	0	0.00%
#13	62	98.41%	5	7.46%	1	1.59%
#14	37	100.00%	3	7.50%	0	0.00%
#15	59	100.00%	6	9.23%	0	0.00%
all	922	98.82%	80	7.98%	11	1.18%

Fig. B.3 shows the event timeline of satellite #10 during the whole time window. There is a major gap in the tracks availability from April 2019 to June 2019 and several gaps in the orbits availability (e.g. January 2020) that limit the application of the methodology. Fig. B.4 depicts the timeline of satellite #07 during September 2019. The manoeuvres performed by the satellite (pink lines) follow a clear pattern of NS burn (straight line) – 2 days – EW burn (dashed line) – 12 days. The problem is that NS burns remain undetectable, since there are not enough tracks between the two burns to perform the track-to-orbit methodology. This is a clear case of application for the orbit-to-orbit methodology. However, this depends on the sensor network and the observation geometry. If enough observations are available between the two burns, the track-to-orbit methodology could be applied. This is illustrated in Fig. B.5, where the timeline of satellite #15 during September and August 2018 is presented. The manoeuvres performed by the satellite (pink lines) follow a pattern similar to that of satellite #07, although now there estimation of the two burns is possible.

4. CONCLUSIONS AND FUTURE WORK

This paper has presented the application of two methodologies, based on orbital and sensor data, to the manoeuvre detection and estimation problem in GEO with real data. On the one hand, the manoeuvre detection based on orbital data is the first natural approach, particularly if observations are not available. These methods rely on statistical analyses performed over TLE or SP catalogue orbital data, and are relatively simple to tune, apply and understand. However, their performance is limited by the orbital data provider, its underlying uncertainty and they have not been conceived to provide estimations of the manoeuvre magnitude. Therefore, we recommend their use only for quick manoeuvre detection assessments and when sensing data is not available.

The first methodology, manoeuvre detection method based on orbital data and applied to SP catalogue, represents the natural evolution of previous works with TLE catalogue. In fact, SP catalogue should be always preferred whenever possible, given the higher accuracy of the ephemerides with respect to TLE data. Consequently, manoeuvre detection based on TLE data should only be considered for past analyses involving years before SP catalogue was available. The analysis performed on manoeuvre detection based on the SP catalogue has confirmed the typical frequency of 14 days in GEO, although 7, 21 and 28 days also appear as typical frequencies. This methodology has also been proven very successful to determine which objects are manoeuvrable and which ones are not, showing good matching with data presented in other public sources. Nevertheless, there are three relevant inherent drawbacks of this methodology: 1) it completely relies on external ephemeris data: SP catalogue is maintained and built up by 18$^{\text{th}}$ SPCS; 2) the manoeuvre estimation is limited: there is an inherent delay due to the time required by the catalogue maintenance process to consider the manoeuvre on the estimation of the post-manoeuvre orbit; and 3) the manoeuvre magnitude cannot be reliably estimated and the manoeuvre epoch resolution is limited to the time span between two catalogue issues (around one day in the case of SP catalogue). The only way to overcome these limitations is the use of observations for the manoeuvre detection and estimation.

The second methodology, based on optical observations, is very different from the previous one, since it does not only aim at detecting manoeuvres but also at estimating them. The orbits used for the manoeuvre detection method based on SP catalogue are estimated by the 18$^{\text{th}}$ SPCS considering large datasets of observations from an large sensor network, and thus they are expected to be well-established orbits, i.e.: enough accuracy for typical cataloguing activities, such as manoeuvre detection and estimation. On the contrary, the methodology based on optical observations uses a much lower number of observations, thus allowing to detect and estimate manoeuvres as soon as enough observations are received (at least four tracks). Observation availability after the manoeuvre is crucial to perform the estimation, as well as the orbit observability, that may impact the detection time or even prevent it. This might be the case of a GEO satellite performing an inclination change manoeuvre by means of a cross-track burn on the node of the orbit, if observed by an on-ground telescope located so that the field of view is pointing towards the node. Even though the observation data available and the limited number of observations available after the manoeuvres, the track-to-orbit methodology has shown success rates (true positives) higher than 96/98% in the isolated/bulk analyses, false positives rate lower than 10% in the bulk analyses and false negatives around 3/1% in the isolated/bulk analyses. Regarding the orbit-to-orbit methodology, the isolated analyses lead to success rates (true positives) higher than 90% and false negatives around 9%. The performance metrics of the orbit-to-orbit methodology are worse than track-to-orbit one, as expected, since the number of estimated parameters (two epochs and six manoeuvre magnitudes) of the former is twice that of the latter. Besides, while the track-to-orbit methodology provides a metric that indicates the goodness of the observations (weighted RMS), the orbit-to-orbit one does not, and thus the selection of the solution is performed assuming the total ΔV is minimum, which is not always the case.

The good results obtained indicate that the methodologies are very suitable for tackling the manoeuvre detection and estimation problem that arises during catalogue maintenance. Therefore, future works will integrate these methodologies in a complete cataloguing process. This will enable the study of the manoeuvre detection and estimation problem including the accuracy of the orbits in the catalogue, the track association and correlation problems and the orbit determination.

ACKNOWLEDGMENTS

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APPENDIX A ADDITIONAL FIGURES: PRELIMINARY BULK ANALYSIS

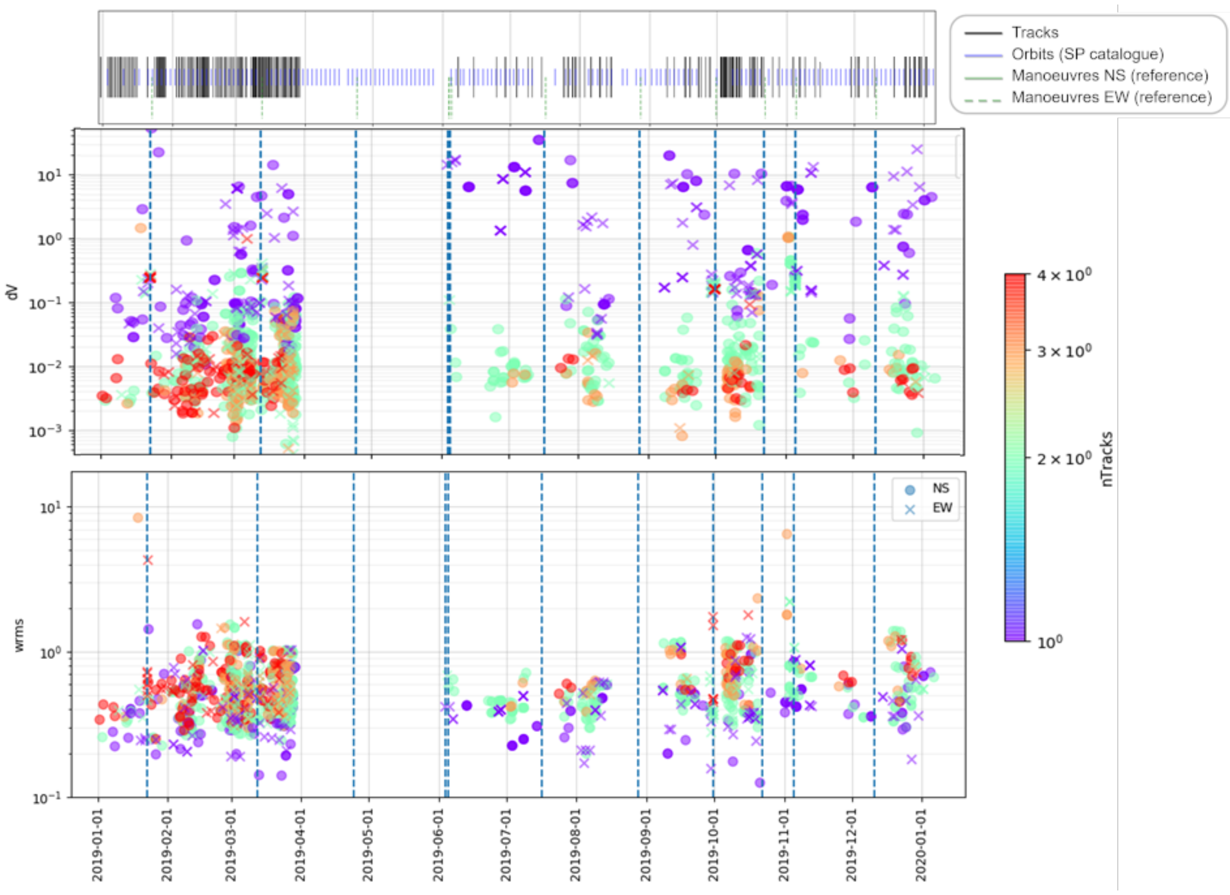

Figure A.1. Every solution found for satellite #00 manoeuvres on 2019.

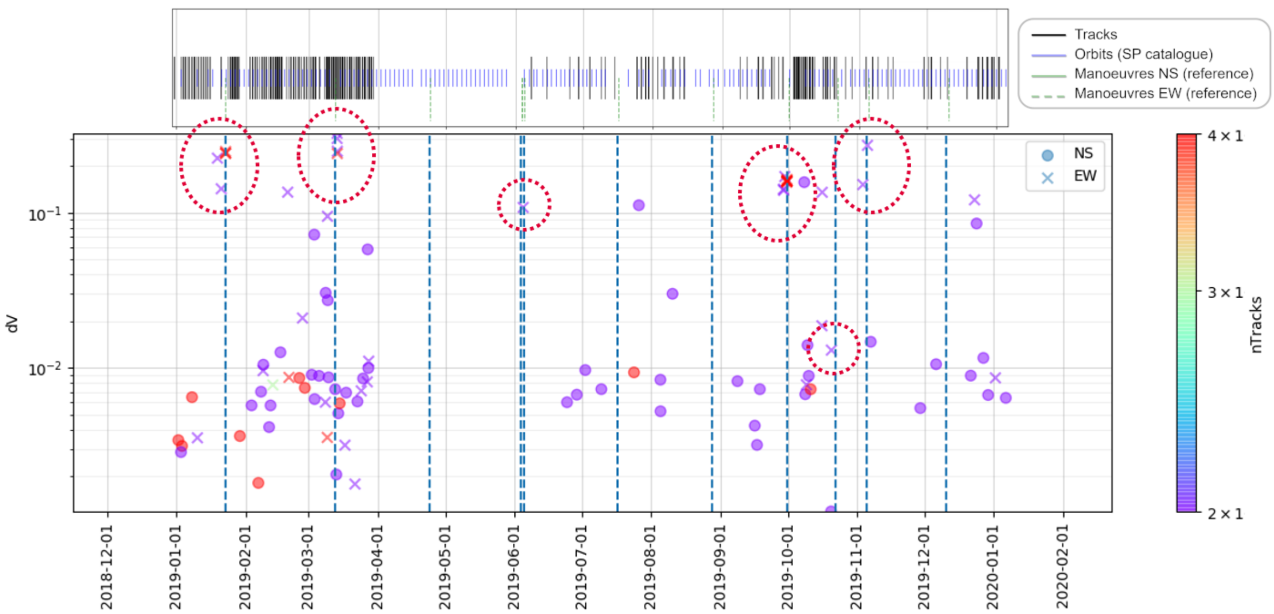

Figure A.2. Selected solutions found for satellite #00 manoeuvres on 2019.

APPENDIX B ADDITIONAL FIGURES: BULK ANALYSIS

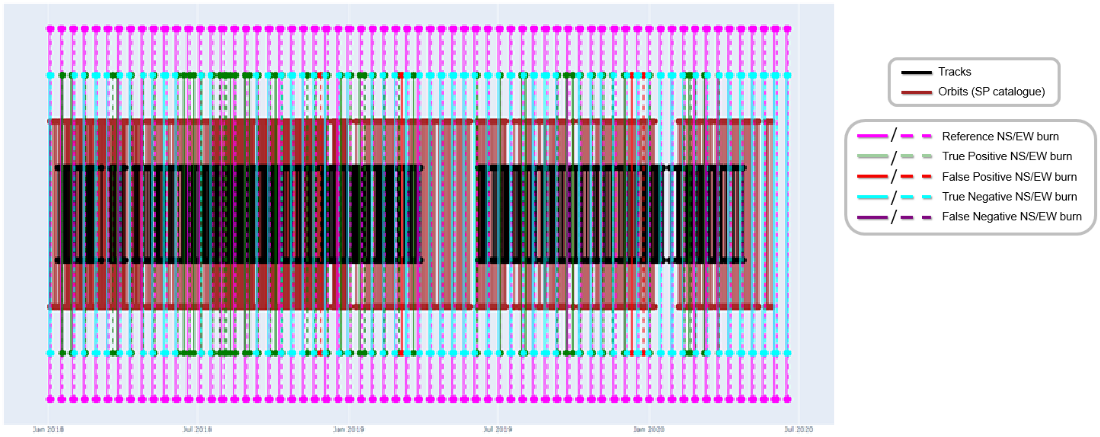

Figure B.3. Bulk analysis of satellite #10 during the whole time window

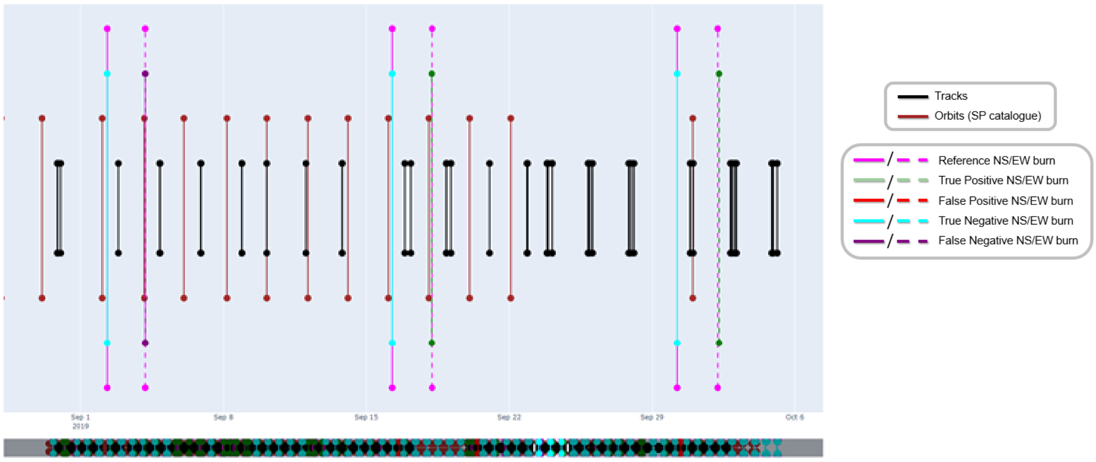

Figure B.4. Bulk analysis of satellite #07 during the whole time window

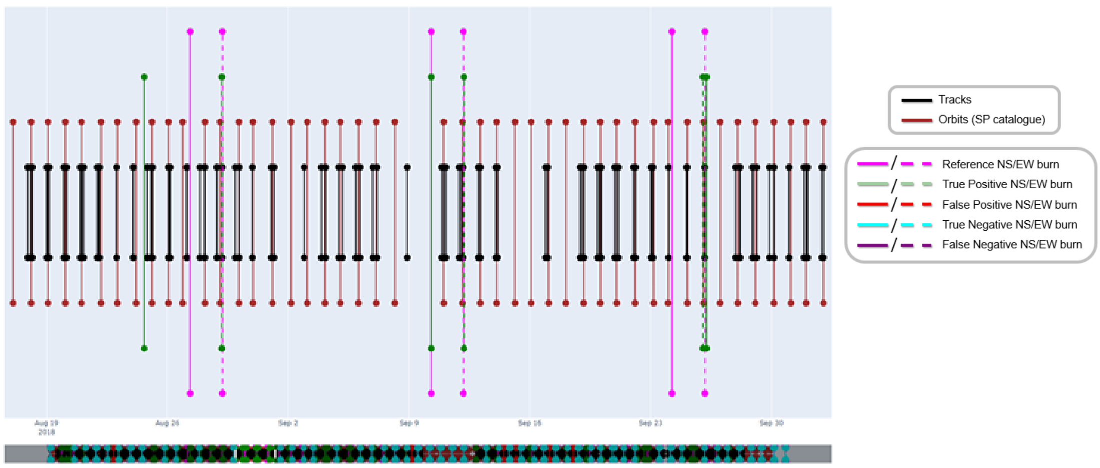

Figure B.5. Bulk analysis of satellite #15 during the whole time window