AACOS : AUTOMATIC ANALYSIS OF SPATIAL OBJECT CATALOG

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ABSTRACT

Space surveillance can be defined as the ability to observe, detect, catalogue satellites maneuvers and map atypical behaviors. This project focuses on the prerequisite necessary to achieve this mapping.
Taking advantage of TLE (Two-Line Elements) open source data, available within space catalogues, a generic and automatic method to identify satellite maneuvers has been developed.

This study has used TLE data for satellites from which maneuvers data were available (CRYOSAT 2, ENVISAT, HAIYANG 2A, JASON, JASON 2, JASON 3, SARAL, SENTINEL 3A, SENTINEL 3B, SPOT 2, SPOT 4, SPOT 5, TOPEX / POSEIDON).
The maneuvers information's have only been used to verify later results. Indeed, to guarantee the genericity and automaticity characteristics, the method has to be developed without any maneuver supervision knowledge. Moreover, as this project, is within a big data environment, everything shall be automatic.

It is within this context that the potential of different options was explored, from the historical MWCF algorithm, going through different types of clustering techniques DBSCAN then OPTIC. Even if these techniques have presented encouraging results, they did not allow to answer the expected: a generic and automatic method. Indeed, they have always some parameters to be manually scaled.
Moreover, while looking at the temporal evolution of the semi-major axis (derived from the mean motion) a clear coherence of its inflexion with the maneuvers could be observed. Detecting maneuvers could then be simplified as detecting certain inflexion points of the curve.
In this view, a new methodology has been developed, that embodies a cross-fertilisation between physics and data mining.
It first isolates all inflexion points within the semi-major axis time evolution. Then, following the aspect of the curve different types of filters are applied to remove the noise and keep only what is expected to be maneuvers. Within the set of satellites of this study, it has been observed that only up to 3% of the temporal evolution of the semi-major axis are maneuvers. To secure the detection it has been double to 6% and this was used as an hypothesis to calibrate filters to the correct level.

With a 5 days lag authorized between the real maneuver and their detection, very good results were obtained for most of the satellite. The results of the maneuvers detection up to February 2020 (end of our extracted data) are: F1 score 81% (52 to 93%), recall 86% (61 to 95%), precision 78% (45 to 97%) and error rate 0.5% (0.2 to 1.3%). This is a sufficient level to consider the method robust enough to fulfil our objective. Let's mentioned that some maneuvers were grouped together in the calculation as they were within the same detection window. It shall also be mentioned that the method required no parameter at all.

1 INTRODUCTION

The space environment monitoring is a key issue since the beginning of the space era. Satellite activities and space debris could be linked to major security issues.
The key step for a reliable monitoring of space is to accurately observe, detect, catalogue satellites maneuvers and map atypical behaviors.
Different catalogues exist to constantly collect and monitor orbital objects and hold the orbital elements of thousands of objects in Two-Line Elements (TLE) format. With the advent of more and more sophisticated techniques of data mining, the nowadays challenge is to use AI to develop an automated analysis for the space object classification.
This study intends to develop technique to mitigate problems linked to Space Situational Awareness.
Even so, this study will not focus only on maneuvers linked to risk mitigation maneuvers (RMMs) but to all types of maneuvers defined by the NASA's Goddard Space Flight Center [6] as: the orbital raising or lowering and the inclination adjustment maneuvers.

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The orbital raising or lowering could be executed as risk mitigation maneuvers (RMMs) with, for example, orbital debris (Debris Avoidance Maneuver (DAM)). However, the raising orbital manoeuvre is also employed to relocate new satellites into their planned mission orbital location or to counteract the effect of atmospheric drag (drag makeup (DMU or DMUM) maneuver). And, the orbital lowering is also employed as an exit manoeuvres when satellites are leaving their nominal orbital position.

Finally, the Inclination adjustment manoeuvre (IAM) is performed periodically to maintain the mission's mean local time.

To fully described the satellite maneuvers within satellite orbit, six standard orbital elements (Keplerian elements) are required: Semi-Major Axis, a; Eccentricity, e; Inclination, i; Argument of Periapsis/Perigee, ω; True Anomaly, v; Right Ascension of the Ascending Node (RAAN), Ω.

However, are all these Keplerian elements required when the goal is only to detect these maneuvers? Looking at the literature, depending on a mathematical or more physical approach, some discrepancies could be noticed on the uses of these Keplerian elements.

The detection of satellite maneuvers has started with, among other, the Moving Window Curve Fitting (MWCF) technique in [5]. It uses sliding window over adjacent segments approximated by polynomial fits to measured large changes (possible maneuvers). Parameters employed are inclination and Semi-Major Axis converted to specific mechanical energy. The TLE data included noise with peaks indicating large enough changes to be maneuvers and that are called outliers. However, these peaks could not directly be considered as a maneuver. Indeed, lags shall be considered as well as a certain level of noise shall be first manually removed to obtain the best possible results, which indicate this type of technique could not be automatized and generalized.

Another way of detecting satellite maneuver is to use clustering techniques.

One of such method is box DBSCAN technic combined to layered analysis approach. Such an approach is detailed in [1] and applied for ENVISAT satellite (for the period 2010 to 2012). The parameters employed are Inclination, epoch day data, Perigee, Eccentricity and Mean Motion. The analyze returns very good results with an error rate of 0.7% and a lag between outliers and the start of the official maneuvers of 4-5 days. Reference is also given to paths for improvement with other clustering approaches, such as: Hierarchical Clustering, OPTICS (Ordering Points To Identify the Clustering Structure) and Adaptive Density Based Clustering.

Bai [2] employs different clustering approaches, among other it proposes and details an unsupervised classification method of K-means, hierarchical, and fuzzy C-means clustering to detect maneuvers within TLE. The article using state vector, entitles to detect three types of maneuvers (large, medium and small-scale orbital maneuvers) using the USSTRATCOM TLE data of three representative satellites: YAOGAN-9, TIANHUI-1, and Envisat. The study highlights a close link between the clustering technique to be employed and the scale of the maneuvers to be detected. They use [5] has a reference set to highlights how their method mitigate or even remove some constraints linked to [5] method. Over the period 2003-2006, methods have been applied to small-scale ENVISAT maneuvers. Results are best with the following configuration uses of two clusters with (δz state vector position axe z, δa semi-major axis, $\delta\omega$ argument of perigee) and the fuzzy C-means clustering technique. The error rate with this configuration is 1,4%, better than [5] but less than in [1]. However, the distinction made in [2] between the three classes of maneuvers raises a question as to generalization potential of the method because it assumes knowledge of the class of maneuver for each of the satellites studied.

In this article, to answer the need of:

- fully generic (one method whatever the satellite),
- fully automatic (no parameter to be tuned, no other information than the TLE ones requested)
- fully deployable in a big data world (minimalist formalism to facilitate its deployment)

a new method of maneuvers detection is proposed and detailed.

2 THE SET OF TEST DATA

This study has used TLE data for satellites from which maneuvers data were available, they are listed hereafter: CRYOSAT 2, ENVISAT, HAIYANG 2A, JASON, JASON 2, JASON 3, SARAL, SENTINEL 3A, SENTINEL 3B, SPOT 2, SPOT 4, SPOT 5, TOPEX / POSEIDON.

These satellites are part of the DORIS French system [3] initiated and maintained by the French Space Agency (CNES).

The data have been downloaded from the space-track.org website [7] from their start-up time point until 01 February 2020 but have been analyzed only for the period where the maneuvers data where available. The maneuvers data have been found using the International DORIS Service interface [3] where, as the TLE data, they are also open source.

3 MANEUVER DETECTION ALGORITHM

This section details the new method DET_PEAK (peak detection) that has been developed.

The methodology DET_PEAK assumes that the number of points selected should not exceed a specific percentage of the total number of points over the entire life cycle of the satellite. This threshold enables noise filtering and has been chosen considering the percentage of points corresponding to maneuvers start with respect to the total number of points over the temporal evolution of the semi-major axis for each satellite of the DORIS constellation. To cover largely enough the highest value is retain as a threshold for all satellites.

This threshold level is not a target level but shall be considered as a capping level called *CL*. The *CL* is the essential parameter of the noise filtering stage but shall be calculated once only even if it can be adjusted with time.

Then using this *CL* value, the DET_PEAK method is based on the idea that detecting maneuvers means detecting certain inflection points in the temporal evolution of the semi-major axis. Note, that the method has been tested on all TLE parameters, and on combination of multiple parameters. This study focuses on its semi-major axis only version that has shown the best quality results.

The DET_PEAK strong points are that there is no parameter to specify and it has a very minimalist formalism that allows it to be deployed very easily in a big data framework individually on all satellites.

It could be described with, first, the detection of inflexion points and, secondly, the filtering of the maneuvers from the noise.

3.1 Detection of inflection points

During the quality control of the TLE data, it has been noticed some missing data as well as some duplicated ones. With an objective of automation and a minimalist formalism, to reduce the impact of these problems a sliding average box (by convolution of 4 box points) is employed on the semi-major axis data.

After this slight smoothing, inflexion points (blue dots in Figure 1) are selected within the temporal evolution of the semi-major axis value.

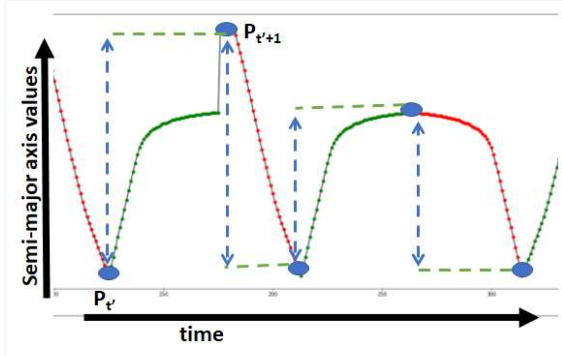

Figure 1. The process of inflexion points selection within the semi-major values temporal evolution.

This process of selection is as following:

- Calculation of the vertical difference (Semi-major axis) between point t and point t + 1.
- Selection of points $P_{t'}$ where the sign of this difference changes.
- Calculation of the vertical distance $V_{t'}$ between the point $P_{t'}$ and $P_{t'+1}$ regardless of the temporal distance between the two points. $V_{t'}$ values alternate between positive values, negative values, or zero values. The proportion of positive and negative values is therefore close but not equal.

3.2 Noise filtering

The noise filtering stage consists first in a breakdown of the temporal evolution by block of 500 points. This time cutting approach is different from taking 500 consecutive units of time and makes it possible to consider the instability of the measurements, the missing values and to focus on a potential number of inflections for an equivalent number of points.

To calibrate the noise filtering, *PP* (PP_{sat} and PP_{sat_block}) values and L_{sat_block} have to be calculated.

PP values are, for the semi-major axis temporal evolution, the percentage of selected points $P_{t'}$ with respect to the total number of points (PP_{sat}) or to the number of points for each block (PP_{sat_block}).

L_{sat_block}, the filtering threshold is calculated per block. This L_{sat_block} enables to filtered out some of the inflexion points, so that only the one that shall be maneuvers are kept.

To calculate the L_{sat_block} value two path are followed depending on the case:

Case 1: if $PP_{sat.}$ and PP_{sat_block} are both greater than CL: $V_{t'}$ are decomposed, by block between $Nb\_V_{sat\_block\_pos}$ and $Nb\_V_{sat\_block\_neg}$ that are the number of positive/negative values with respect to the number of points of the considered block.

- If $Nb\_V_{sat\_block\_pos}$ is lower than the number of values allowed by CL ($Nb\_CL_{\_block}$). The L_{sat_block} filtering threshold is the level that will keep only the values from the maximum one to ($Nb\_CL_{\_block}$ - $Nb\_V_{sat\_block\_pos}$) level one.

- If $Nb\_V_{sat\_block\_pos}$ is greater than the number of values allowed by CL ($Nb\_CL_{\_block}$). The L_{sat_block} value will be the 90% quantile level of the positive $V_{t'}$ within the considered block.

Case 2: if $PP_{sat.}$ and PP_{sat_block} are less than CL, the L_{sat_block} value is the 20% quantile level taken from all $V_{t'}$ in absolute values within the considered block.

The filtering threshold L_{sat_block} is applied as a threshold on $V_{t'}$ in absolute values. All $V_{t'}$ in absolute values under the threshold are considered as noise.

Finally, positive points are also filtered out, because the start of maneuvers correspond to upward inflections not downward ones.

All the other points are considered as start points of maneuvers.

3.3 Method validation

The method DET_PEAK has been applied to the temporal evolution of the semi-major axis for each satellite of the DORIS constellation. To evaluate the method, the set of points that have not been filtered out have been compared, for each satellite, to the real set of maneuvers start position.

Some classical statistical tools have been used such as the recall to evaluate the impact of missing detection (100% equals no missing detection), the precision to evaluate the false maneuvers detection (100% equals no false maneuvers detection).

The F1-score and error rate have also been calculated. The F1-score is an indicator that mix the precision (how many instances are correctly classified) and robustness (is the number of incorrect instances significant). An F1-score of 100% correspond to a perfect maneuver detection. The error rate enables to evaluate the proportion of errors, the closest it is from 0 the less error there is.

These performance metrics are built using a confusion matrix. The way the confusion matrix is built considers a lag parameter ε. This lag parameter could be up to 10 days and as explained in [5] accounts for the "broadening" of maneuvers detection event peaks."

In practice, including a lag parameter $\boldsymbol{\varepsilon}$ in the analysis changes the definition of the confusion matrix, because it is used to loosen the classical definition. The loosen version could be detailed as following:

- False Negative (FN): $P_{t'}$ is a false negative if the algorithm does not detect a maneuvre at time t' while there is one in the interval [t', t' + ε].
- True Positive (TP): $P_{t'}$ is a true positive if the algorithm does detect a manoeuvre in the interval [t', t' + ε]. However, if within the interval the maneuvres have already been detected, the point is not considered as a TP but as a true negative.
- False Positive (FP): $P_{t'}$ is a false positive if the algorithm does detect a manoeuvre at time t' while there is none in the interval [t', t'+ε].
- True Negative (TN): $P_{t'}$ is a true negative if the algorithm does not detect a manoeuvre at time t' while there is indeed none in the interval [t', t'+ε].

Let's mentioned that if some maneuvers where to close to each other and so in the same lag interval ε, they have been grouped together in the calculation.

These performance metrics will enable to compare the results of the DET_PEAK method with the one available in the literature.

4 DATA ANALYSIS

Within the period of the analysis for each of the satellite of our set, the temporal evolution has been cut by block of 500 points. As mentioned previously, there is duration fluctuations between the different blocks. Hereafter is proposed the list of duration, first the mean in days then the value of minimum and maximum for each of our satellites:

CRYOSAT 2: 326 days (188 to 630), ENVISAT: 169 days (130 to 312), HAIYANG 2A: 180 days (142 to 229), JASON: 410 days (303 to 483), JASON 2: 326 days (201 to 585), JASON 3: 238 days (186 to 287), SARAL: 315 days (196 to 542), SENTINEL 3A: 128 days (103 to 164), SENTINEL 3B: 278 days (278 to 278), SPOT 2: 157 days (131 to 332), SPOT 4: 148 days (124 to 276), SPOT 5: 150 days (116 to 172), TOPEX/POSEIDON: 443 days (425 to 454)

Even considering this aspect, the TLE have clearly a fluctuating acquisition time unit. These fluctuations shall impact the detection and the level of quality of the detection depending on selected lags (3, 5 or 10 days). Indeed, looking at the data, it has been noticed that the maximum duration between two-time units is for each of the DORIS satellite in days:

CRYOSAT 2: 4.24 , ENVISAT: 2.79, HAIYANG 2A: 11.25, JASON: 4.49, JASON 2: 8.04, JASON 3: 3.99, SARAL: 6.71, SENTINEL 3A: 1.96, SENTINEL 3B: 3.93, SPOT 2: 2.96, SPOT 4: 3.17, SPOT 5: 3.02, TOPEX/POSEIDON: 3.04

This is not the average case but implies a structural potential problem with a lag of 3 days in the results.
Moreover, in the time series literature, unevenly spaced time series are mainly occurring when there are missing values or/and when a multivariate data sets consist of time series with different frequencies [4]. Usually, unevenly spaced time series may be embedded into continuous diffusion processes or transformed into an equally spaced data using some form of interpolation. However, the method shall be kept as simple as possible to facilitate its deployment on a large amount of satellite data and the gain using interpolation is questionable. Therefore, data were kept in the raw state.

5 DET_PEAK METHOD RESULTS ANALYSIS

The DET_PEAK methodology is based on the capping level (*CL*). This *CL* level has been chosen considering the percentage of maneuvers observed in the DORIS ensemble of data.
The study period of DORIS data is summarized in Table 1 with the number of maneuvers as well as the percentage of maneuvers start points it represents (nb of maneuvers). The maximum level of the percentage of maneuvers is 3.4%. However, it should be notice that the period covered by Sentinel 3B is short, meaning that this percentage includes a lot of maneuvers linked to launching and orbital adjustment of the satellite. To take it into consideration, the level of 6% has been considered as a reasonable choice for the CL. This 6% represents a maximum of 3% positive inflexions (for the maneuvers starting points) and 3% of negative inflexions between the maneuvers.
The results presented in this section, have been obtain following the DET_PEAK method, without any other treatment.
Using this *CL* value, the results are presented globally, over the period detailed in Table 1, for all the DORIS constellation satellites. Then focus will be given to the results of Envisat comparing the performances with the other method cited in the literature.

5.1 Results for DORIS constellation satellites

To put the percentage of maneuvers of Table 1 into perspective the two next columns gives the results of the inflexion point selection phase. The percentage of peaks is the number of inflexion points with respect to all the other points of the time series and the percentage of negative inflexions, the percentage that is considered as maneuvers before noise filtering. As could be seen some satellites present a level of peaks far above the *CL* value.

The Table 2 presents in percentage the F1 score, the recall, the precision and the error rate for all DORIS satellites over the global period mentioned for each one in Table 1 and for two lag options 10, and 5 days. The calculation uses a confusion matrix build as mentioned in 3.3.

Table 1. DORIS constellation summary.

	Start date	**Last date**	**Nb of maneuvers**	**% of maneuvers**	**% of peaks**	**% of negative inflexions**
CRYOSAT 2	01/05/2010	16/11/2019	121	2,3	4,9	2,3
ENVISAT	18/04/2002	06/04/2012	176	1,6	9,1	2,9
HAIYANG 2A	30/07/2012	10/09/2019	48	0,7	21,3	9,2
JASON	10/12/2001	25/06/2013	120	2,4	8,2	2,7
JASON 2	24/06/2008	04/10/2019	109	1,7	6,4	2,2
JASON 3	28/01/2016	06/12/2019	22	0,8	4,1	1,2
SARAL	26/02/2013	03/06/2019	59	1,6	4,8	2,2
SENTINEL 3A	01/03/2016	12/12/2021	34	0,6	2,1	0,9
SENTINEL 3B	28/04/2018	18/10/2019	31	3,4	5,1	1,8
SPOT 2	20/01/2000	30/07/2009	83	0,8	14,4	4,9
SPOT 4	07/01/2000	25/06/2013	103	0,6	10	3,3
SPOT 5	06/05/2002	02/12/2015	111	0,7	12,5	3,9
TOPEX/POSEIDON	09/01/2000	20/11/2004	23	1,2	25	10,2

Best results are, logically, obtained with the 10 days lag. For this lag, at the exception of TOPEX/POSEIDON that will be detailed later, recall is always above 80% so only less than 20% of maneuvers are not detected. The precision presents more fluctuations with more than 50% of false positive for Haiyang 2A, JASON 3 et TOPEX/POSEIDON. This could show the limits of the noise filtering of the DET_PEAK method or, after decomposition trough time, some period with abnormal instabilities within a satellite trajectory.

Table 2. Results of the DET_PEAK method for Doris constellation satellites.

Sat. Name	**LAG 10 days**				**LAG 5 days**			
	F1	Recall	Precision	Error rate	F1	Recall	Precision	Error rate
CRYOSAT 2	90	85	95	0,43	83	78	90	0,71
ENVISAT	90	85	96	0,3	85	79	92	0,46
HAIYANG 2A	62	85	48	0,72	47	69	36	1,04
JASON	85	79	92	0,67	72	62	86	1,18
JASON 2	85	88	83	0,52	75	73	77	0,83
JASON 3	74	95	60	0,52	68	86	56	0,63
SARAL	90	92	89	0,33	74	78	71	0,88
SENTINEL 3A	83	91	76	0,24	78	88	70	0,32
SENTINEL 3B	93	90	97	0,44	75	65	91	1,44
SPOT 2	84	83	85	0,24	81	81	82	0,28
SPOT 4	78	87	70	0,31	72	84	63	0,41
SPOT 5	85	89	81	0,21	74	78	71	0,37
TOPEX/POSEIDON	52	61	45	1,3	41	48	35	1,6

For example, the temporal details explaining for TOPEX/POSEIDON the results are shown in Figure 2 and statistically represented in Table 3. Figure 2 represents the temporal evolution of the semi-major axis values from 09/01/2000 to 20/11/2004, decomposed by 500 points blocks. The vertical lines indicate when a maneuver has been flagged (a solid / dotted line for: detected / not detected maneuvers; a bleu / red line for Orbit maintenance maneuver / Orbit transfer maneuver) by the DORIS Service interface. The color dots materialized the peaks that has been employed by the DET_PEAK method. The colors is to highlights the way the noise filtering phase works within the DET_PEAK method: blue dots when selected correctly as maneuver (TP), red when selected incorrectly as maneuvers (FP), green points when filtered out properly by the noise filtering phase as "not a maneuver". The top block presents less noise than the mid ones. More precisely the noise is increasing at the end of the top block. All the false positive are within this phase of higher noise period. Two of the false negatives are within the top and the mid-block, all the others are in the low block and temporally during the drift maneuvers that entitles to coordinate TOPEX/POSEIDON with the orbit of his successor JASON.

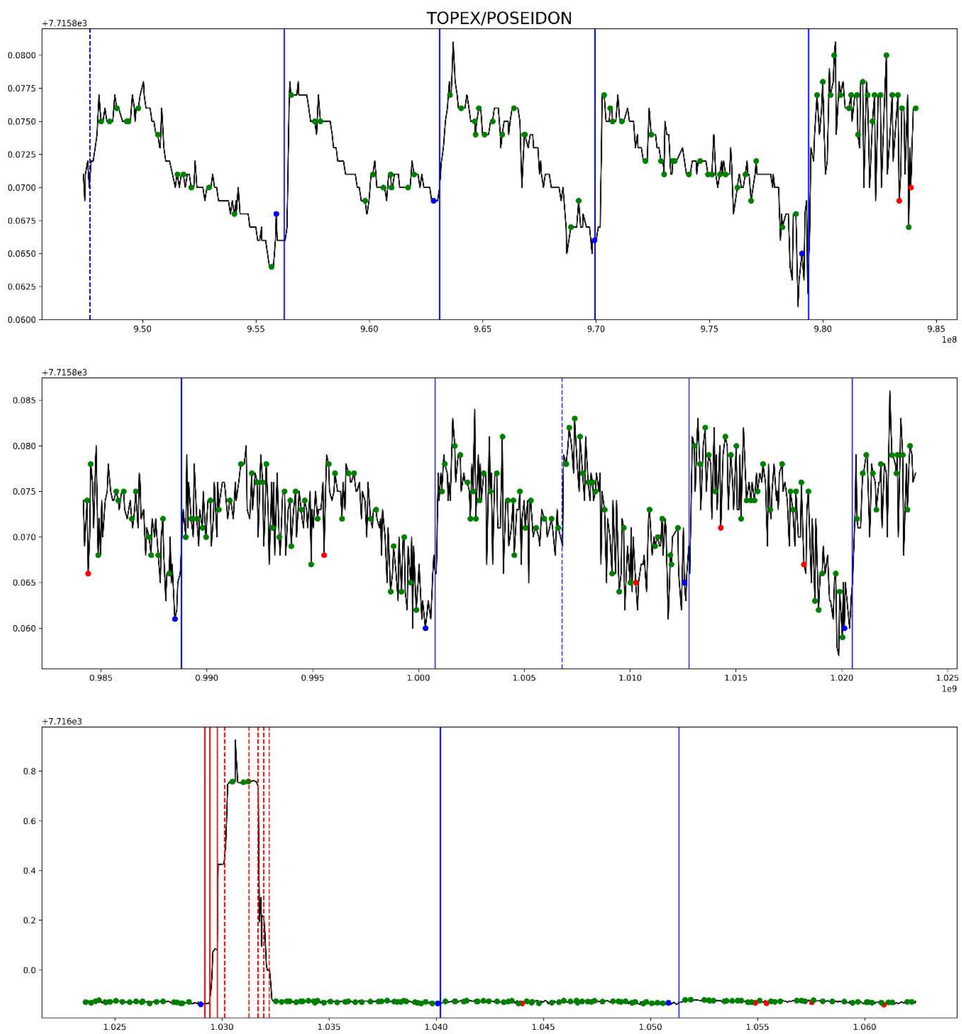

Figure 2. Semi-major axis values evolution by block of 500 points for TOPEX / POSEIDON with maneuvers as well as DET_PEAK filtering information.

From a statistical point of view results could then be decomposed by blocks as presented in Table 3 with 10 days of lag. This decomposed vision enables to better understand the way the DET_PEAK method performs.

Table 3. Results of the DET_PEAK method for TOPEX / POSEIDON satellites per block of 500 points

	F1	Recall	Precision	Error Rate
Top	73	80	67	0,6
Mid	57	80	44	1,2
Bottom	50	50	50	2,02

5.2 Focus on the ENVISAT results

The following section will describe the results on the DET_PEAK method for the satellite ENVISAT. This satellite has been used since the [5] article as a reference in the literature.

A global vision has been given in the previous section. In this section, the results are, first detailed through 500 points blocks and, secondly on the time windows of ENVISAT literature results to facilitate the understanding of the DET_PEAK performance compared to other.

In Table 4 is presented the results by blocks of 500 successive points (iter_nb) covering the period 18/04/2002 to 06/04/2012 and with an authorized lag of 10 or 5 days. Results are excellent through time with an exception for block 16 and 18.

The block 16 is covering the period 19/12/2009 to 20/05/2010, where recall is falling to 57% as 3 maneuvers were not presenting a marked upscale of the semi-major axis value.

The block 18 is covering the period 21/10/2010 to 21/03/2011, where recall is falling to 40%. However, looking at Envisat newsletter, the satellite has started an orbital change moving to a lower orbit. Indeed, during the period 22/10/2010 to 02/11/2010 a series of satellite maneuvers were performed to bring Envisat to its new orbit and the Envisat data flow was suspended

Table 4 - Results of the DET_PEAK method for ENVISAT satellites per block of 500 points

iter_nb	LAG 10 days				LAG 5 days			
	F1	Recall	Precision	Error rate	F1	Recall	Precision	Error rate
0	100	100	100	0	100	100	100	0
1	100	100	100	0	92	86	100	0,2
2	100	100	100	0	95	91	100	0,2
3	82	70	100	0,6	82	70	100	0,6
4	88	100	78	0,4	67	86	55	1,2
5	100	100	100	0	100	100	100	0
6	100	100	100	0	89	100	80	0,2
7	100	100	100	0	100	100	100	0
8	86	75	100	0,2	86	75	100	0,2
9	100	100	100	0	100	100	100	0
10	92	86	100	0,2	92	86	100	0,2
11	91	83	100	0,2	91	83	100	0,2
12	82	70	100	0,6	82	70	100	0,6
13	83	77	91	0,8	73	62	89	1,2
14	88	78	100	0,4	80	67	100	0,6
15	95	100	91	0,2	86	90	82	0,6
16	73	57	100	0,6	67	57	80	0,8
17	93	88	100	0,2	93	88	100	0,2
18	57	40	100	1,2	57	40	100	1,2
19	100	100	100	0	100	100	100	0
20	86	86	86	1,5	72	64	82	2,62

Table 5. Results of the DET_PEAK method for ENVISAT satellites compared to literature windows (period covered) results.

Literature method (versus DET_PEAK)	Period covered	Literature method				DET_PEAK			
		F1	Recall	Precision	Error rate	F1	Recall	Precision	Error rate
MWCF [5]	2003-2006	95	91	100	0,13	94	91	98	0,16
Box DBScan and layered analysis [1]	2011	81	76	86	0,75	86	79	95	0,5
fuzzy C-means clustering [2]	2003-2005				1,4				0,97

The results of the DET_PEAK method, for the ENVISAT satellite, could be compared to the literature ones presented in Table 5 and detailed in the introduction. The performance of the DET_PEAK methods for ENVISAT are equivalent to the MWCF method ones and are better than the one of the Box DBSCAN and layered analysis and of the fuzzy C-mean clustering ones.

6 CONCLUSIONS

With a 5 days lag authorized between the real maneuver and their detection, very good results were obtained for most of the satellite. Results of the maneuvers detection up to February 2020 (end of our extracted data) for the satellite of the DORIS constellation are: F1 score 81% (52 to 93%), recall 86% (61 to 95%), precision 78% (45 to 97%) and error rate 0.5% (0.2 to 1.3%). This is a sufficient level to consider the method robust enough to fulfil our objective. It shall also be mentioned that the method required no parameter at all to answer the need of being:

- fully generic (one method whatever the satellite),
- fully automatic (no parameter to be tuned, no other information than the TLE ones requested)
- fully deployable in a big data world (minimalist formalism to facilitate its deployment)

This new method of maneuvers detection embodies a cross-fertilisation between physics and data mining**.** To deepen the DET_PEAK limits the worst case (Topex/POSEIDON) was detailed and results could be explained by a major drift maneuver.

To go further, some questions will need to be deepened: is this technique valid on all types of satellites? Can the areas of instability where the method is less robust be detected in advance to indicate where the level of uncertainty is increasing?

Finally, this method shall be challenged more largely to other satellite maneuvers detection methods. The ratio: benefit (automatic, without parameterization, minimalist formalism for optimized deployment) versus robustness of the results will then be refined for its deployment on a large amount of satellites.

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