Technique for GEO RSO Station Keeping Characterization and Maneuver Detection

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Abstract

As the Geosynchronous satellite population increases so does the importance of accurate catalog maintenance for purpose of conjunction assessment and spacecraft operator situational awareness, particularly for operators in dense regions or collocated slots. The following presents the design, results, and limitations of an algorithm developed to aid these efforts by characterizing maneuver histories of geosynchronous satellites using public domain satellite TLE histories. Central to the algorithm is use of basic signal processing techniques to enhance the ability to detect small orbit changes amongst the noise in the raw data. After filtering out single point inconsistent outliers the algorithm processes each orbit state with a temporal lead trail window of surrounding orbit states being propagated over a range of common epochs with key metrics being recorded. Two methods are then used to characterize the maneuver history. A maneuver detection algorithm flags potential maneuver events at any epoch where the comparison metrics between orbit states exceed several checks. Maneuver events are characterized as In-Plane or Out-of-Plane events, referring to the direction of the imparted change in velocity relative to the satellite orbital plane. The second method performs a maneuver frequency fit to the data to determine to what degree any pattern of periodic maneuvering exists. Also characterized is whether electric or chemical propulsion methods are being used. To illustrate this approach several examples using public domain orbit state data are processed with results provided.

1. Introduction and Background

Geosynchronous (GEO) satellite station-keeping maneuvers introduce unmodeled orbit state changes that can present a challenge to timely and accurate satellite catalog maintenance. Knowledge of historical station keeping behavior of GEO Resident Space Objects (RSOs) could enhance catalog maintenance by allowing a priori assumptions about future behavior to effect how observations are correlated and processed. The following sections present an automation suitable technique for detection and characterization of past station keeping maneuver histories. The algorithm is designed to work within the limitations of the Two Line Element (TLE) data from the public catalog [10] but can also be used with other data sets. In addition to public catalog TLE data, public domain commercial operator orbit state and maneuver data [3] [5] was used, for purpose of comparison.

2. Geosynchronous Orbit Station Keeping

GEO satellite orbits are affected by a number of perturbations which cause their inclination, longitude, and eccentricity to drift over time. To overcome these effects regular station keeping maneuvers are often used to maintain a satellite in its assigned longitude and inclination box which is typically +/- 0.1° or less. The frequency of station keeping maneuvers can vary greatly depending on the type of thrusters being utilized, crew constraints, payload and ground station pointing requirements, cooperative station keeping requirements with collocated spacecraft, and other factors. However, operators of spacecraft utilizing chemical propulsion typically perform regular station keeping burns at intervals ranging from once every week up to only once every couple of months. Satellites using electric propulsion perform much lower thrust longer duration burns and typically maneuver much more frequently, often multiple times per day [4].

Inclination drift is caused by third body effects of the sun and moon. This is a result of the geostationary orbit plane and the orbital plane of the earth and moon not being aligned. For a typical beginning of life GEO communication satellite this causes the inclination to increase at a rate of approximately 0.85° per year [9], requiring somewhere in the neighborhood of 46 m/s of delta-V annually to counteract. Maneuvers to reduce inclination and maintain it near zero are known as North-South station keeping and can often be the largest contributor to GEO satellite propellant usage.

Satellite longitude at GEO is primarily affected by obliquity of earth's equator as well as solar radiation pressure. These perturbations tend to cause satellites to drift towards one of the GEO gravity wells located at 73°E and 104°W. Eccentricity also tends to increase as a result of these perturbations however current strategies often incorporate eccentricity corrections in East-West station keeping maneuvers. Depending on the frequency and operational strategy, East-West station keeping maneuvers typically impart between 0.05 and 0.2 m/s of delta-V per maneuver [7].

In addition to station keeping maneuvers many satellites also periodically impart small amounts of delta V, typically 0.001 to 0.005 m/s, in the process of performing momentum dumps to reduce accumulated momentum in the reaction wheels used for attitude maintenance.

3. Algorithm Description

The maneuver characterization algorithm is divided into three functional parts: filtering of raw data, processing of the filtered data, and characterization of the station keeping history. All code was written in Python with use of the Matplotlib package for plotting. All orbit propagation is accomplished with the Python SGP4 package [8].

3.1 Filter Function

The filter function processes the raw orbit state data and removes any data points that fail a consistency check with the surrounding data. For each orbit state in the satellite ephemeris, the trailing and leading orbit states are propagated to the epoch of the center orbit state, Fig. 1. The range is then compared between each combination of the three orbit states. If the center state is valid, both the propagated lead and trail states are expected to compare more closely with the center state, in terms of range, than the propagated lead and trail state do to each other. If this assumption does not hold true then the center state is rejected.

This approach only rejects data when the adjacent points are consistent with one another. This ensures that orbit state changes due to maneuvers are unlikely to cause data to be thrown out. The filter would not remove data when multiple inconsistent orbit states occur in a row. This is advantageous with a noisy data source such as the available TLE data sets. Fig. 2 shows a short snapshot of inclination history for DIRECTTV12 with the filtered out states shown in blue. From 2010 to 2014 DIRECTTV12 had 1859 orbit states in the public TLE catalog. When duplicates and inconsistent data were removed, per the described filtering process, 1661 remained.

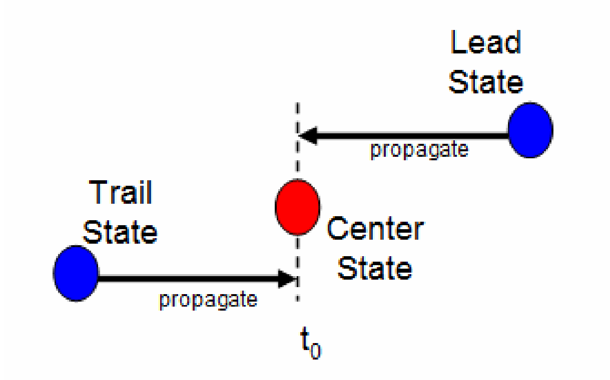


Fig. 1: Propagation to Center Epoch for Range Based Orbit State Consistency Filter

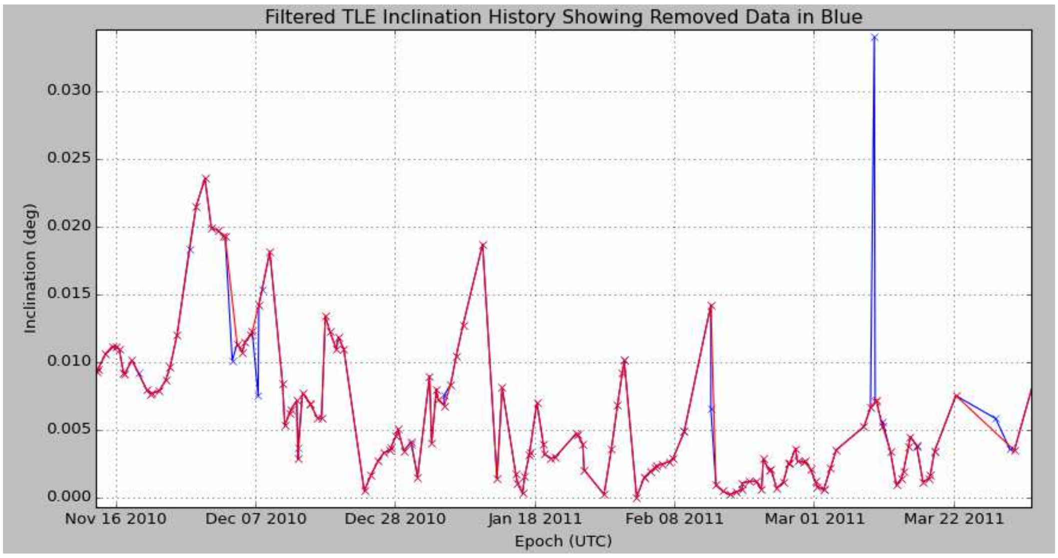
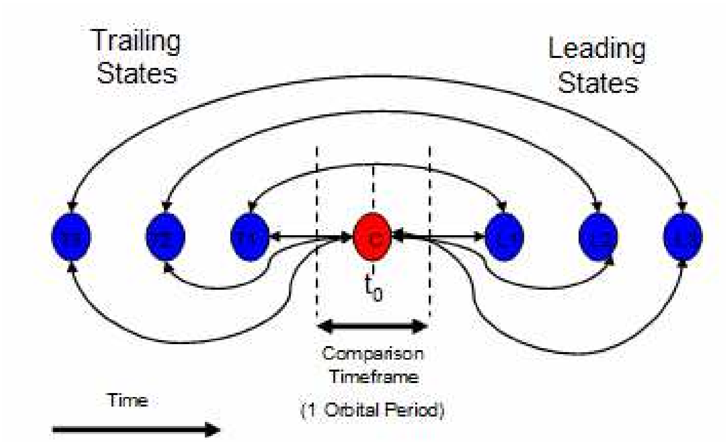


Fig. 2: Example TLE Inclination History with Filtered (Red) and Unfiltered (Blue) States

3.2 Processing Function

This function processes the filtered data and produces the orbit state comparisons used later by the characterization function. At each orbit state in the history, a window of three leading and three trailing states are propagated and compared to the center orbit state as well as to each other, Fig, 3. Each comparison is done over an interval of one orbital period centered on the epoch of the center state. Over this interval the max Radial, InTrack, and CrossTrack magnitudes are recorded between each pair of states being compared, Fig. 4. Using max position delta over one orbital period allows for combining position and velocity differences between states in a single metric. Using the RIC frame is convenient for dealing with differences between orbit states as well as for categorizing the maneuver necessary to achieve the observed orbit state difference.

Comparing a lead and trail window of states helps to overcome noise in the data to discern maneuvers that would not be apparent if each state were compared only with the next state in the file. This does however increase the minimum temporal spacing needed between maneuvers to detect them as two separate maneuvers.



Fig, 3: Nine orbit state comparisons made for each state in the history

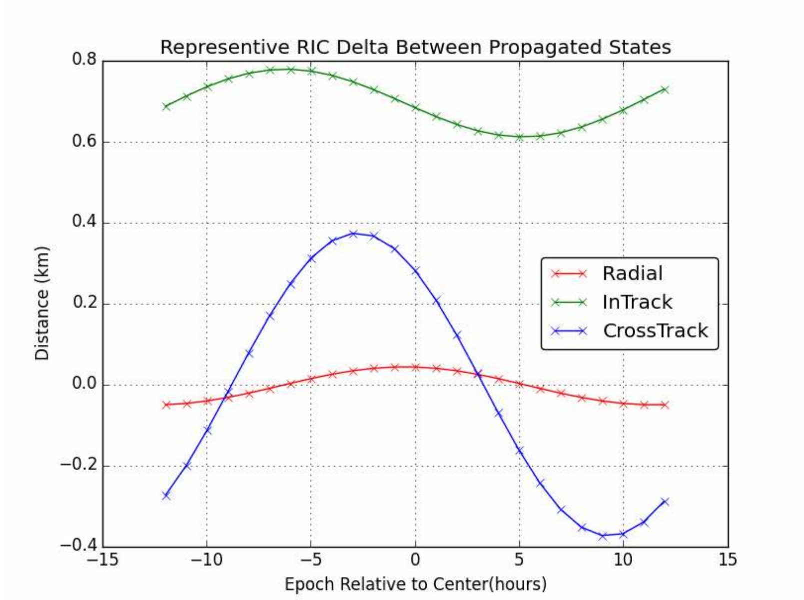


Fig. 4: Example RIC frame comparison between two RSO orbit states over one orbital period

3.3 Characterization Function

The third function uses the compiled history of orbit state comparisons to attempt to characterize the station keeping behavior of the satellite. Two different methods of characterizing maneuver history are implemented. The first, the Detection Method, uses metrics derived from comparison of adjacent orbit states to identify times were it is statistically probable that the satellite performed a maneuver. The second method, the Frequency Fit Method, assumes that the satellite typically performs maneuvers at some regular frequency then attempts to find a frequency and phasing for those regular maneuvers that fits the data.

Several user input parameters can be adjusted to effect the operation of the algorithm, Table 1. Unless otherwise noted, the listed default values were used for all test cases. The Lead/Trail Range Filter setting eliminates any data points without either a trailing or lead orbit state whose range at common epoch isn't within the user input distance threshold. This can be used to eliminate large outliers in the data that were not filtered out in the previous function because the lead and trail states were not consistent with each other. The other tunable parameters affect the operation of the two maneuver characterization functions.

Table 1: User settable algorithm parameters

Tunable Parameter	Default Value
Lead/Trail Range Filter	20 km
Potential Maneuver Threshold	2σ
Maneuver Flag Lead vs. Trail Threshold	1σ
Maneuver Flag Lead vs. Center Threshold Frequency Fit Window	1σ 4 Days

Three primary metrics are compiled from the orbit state comparison data described in Section 3.2. This is done separately to characterize out of plane and in plane maneuvers. For out of plane maneuver characterization the CrossTrack component of the orbit state comparisons is used and similarly for in plane the Radial and InTrack components are used. Satellite maneuvers that include both an out of plane and in plane component are treated as two separate maneuvers. All three metrics summarize the comparison data in terms of standard deviations from the mean values for the underlying comparison.

Metric #1: Standard deviation of the first lead state versus the center state

Metric #2: Sum of the standard deviations of the first through third lead states versus the center state

Metric #3: The value of Metric #2 minus the sum of the standard deviations of the first through third trailing states versus the center state.

3.3.1 Maneuver Detection Method

The Maneuver Detection method assumes that in the presence of a maneuver the next three orbit states after the maneuver would have conspicuously high deltas versus the last data point prior to the maneuver. This assumption is captured by Metric #2. By using the leading three orbit states to detect maneuvers instead of one (i.e. Metric #1) inaccurate orbit state knowledge can be partially overcome at the expense of increasing the time necessary between maneuvers to discern them as separate events. Metric #3 takes this a step further by subtracting out the deltas from the three orbit states prior to the maneuver. This effectively requires that three fairly consistent orbit states exist prior to a maneuver for that maneuver to be detected by the algorithm. This reduces false positives but can also filter out legitimate maneuvers that occurred in periods of noisier than average orbit state data.

By default the maneuver detection method uses Metric #3, flagging a potential maneuver at the epoch of any data point where the metric exceeds a threshold number of standard deviations, see Table 1. Two additional checks are then performed to reduce the chance that a flagged maneuver is due to temporary noise in the orbit state data. For the potential maneuver to be passed as actual the comparison of the center state to all three leading orbit states must be above a threshold number of standard deviations from the mean, see Table 1. Second, comparisons of the first leading versus first trailing and similarly the second and third lead trail pairs must also be above a threshold number of standard deviations above the mean value of the same comparisons over the entire dataset, Table 1. This throws out potential maneuvers if there is a post maneuver orbit state that agrees closely with a pre maneuver orbit state. After these two checks to reduce false positives, any remaining maneuvers that are adjacent to one another are then collapsed to one assumed maneuver and the results reported.

3.3.2 Frequency Fit Method

Rather than detecting individual maneuvers, the Frequency Fit Method attempts to find a station keeping maneuver cadence that best fits the data. This approach can work well for cases where a satellite performs regular maneuvers but the ratio of the maneuver signature to the random error in the orbit state data is relatively low.

Separately for out of plane and in plane maneuvers this method iterates through assumed frequencies and phasing of station keeping maneuvers to find a best fit to the data. In a given iteration, if the assumed frequency were for example 10 days and the phasing were one day, then the assumed maneuver epochs would start one day after the first orbit state and continue at a frequency of every 10 days. Whole number frequencies between 8 and 65 days are checked with phasing at each frequency between 0 to the frequency in 0.5 day increments, resulting in a total of 4,234 combinations checked.

Each combination of frequency and phasing is evaluated by taking all orbit states in the history and subtracting out those within a configurable window after each assumed maneuver epoch. By default the window is four days, Table 1. The mean value of Metric #2 for all remaining points is then recorded. The best fit frequency and phasing pair is that which minimizes the mean value of Metric #2 for the remaining points, representing that a maximal amount of aberration due to real maneuvers was removed. If the satellite was performing maneuvers at regular intervals a conspicuously low mean value for one of the iterations will occur.

4. Example Cases and Results

The following test cases were chosen to illustrate use of the algorithm with a wide range of GEO satellite maneuver behavior and where possible allow comparisons to published maneuver history data.

4.1 Discrete Maneuvers: EUTELSAT28A (SCC#26719)
4.2 Frequent Low Thrust Maneuvers: INMARSAT5F1 (SCC#39476)
4.3 Evaluation versus Operator Orbit State and Maneuver Data: Multiple Intelsat Satellites
4.4 Slot Changes, Disposal, and End of Life: INTELSAT2 (SCC#23175)
4.5 Previously Studied LEO Satellite with Known Maneuver History: ENVISAT (SCC# 27386)

4.1 Discrete Maneuvers

EUTELSAT28A (SCC#26719) is a GEO communication satellite currently operated by commercial services provider Eutelsat at 28.5°E, providing digital television services over Europe. Built by Alcatel Space on the Spacebus 3000 platform it represents a typical medium size GEO spacecraft utilizing chemical propulsion for both E-W and N-S station keeping. January through June of 2012 was chosen for the test case since the publicly published TLE data contained no extended outages during that period. The six month timeframe was deemed sufficient for illustration purposes although in practice a larger span may be desirable in some instances.

The default Lead/Trail Range Filter of 20km, see Table 1, eliminated four out of the 189 orbit states over the six month period. The remaining 185 orbit states represent an average spacing between points of approximately 1.0 days. The other default settings were used with the exception of the Maneuver Flag Lead vs. Trail and Lead vs. Center thresholds which were set to 0 σ. With the settings at the default 1 σ a total of 11 maneuvers were detected, however a visual inspection determined that the filters for reducing false positives were also eliminating a significant number of likely real maneuvers. It was therefore determined to turn off the filters for this case which resulted in a total of 29 maneuvers detected.

Fig. 5 shows the RIC component deltas between each orbit state and the next orbit when compared using the method described in Section 3.2. A significant amount of variability exists, especially in the InTrack component but is within the typical range seen for GEO RSOs in the public domain TLE catalog. The variability is due to a combination of spacecraft maneuvers, error in orbit state knowledge, and propagation modeling error.

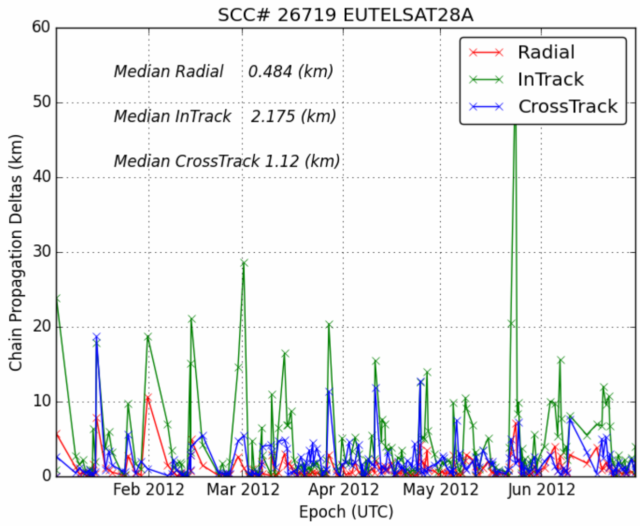


Fig. 5: Chain Propagation Results for EUTELSAT28A

The frequency fit method of characterizing maneuvers resulted in a best fit of 14 days between maneuvers for both Out of Plane and In Plane maneuvers, Fig. 6. The success metrics for the best fit were conspicuously better than the surrounding data. Fourteen days also corresponds well both with satellite operator norms and with a visual inspection of the plotted data in Fig. 7 and Fig. 8. It is therefore believed that the frequency fit method accurately identified a true pattern in the station keeping of EUTELSAT28A.

Fig. 7 summarizes the results for out of plane maneuvers. Inclination and RAAN are plotted in the upper subplot along with the maneuvers flagged by the detection method, red dots, and the frequency fit method, vertical dashed lines. The Maneuver Detection Method appears generally effective at detecting maneuvers, with several maneuver signatures clearly visible in the metrics plot. However during some periods, notably late February to early March, the noise in the data appears to have overcome the signature of the station keeping maneuvers. There were also several maneuvers identified that may be false positives or have been flagged as two maneuvers when likely only one occurred. However, enough maneuvers had a clear signature in the derived metrics that the Frequency Fit Method was able to identify a likely operational tempo for station keeping. The Frequency Fit Method appears to have been generally consistent with the visual representation of the data. A dashed black line appears within four days of most visually recognizable spikes in the data.

Fig. 8 summarizes the in plane maneuvers. Semi-Major Axis (SMA) relative to GEO orbit radius and Eccentricity are plotted along with the maneuver detection and frequency fit results. Similar to the Out of Plane results the Maneuver Detection Method is believed to be more accurate in determining the likely epoch of any given single burn while the Frequency Fit Method is better at characterizing the overall scheme of the maneuvers.

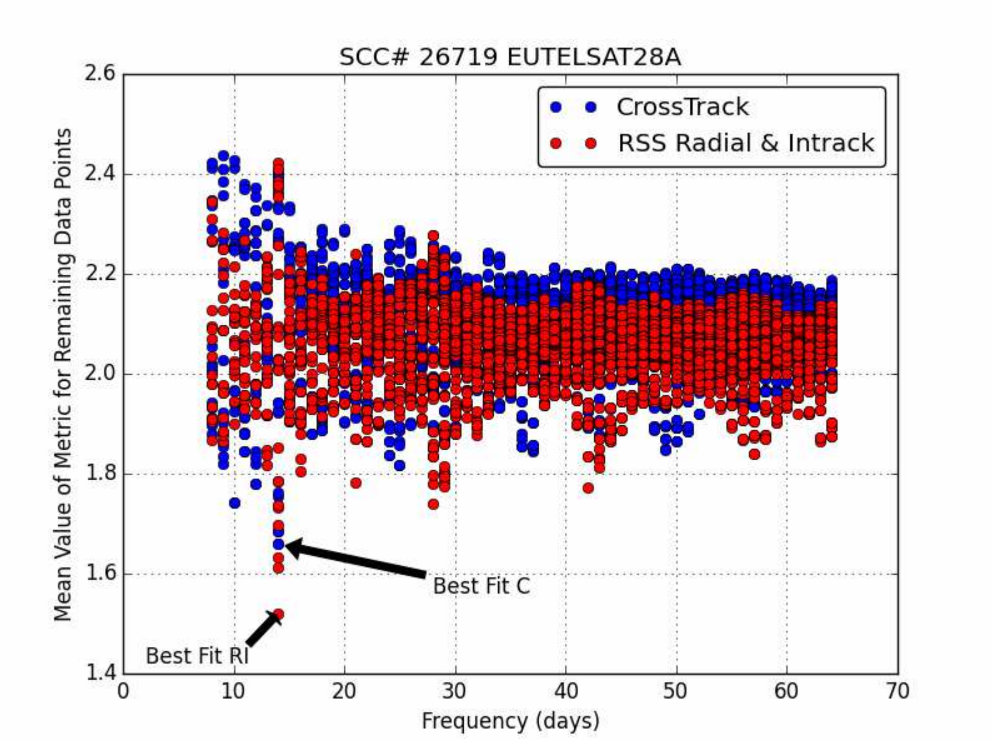


Fig. 6: Frequency Fit Metrics for EUTELSAT28A

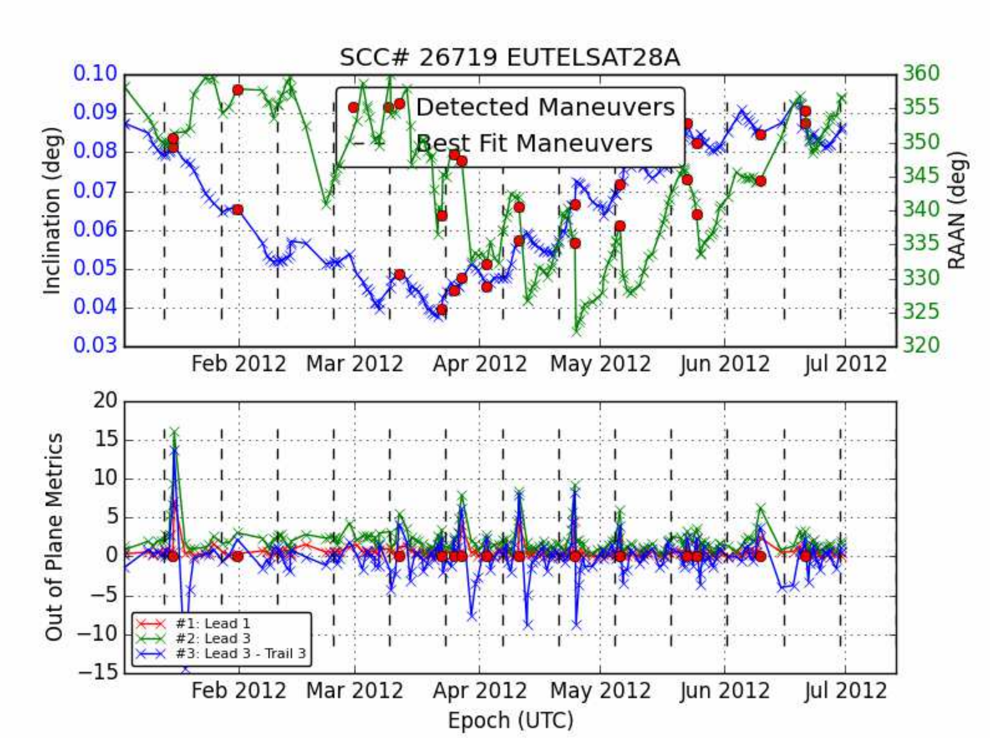


Fig. 7: Out of Plane Maneuver Detection and Frequency Fit Results for EUTELSAT28A

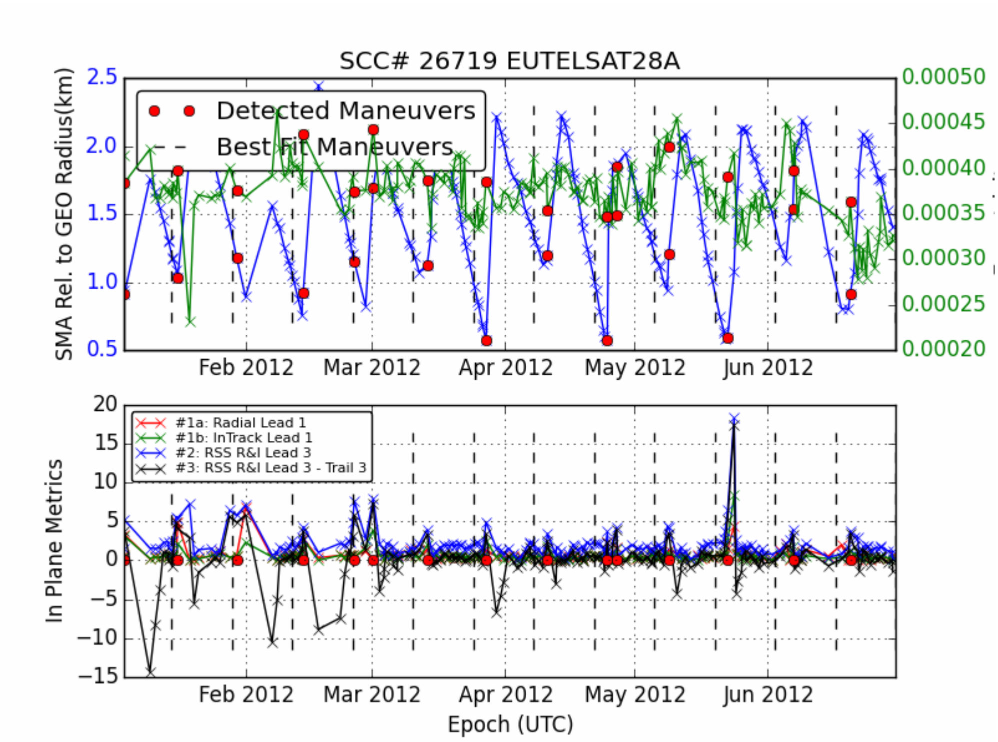


Fig. 8: In Plane Maneuver Detection and Frequency Fit Results for EUTELSAT28A

4.2 Frequent Low Thrust Maneuvers

INMARSAT5F1 (SCC#39476) is a GEO communication satellite currently operated by commercial services provider Inmarsat at 63°E, providing high-speed broadband mobile satellite communication services over the Indian Ocean. Built by Boeing on the BSS-702HP platform it utilizes Boeing's low thrust Xenon Ion Propulsion System (XIPS) for both N-S and E-W station keeping. Station keeping maneuvers performed with the XIPS system are typically very long duration and are performed very frequently as compared to high thrust lower frequency maneuvering for chemical systems. Since INMARSAT5F1 is a relatively new satellite, the most recent available six month period was chosen as the test case timeframe in order to best represent the long term operational station keeping tempo.

Satellites performing frequent low thrust maneuvers utilizing electric propulsion represent a challenge in characterizing maneuver history. For North-South maintenance for example, station keeping maneuvers would typically be performed twice a day. With TLE data available only at a frequency of approximately one orbit state per day this makes individual maneuvers impossible to discern in the data. The goal of this algorithm therefore is to simply identify that the satellite being analyzed is likely performing frequent low thrust maneuvers.

The default tunable parameters, as shown in Table 1, were used for analyzing INMARSAT5F1. Fig. 9 shows the chain propagation results, indicating the amount of noise in the data. The median values are similar to EUTELSAT28A and several spikes exist which could be due to maneuvers or state knowledge error.

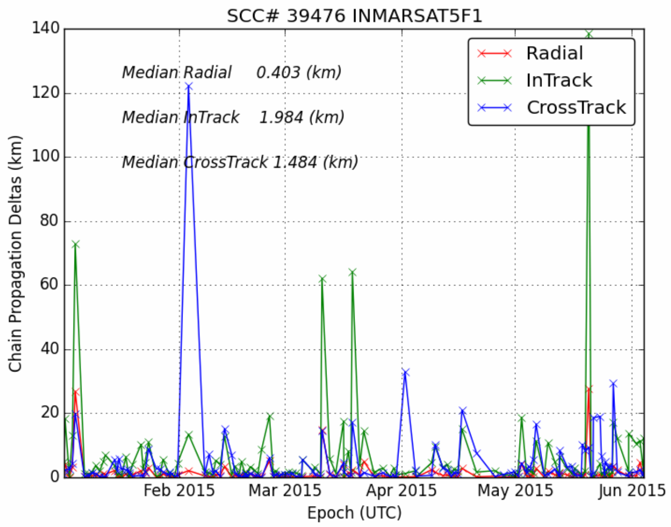


Fig. 9: Chain Propagation Results for INMARSAT5F1

Examining the results in Fig. 10, Fig. 11 and Fig. 12 it can readily be determined with no a priori knowledge that INMARSAT5F1 is very likely performing frequent low thrust station keeping maneuvers. A visual inspection of the Keplerian element plots show that INMARSAT5F1 is actively maintaining both a N-S and E-W station keeping box. Fig. 10 shows that the frequency fit method did not result in a conspicuous best fit frequency for maneuvers. The best fits that were tagged by the algorithm were only slightly better than the surrounding frequency fits. From this it can be concluded that INMARSAT5F1 is not performing detectable burns at any regular interval between 8 to 65 days in frequency. Only a single Out of Plane and single In Plane maneuver were flagged by the Maneuver Detection Method. A single station keeping burn would not have been sufficient to maintain the observed box for a six month period. Furthermore, the median noise in the data as seen in Fig. 9 is not so extreme as to make chemical burns undetectable.

With no a priori knowledge it can therefore be concluded with some certainty that INMARSAT5F is likely performing frequent low thrust maneuvers and that they are at some frequency of greater than once per every eight days. Making it highly likely that INMARSAT5F is utilizing electric propulsion.

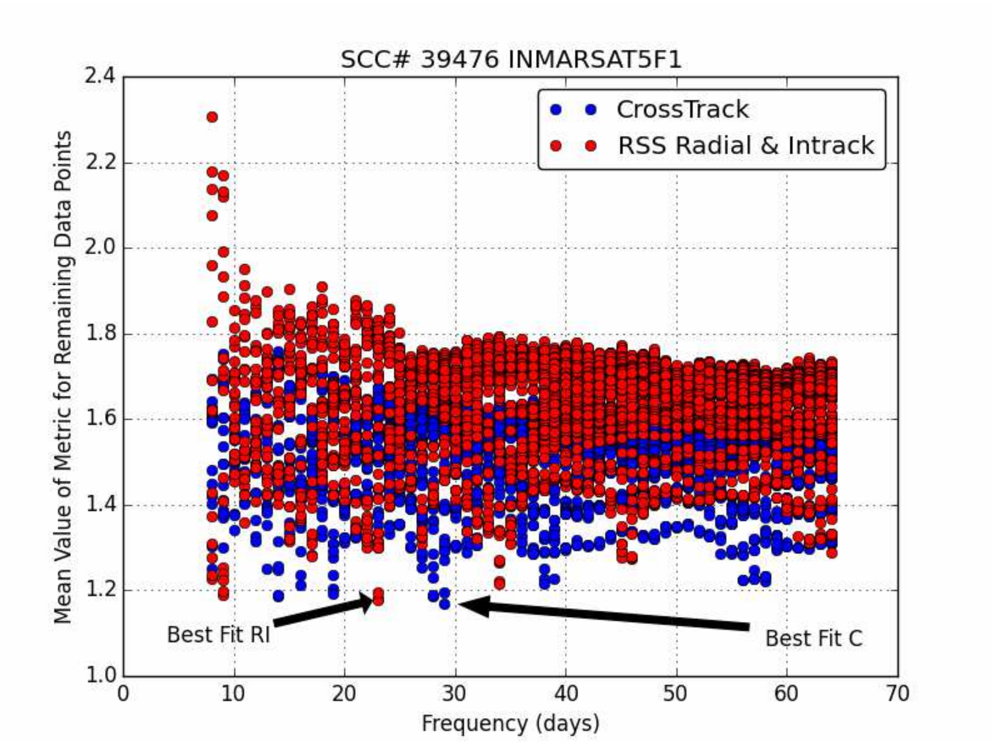


Fig. 10: Frequency Fit Metrics for INMARSAT5F1

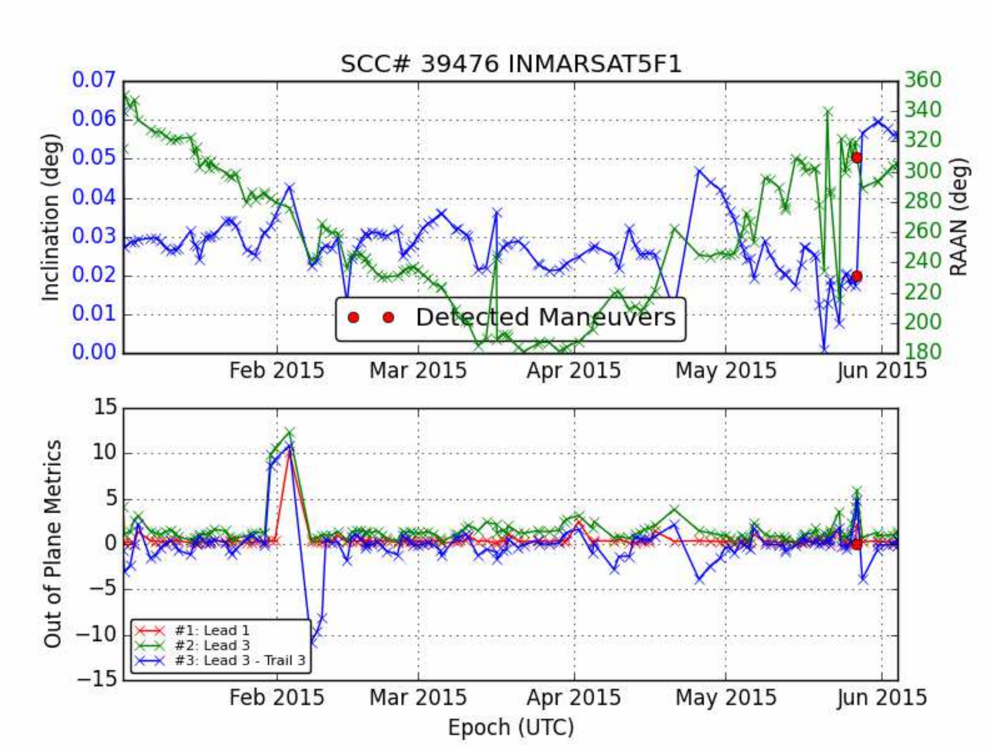


Fig. 11: Out of Plane Maneuver Detection Results for INMARSAT5F1

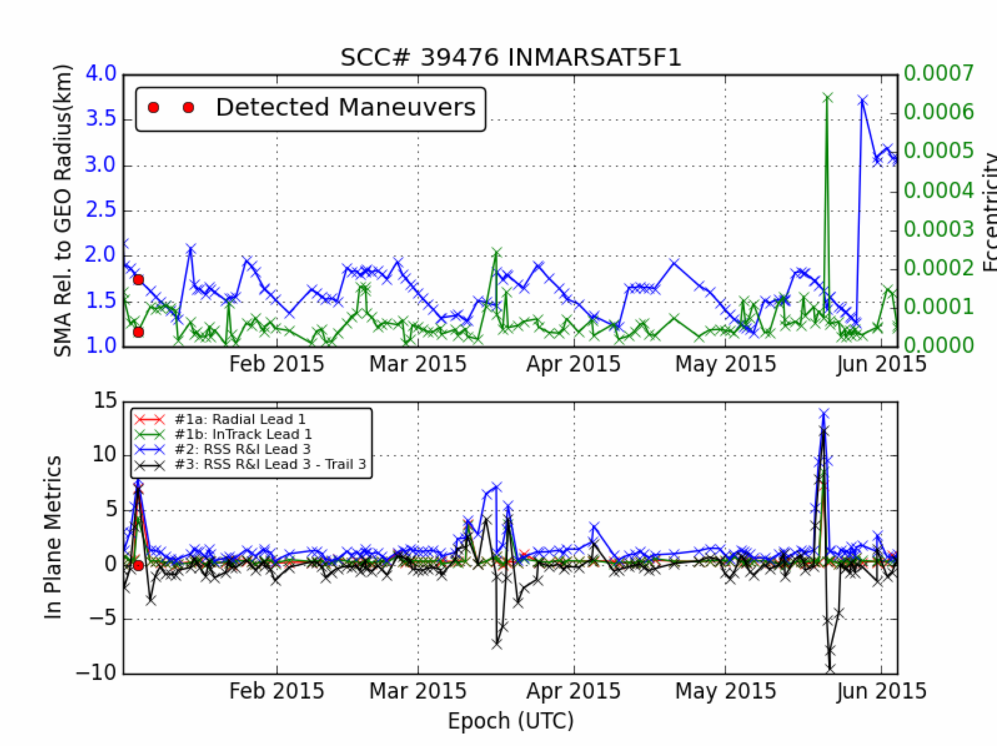


Fig. 12: In Plane Maneuver Detection Results for INMARSAT5F1

4.3 Evaluation versus Operator Orbit State and Maneuver Data

This test case uses the Maneuver Detection method against both the public TLE catalog data and operator state data and evaluates both against known maneuver times published for a number of Intelsat satellites. Intelsat provides weekly ephemeris files and maneuver updates for a number of satellites [5]. Four satellites were selected to compare to the data from the public TLE catalog in order to determine if maneuvers were detectable. By comparing the results of the Maneuver Detection Method on the same satellites with two data sources, it was possible to evaluate the performance of the algorithm by treating the operator state data as the truth data set. One limitation of this approach is that Intelsat does not provide covariance data with their operator ephemeris, so there is no ready way to assess the accuracy of the truth data set. The spacecraft used for analysis are all active geostationary communications satellites which are regularly station kept using chemical propulsion. In order to perform this comparison, the Intelsat Keplerian element ephemeris data files were converted to TLE format. In most cases Intelsat provided weekly ephemeris file updates. In order to compare these to the catalog TLE data, the ephemeris was propagated and TLE data generated in 12 hour increments between operator states. This allowed the Maneuver Detection Method a fuller data set to process as compared to the catalog data which is typically at one day intervals. For each spacecraft, data was created for the week before and the week after a maneuver. The Maneuver Detection method was run on each data set with the results summarized in Table 2**Error! Reference source not found.**. All analysis used the default algorithm settings with no tuning of parameters, see Table 1.

Five out of the six know of the known maneuvers were detected in the operator state data. Using the public TLE catalog data two of four burns were detected with the remaining two burns not counted because there was not yet enough post burn TLEs in the published catalog as of the date of this analysis. The results demonstrate the dependence of the maneuver detection algorithm on the accuracy and currency of the orbit state data source.

Intelsat 1002 was the most extensive test case with three known burns over a period of three weeks. The algorithm picked out all three in the operator data and two out of three in the public TLE catalog data. The cross track metric for both the operator data and the TLE catalog data are shown in Fig. 13 and Fig. 14 respectively. The difference between the two figures clearly shows the increased noise in the TLE data relative to the operator state data. In the operator data all three known burns are clearly visible in the lower detection metrics plot as well as an additional burn in early May.

In the case of Intelsat 905 and 907, the maneuver was successfully detected in the operator data but there was insufficient post maneuver data from catalog data to evaluate. The Intelsat 906 maneuver was not detected in either the operator or the catalog data. It is possible that this maneuver was very small or the operator data provided was in error.

Table 2: Results of Operator State Data Analysis

SCC Number	Common Name	Maneuver Date	Maneuver Type	Detected in Operator Data	Detected in TLE Data
28358	Intelsat 1002	5/15/2015	Not Specified	Detected	Not Detected
28358	Intelsat 1002	5/29/2015	North-South	Detected	Detected
28358	Intelsat 1002	6/3/2015	East-West	Detected	Detected
27438	Intelsat 905	6/6/2015	Not Specified	Detected	Insufficient Data
27513	Intelsat 906	6/7/2015	Not Specified	Detected	Not Detected
27683	Intelsat 907	6/4/2015	North-South	Not Detected	Insufficient Data

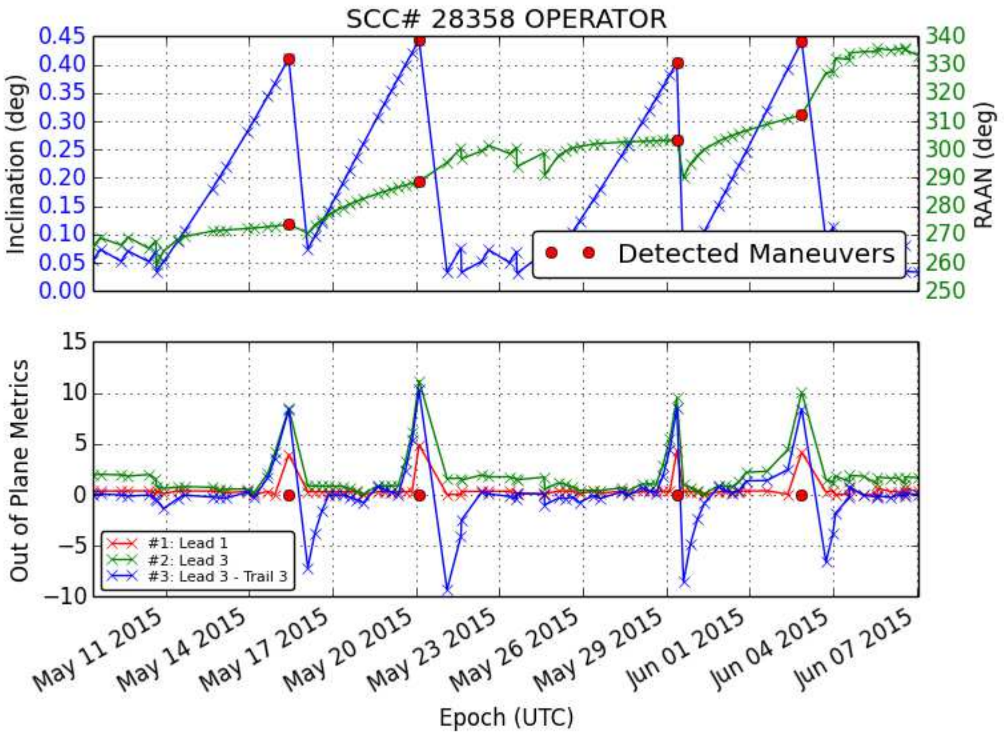


Fig. 13: Intelsat 1002 Operator Data – Out of Plane Metric

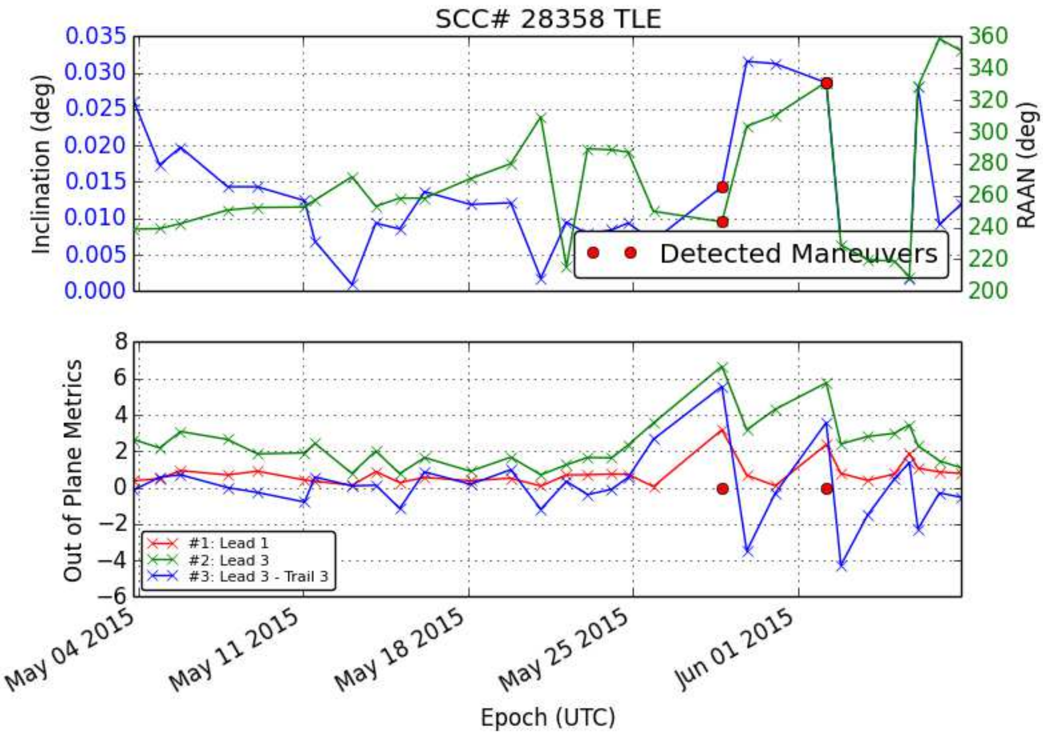


Fig. 14: Intelsat 1002 Public Catalog Data – Out of Plane Metric

4.4 Slot Changes, Disposal and End of Life

INTELSAT2 (SCC#23175) was a commercially operated GEO communications satellite launched in 1994 operated for most of its life at 169°E. The following uses orbit state history data from June 2010 through June 2011 to illustrate the maneuver detection algorithms ability to detect burns other than station keeping burns.

The default parameters shown in Table 1 were used with the exception of the Lead vs. Trail and Lead vs. Center maneuver thresholds which were set to 0.5 σ for Out of Plane and 0.0 σ for In Plane maneuver detection.

Fig. 15 shows the chain propagation results for INTELSAT2. As expected of a satellite that is no longer performing station keeping maneuvers, the median values for the Radial and CrossTrack components are much lower than for the previous cases.

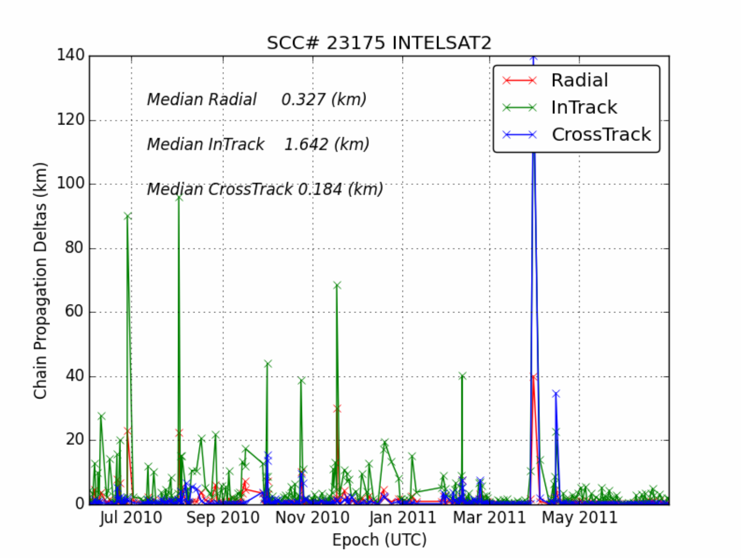


Fig. 15: Chain Propagation Results for INTELSAT2

Fig. 16 and Fig. 17 show the orbit state history and detected maneuvers for INTELSAT2. Since INTELSAT2 was not actively station keeping the frequency fit method is not shown. In Fig. 17 it can been seen that INTELSAT2 performed a set of slot change maneuvers, presumably two sets of Hohmann transfers, in July through August of 2010. It then performed another slot change in September through November of 2010. Both slot changes moved to a near-circular sub-sync orbit that caused the satellite to drift to the East. Both sets of maneuvers were detected by the algorithm as well as one likely false positive. Based on the effected orbit change the detected slot change maneuvers were likely approximately 0.5 m/s each.

After repositioning with two slot changes INTELSAT2 appears to have transferred to a super-sync disposal orbit 300km above GEO in January 2011. Following the transfer to the disposal orbit it appears that several additional maneuvers occurred in March and April 2011 that altered Semi-Major and Inclination slightly and also shifted RAAN. The detected post disposal maneuvers are corroborated by public domain letters from Intelsat to the Federal Communications Commission [1] [2] indicating that after the disposal of the satellite significant amounts of fuel remained requiring the additional maneuvers to fully deplete the tank.

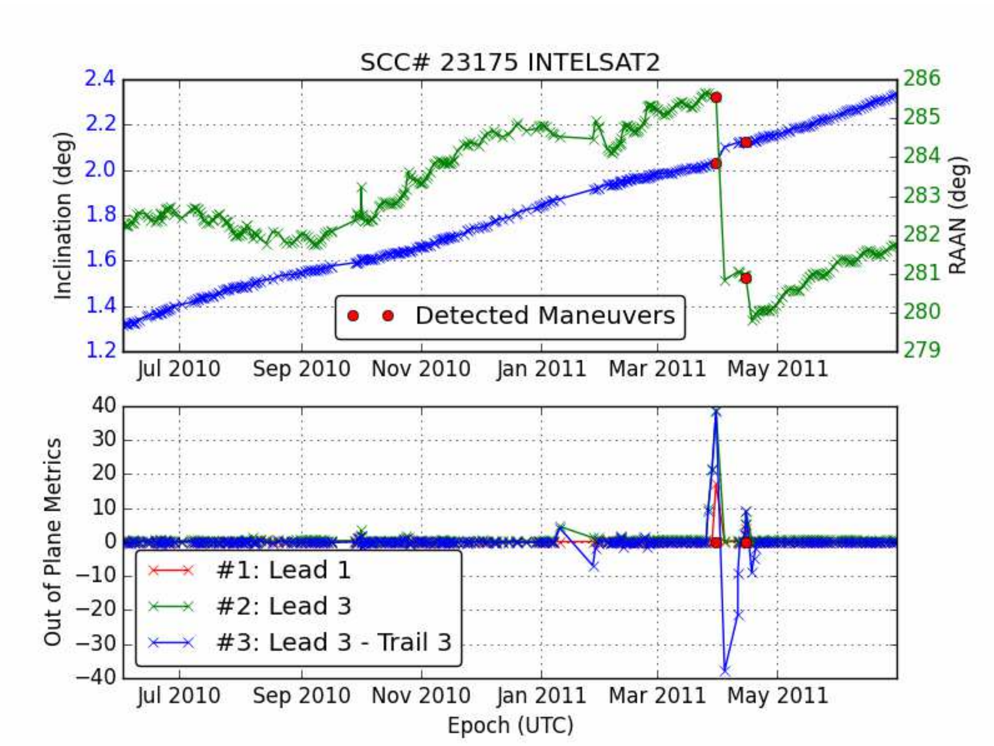


Fig. 16: Out of Plane Maneuver Detection Results for INTELSAT2

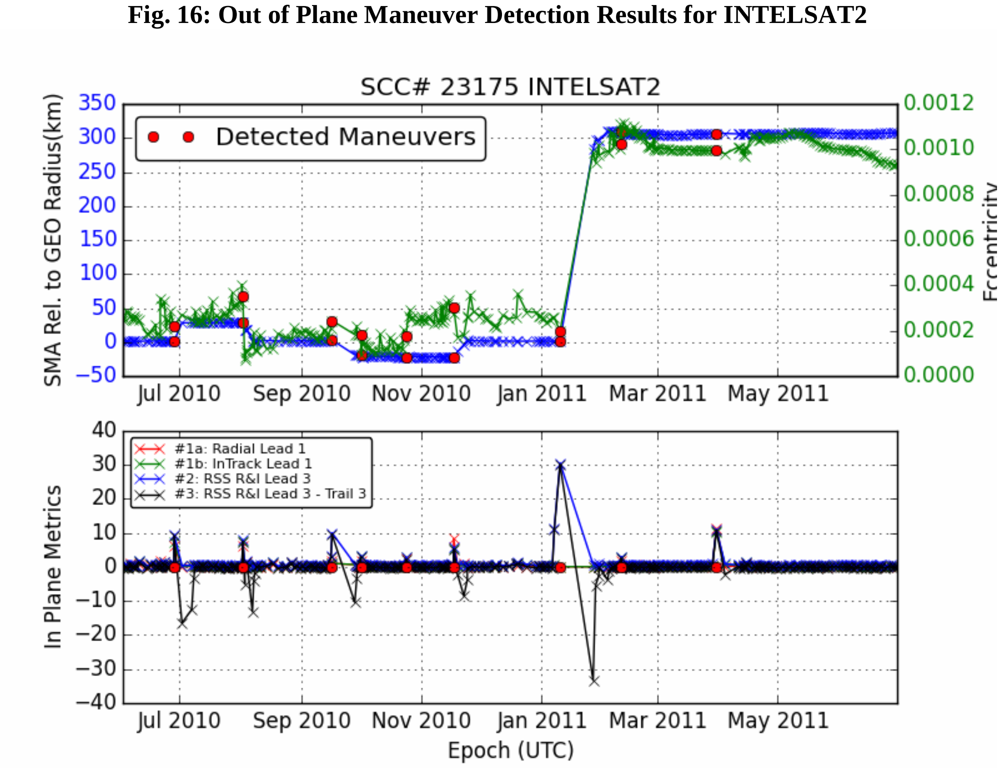


Fig. 17: Out of Plane Maneuver Detection Results for INTELSAT2

4.5 Previously Studied LEO Satellite with Known Maneuver History

ENVISAT (SCC# 27386) is a retired European Space Agency civilian earth observation satellite in a LEO sun synchronous polar orbit. Data for all ENVISAT maneuvers are publicly available, allowing for evaluation of the algorithm for detecting maneuvers versus truth data, ENVISAT was also one of two LEO maneuver detection examples used by Kelecy [6].

The default algorithm settings were changed, Table 3, to take advantage of the much more accurate orbit state knowledge for ENVISAT as compared to the GEO test cases, see Fig. 18.

Table 3: User settable algorithm settings

Tunable Parameter	Default Value
Lead/Trail Range Filter	2 km
Potential Maneuver Threshold	4σ
Maneuver Flag Lead vs. Trail Threshold	0.75σ (0.6 σ In Plane)
Maneuver Flag Lead vs. Center Threshold	0.75σ (0.6 σ In Plane)
Frequency Fit Window	4 Days

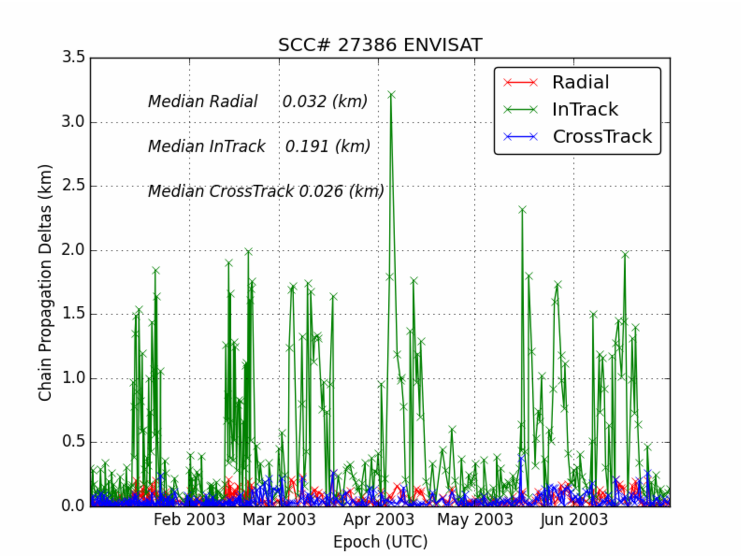


Fig. 18: Chain propagation results for ENVISAT

Over the analyzed period from January through June 2003 all eight ESA reported maneuvers were detected with two false positives, Table 4. The detected maneuvers were an average of four days after the ESA reported maneuver epochs with a min of zero and max of seven days. Fig. 19 and Fig. 20 show the orbit state history with maneuvers overlaid. Detected maneuvers show a much higher signature above the noise in the data then for the GEO cases.

Kelecy [6] analyzed Envisat with a different algorithm over a period of three years, spanning the data analyzed here, and reported successful detection of 49 out of 78 maneuvers with no false positives. The results presented here tentatively suggest that this method may be more effective at picking out relatively small maneuvers from the noise. However more comparative analysis would be needed.

Table 4: Detected maneuvers as correlated to published ESA maneuver data

Type Detected	Date Detected	ESA Reported Equivalent Maneuver	Delta (Days)	Notes
RI & C	1/21/2003	1/14/2003	7	
RI	2/13/2003	2/12/2003	1	
C	2/24/2003	2/21/2003	3	Large Inclination Maneuver
RI	3/9/2003	3/4/2003	5	
C	3/17/2003	NA	NA	False Positive
RI	4/4/2003	4/4/2003	0	
C	5/15/2003	5/14/2003	1	
C	5/25/2003	5/20/2003	5	Large Inclination Maneuver
C	5/29/2003	NA	NA	False Positive
C	6/13/2003	6/7/2003	6	

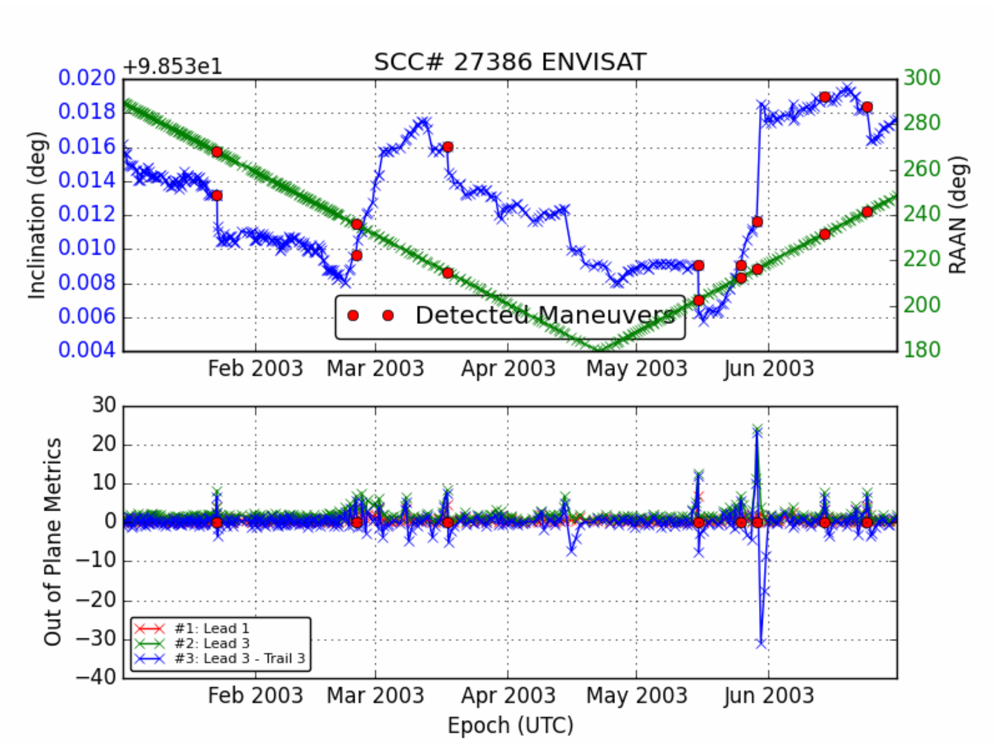


Fig. 19: Out of Plane Maneuver Detection Results for ENVISAT

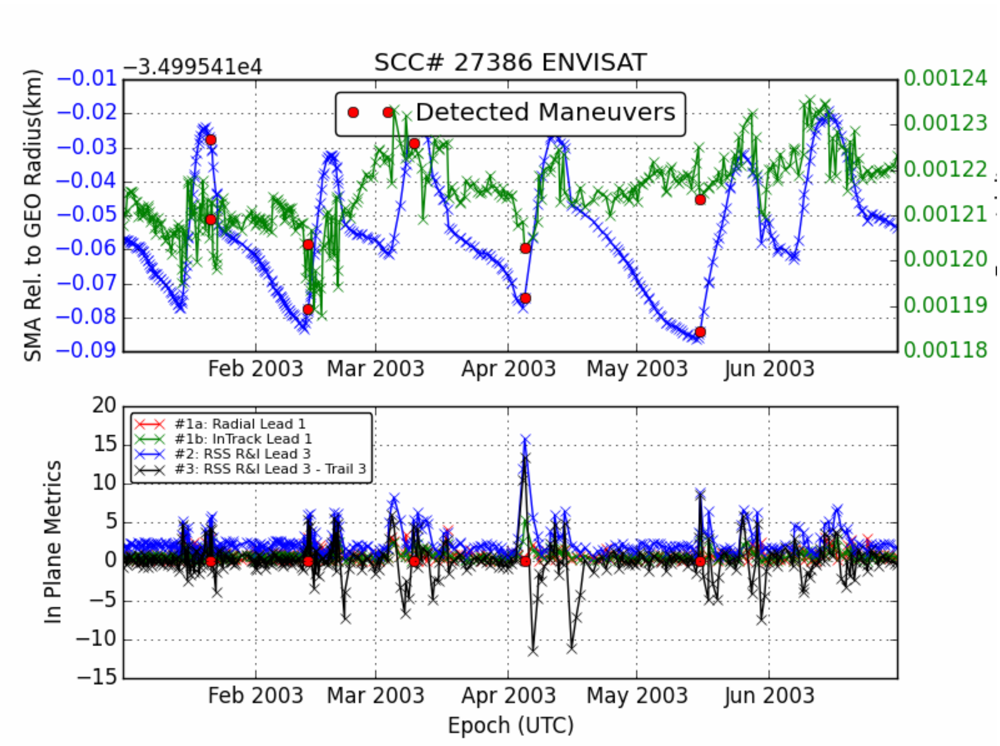


Fig. 20: In Plane Maneuver Detection Results for ENVISAT

5. Summary and Conclusions

The results of this study demonstrate the algorithms ability to characterize GEO spacecraft maneuver history from publicly available TLE orbit state data. Examples of both chemical and electric propulsion were shown. In the case of chemical propulsion with N-S and E-W station keeping maneuvers at bi-weekly intervals the algorithm was able to determine the interval of the maneuvers as well as identify many of the individual maneuvers although some were missed due to noise in the data. For the electric propulsion case it was shown that the fact that the satellite was performing frequent low thrust station keeping maneuvers could be concluded from the TLE data alone.

The third test case compared the algorithms effectiveness with the public TLE data versus more accurate operator state data. It also confirmed the accuracy of low signature detections made in the TLE data, although several other maneuvers were missed. Test case four demonstrated a less challenging case where it was shown that larger non-station keeping maneuvers could be clearly detected. Finally, it was shown that for a LEO test case, where orbit state knowledge was more accurate than the GEO test cases, that all eight known burns in a sample period could be detected with two false positives.

Overall the approach was found to be effective at characterizing maneuver schemes that would otherwise be undetectable from the noise in the data. Chain propagating the history of orbit states to common epochs and comparing them in the RIC frame was found to be a convenient and useful way of estimating the noise floor in the data. In the discretely maneuvering case it was found that in some cases the maneuvers did not have a large enough signature relative to the noise floor to be detected. In this case the frequency fit method of determining the historical cadence of maneuvers was very useful in filling in the big picture. Use of the max magnitudes of a RIC frame comparison between orbit states over an interval of one orbit period was found to be a valid way of condensing position and velocity differences down a single metric.

Identified areas for improvement include identification of suitable evaluation metrics to allow automating of filter tuning. It would also be useful to use the average noise in the data to quantify the magnitude of a burn required to allow detection with the given algorithms.

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