Satellite Maneuver Detection Using Two-line Element (TLE) Data

Tom Kelecy
Boeing LTS, Colorado Springs, CO / Kihei, HI

Doyle Hall
Boeing LTS, Colorado Springs, CO / Kihei, HI

Kris Hamada
Pacific Defense Solutions, LLC, Kihei, HI

Maj. Dennis Stocker
Air Force Research Laboratory / DET15, Kihei, HI

ABSTRACT

This paper summarizes the methods and limitations of deriving satellite maneuver information from historical two-line element (TLE) data. Each TLE contains the orbital information of an earth-orbiting object at a particular epoch time, and is used to calculate object state vectors. A TLE "time-history" comprises a list of TLEs measured over an extended period of time, and therefore contains information on orbital perturbation effects, both environmental and non-environmental. The non-environmental perturbations of interest for active satellites are thrusting maneuvers. This paper describes the design, implementation and performance of a TLE-based maneuver detection algorithm. Algorithm performance is measured relative to several spacecraft with known maneuver histories. TLE time-histories may also be used to estimate satellite masses, because the recorded environmental perturbations depend on a satellite's area-to-mass ratio (A/m). Estimates of a "best-fit" A/m value for a satellite can be derived by performing a least-squares comparison of the orbital elements taken from the TLE history with analytically-derived orbital elements. However, in order for the least-squares analysis to yield an accurate A/m estimate, all forces that significantly perturb the orbit need to be appropriately modeled, including maneuver thrusting for active satellites. The focus of this work is on the development and assessment of techniques that allow maneuvers to be detected from the historical TLE data, and thus support trending of the A/m ratio. The results show surprisingly reliable detection of maneuvers down to delta-velocity magnitudes at the centimeter-per-second level or less, provided the algorithm parameters are "tuned" appropriately.

1. INTRODUCTION AND BACKGROUND

Detecting maneuvers of objects for which historical TLE data are available is a useful capability, in particular, for active objects for which no operational information is available. Detection in real-time is required in order to adequately react in a timely fashion to either spacecraft anomalies, or a possible threat to nearby "accessible" satellite assets. For active objects that are regularly tracked, maneuvers can be detected and patterns or trends in maneuver types and magnitudes recorded. This information could be used to anticipate when future maneuvers might occur, and possibly what type of maneuver might occur. This information, in turn, can be provided to tracking assets as direct tasking of those satellites to allow for the near real-time maneuver detection and assessment. This capability might also be beneficial in reducing the number of active satellites that become "lost" due to maneuvers that occur between tracks. A "notional" operational concept is depicted in Figure 1. Note that the off-line maneuver detection also serves as an input to the mass estimation process which utilizes the A/m history and object size information to derive an estimate of object mass [1].

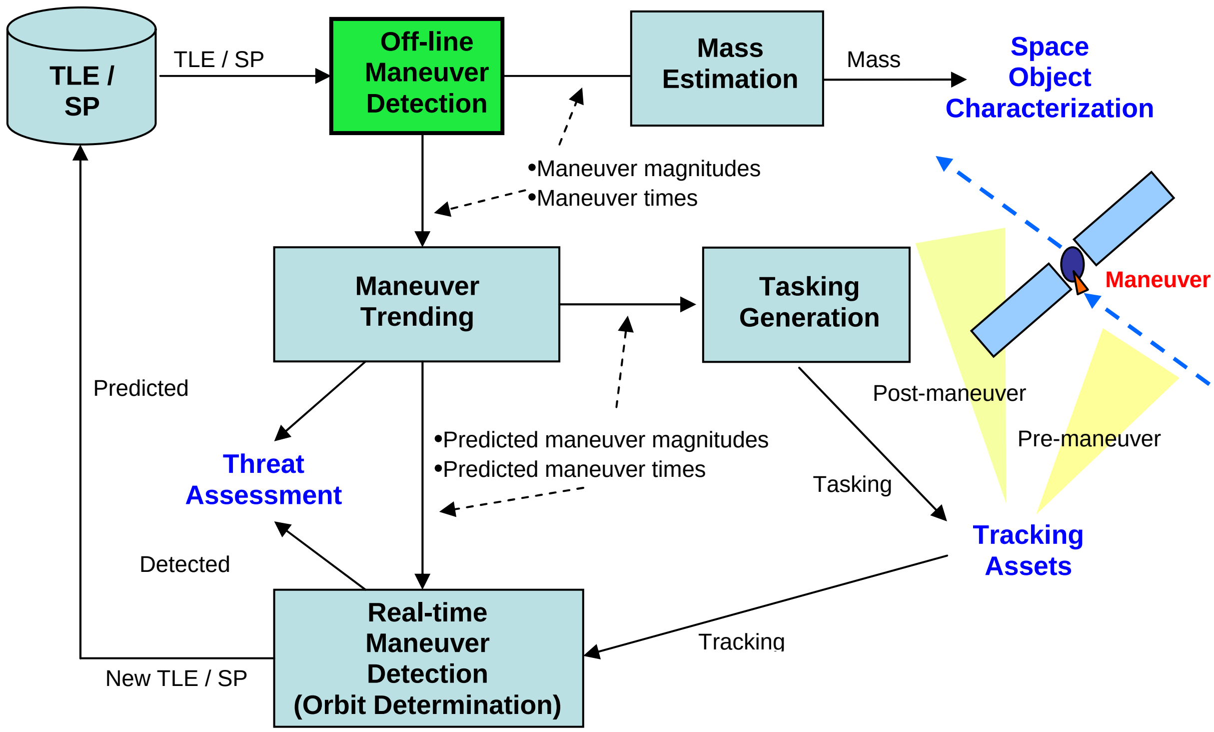

Fig. 1 Maneuver Detection Notional Operations Concept.

As an algorithm development and performance assessment effort, this study applies this notional operational concept to a set of active satellites with known maneuver times and magnitudes. This provides the means to assess the performance and sensitivity of the maneuver detection methods. This "test data" will be discussed for each of the satellites, along with the associated maneuvers. The maneuver detection algorithm is then described, and its attributes and limitations discussed. Finally, the algorithm is applied each test object the results compared to the known maneuvers. This performance analysis provides insights into what factors influence maneuver detection performance.

2. TEST DATA SUMMARY

This study focuses on Topex (SSN# 22076), and Envisat (SSN# 27386), for which both high-quality TLE data and known maneuver histories are available. The TLEs were downloaded from the Space-Track web site [2], while the maneuver history for each of the satellites was retrieved from the NASA "Maneuver History" web site [3], both unclassified data sources. Although maneuver histories were also available for ERS-1, ERS-2 and GFO-1 satellites, the two selected satellites provide a representative example the simplest and most complex maneuvers displayed by the entire set,

Topex represents a "simplest case" for assessing the maneuver detection performance because of its relatively simple maneuver history. Alternatively, Envisat represents more of a challenge because its TLE contain a fairly dense maneuver history of both small and large amplitude orbit-control maneuvers. The two satellites also cover two distinct LEO orbit regimes with Topex having an altitude of around 1336.3 km, and Envisat an altitude of around 781.4 km. The maneuvers generally comprise "fine control" maneuvers and "orbit control" maneuvers, representing in-plane (energy) maneuvers and out-of-plane (inclination) maneuvers, respectively. The fine-control maneuvers have relatively small velocity magnitude changes (ΔV), ranging from millimeters-per-second to centimeters-per-second. Orbit-control maneuvers have much larger ΔVs on the order of meters-per-second.

2.1 Topex TLE Data and Maneuver Summary

Figures 2.a and 2.b show the Topex semi-major axis and inclination histories derived from the TLEs. They cover a period of roughly mid 1992 through mid 2006 (approximately 14 years). The time between adjacent TLEs averages around 24 hours. The orbit has a mean motion of 12.81 revs/day, an average altitude of 1336.3 km, and an inclination of around 66˚. Figure 2.a illustrates the known maneuver history by the over-plotted vertical green lines, indicating the last recorded Topex maneuver in early 2003. All green lines represent in-plane ("energy" changing) maneuvers on the order of millimeters-per-second in magnitude. The 24 maneuvers performed over the period had an average ΔV magnitude of 4-5 millimeters-per-second.

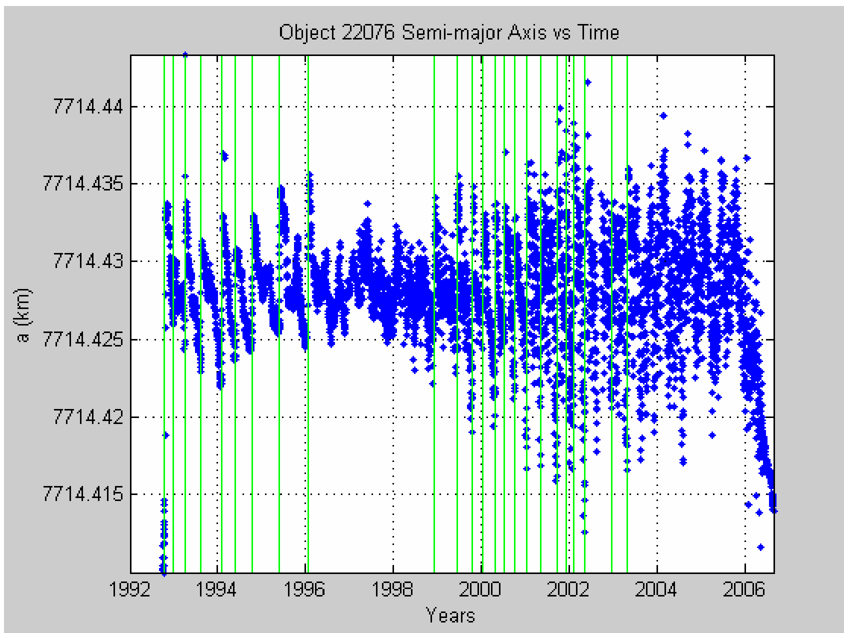

Fig. 2.a. Topex (22076) Semi-major Axis History

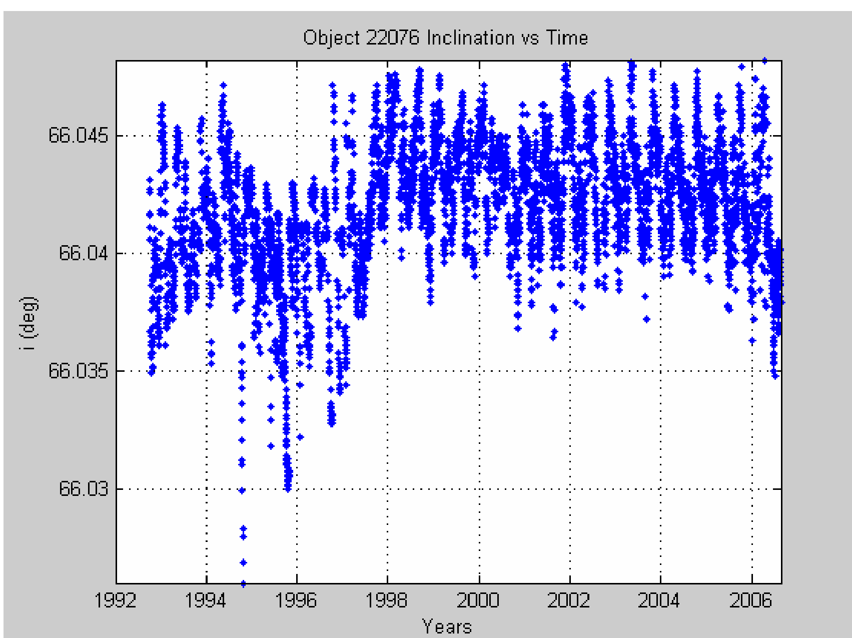

Fig. 2.b. Topex (22076) Inclination History

2.2 Envisat TLE Data and Maneuver Summary

Figures 3.a and 3.b show the Envisat semi-major axis and inclination histories, spanning early 2002 through mid 2006 (approximately 4 years), with an average time between adjacent points ≈30 hours. The orbit has a mean motion of 14.32 revs/day, an average altitude of 781.4 km, and an inclination of around 98.5˚. The vertical green lines show the fine-control maneuvers, and the vertical black lines represent the less frequent but larger amplitude orbit control maneuvers. Although no known maneuvers are tabulated after the beginning of 2006, the semi-major axis behavior in Figure 3.a strongly suggests that some activity is occurring. There 64 fine-control maneuvers had an average ΔV of 1.0-1.5 centimeters-per-second, while the 14 orbit-control maneuvers range from 1.0-1.5 meters-per-second.

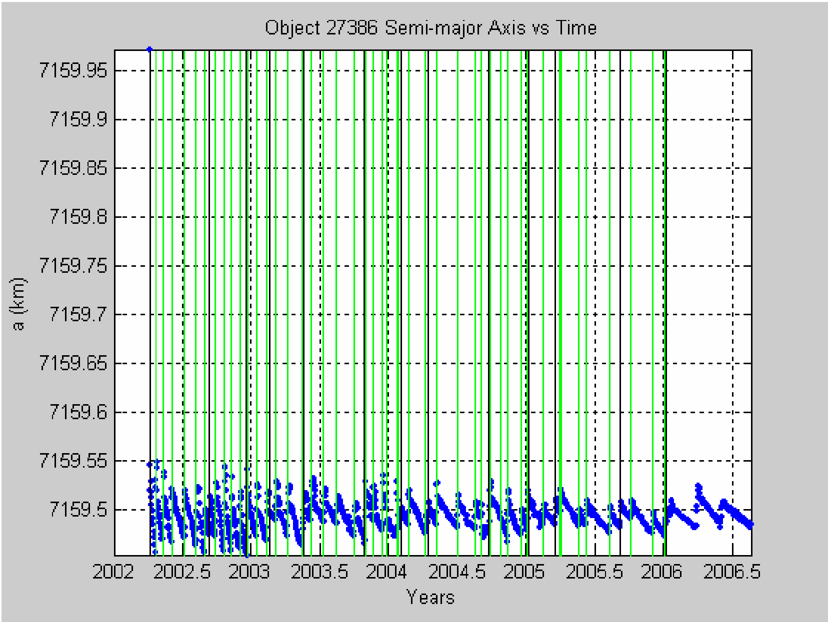

Fig. 3.a. Envisat (27386) Semi-major Axis History

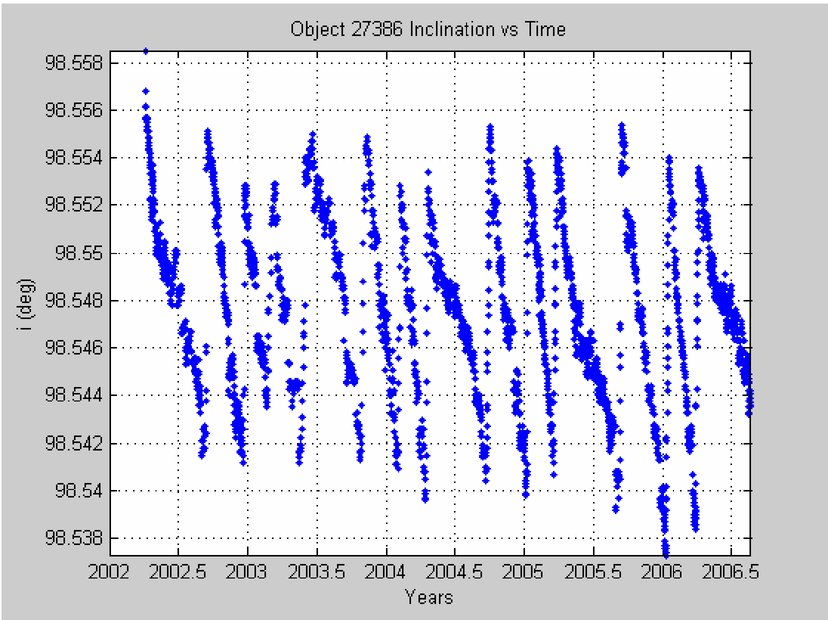

Fig. 3.b. Envisat (27386) Inclination History

3. MANEUVER DETECTION ALGORITHM

Active satellites typically implement two types of maneuvers. The first and most prevalent are in-plane maneuvers which change the shape (eccentricity) and size (altitude) of the orbit, and hence the orbital energy. In-plane maneuvers manifest as abrupt temporal changes in the mean motion, semi-major axis, energy, and/or eccentricity. Out-of-plane maneuvers manifest themselves as abrupt changes in the inclination or node in the TLE time-history. Most (if not all) of the orbit-control maneuvers examined in this analysis are out-of-plane inclination maneuvers.

Any approach that attempts to derive abrupt changes in orbital elements needs to account for the existence of inaccuracies (or "noise") in the TLE data. This noise results from the imperfect quality of the measurements used to derive the TLEs in the orbit determination process, and uncertainties in the modeling processing (such as inaccurate or incomplete atmospheric densities, solar fluxes, etc.). In this context, the term "abrupt" does not necessarily imply discrete and/or instantaneous changes. In fact, this analysis indicates that the post-maneuver TLE data typically suffer a time "lag" on the order of days before showing the effects of a known maneuver (more details are presented below).

The approach used in this analysis detects such abrupt changes in orbital parameters by identifying aberrantly large differences between adjacent segments of smoothed data, an approach similar to that used in previous analyses [4]. The smoothed (or filtered) data represents a sliding-average over a user-specified time period. In this case, the filter entails calculating a polynomial fit of all of the data within the interval. Figure 4 illustrates this approach where the differencing is applied to adjacent filtered segments of data. The method fits a polynomial to the leading segment, and separate polynomial to the trailing segment, and the difference between the leading and the trailing segments is computed at an extrapolated mid-point time.

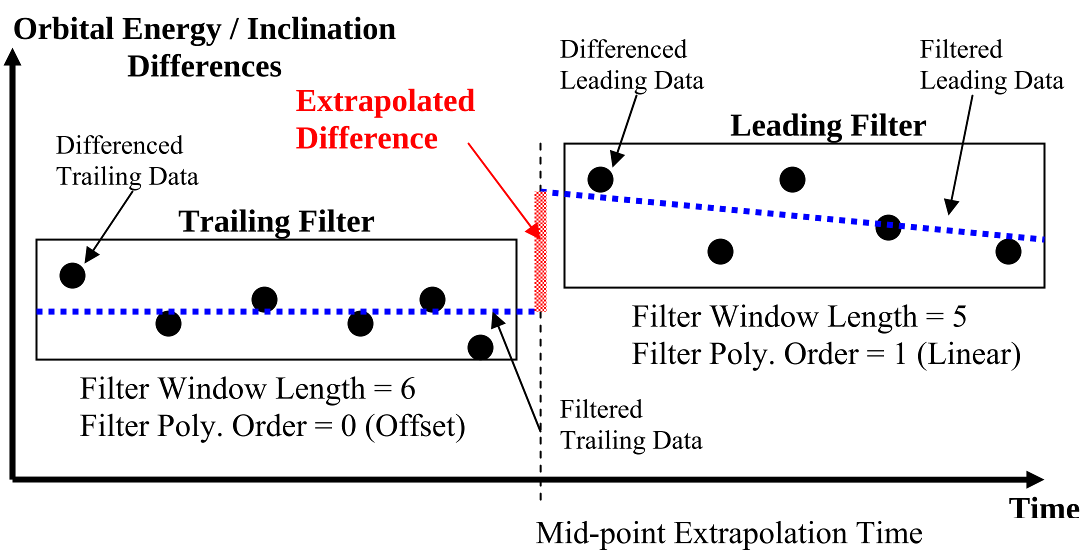

Fig. 4. Data Differences from Adjacent Filtered Segments

The maneuver detection process examines the data by computing the filtered differences between each adjacent data segment, looking for anomalously large differences that exceed a user-defined threshold. To be able to appropriately quantify and analyze the performance of the maneuver detection based on this approach, one must assess the noise statistics of the data. Outliers, whether due to maneuvers or other data anomalies, must be accounted for when determining the 1-σ statistic of the data. Once this statistic is determined, one can then establish the maneuver detection limit as a linear function of the statistics. A simple "n-σ" criterion is used for maneuver detection in this algorithm. Furthermore, an iterative routine removes outliers in the computation of the 1-σ statistics.

MATLAB was used to develop the maneuver detection prototyping code and associated utilities used in the performance analysis. The TLE and known maneuver time histories are inputs to the algorithm. Figure 5 provides a schematic description of the maneuver detection algorithm and analysis process.

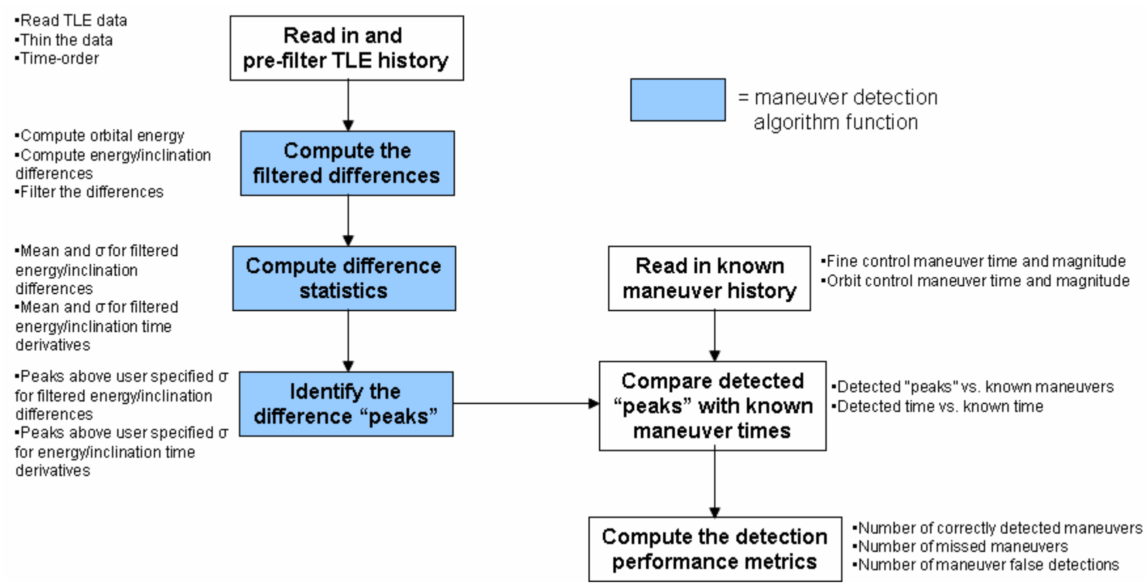

Fig. 5. Maneuver Detection and Analysis Algorithm

Potential maneuvers are flagged by examining all differences that exceed a user-specified limit between each adjacent filtered data segments. Typically, these differences plotted as a function of time form a peak with the apex representing the largest difference. Analyses conducted so far indicate these peaks are highly correlated with the known maneuvers (see "Analysis Results" section) but tend to lag the known maneuver time. Figure 6.a illustrates this lag, where the peak of the semi-major axis time series, in this instance, lags the known maneuver time (green vertical line) by approximately 18 days. To account for this effect, the maneuver detection algorithm includes a "lag parameter" that accounts for the "broadening" of the maneuver detection event peaks in the filtered differences, and hence, the time lag between the maximum filtered difference peak and the known maneuver time.

This lag might be caused by a combination of the maneuver detection filtering and/or the TLE-determination process itself. It is the measurements and geometric changes over time that are required to reflect a new satellite orbit state after the nearly instantaneous change that occurs as the result of a maneuver. There is likely some characteristic time, measured on the order of days, that is required for the state to converge. The filtered energy differences and detection peak above the detection threshold (red horizontal lines) corresponding to this maneuver is shown in Figure 6.b. A refined maneuver detection algorithm would take this time lag into account, but that is beyond the scope of this study. A scheme that accommodates this lag in the mass determination process is outlined in the final section of this report.

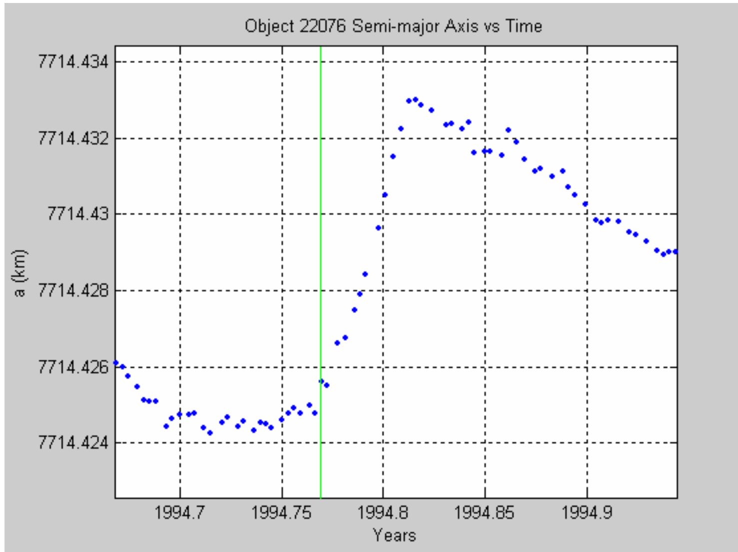

Fig. 6.a. Topex Semi-major Axis and Known Maneuver (green line)

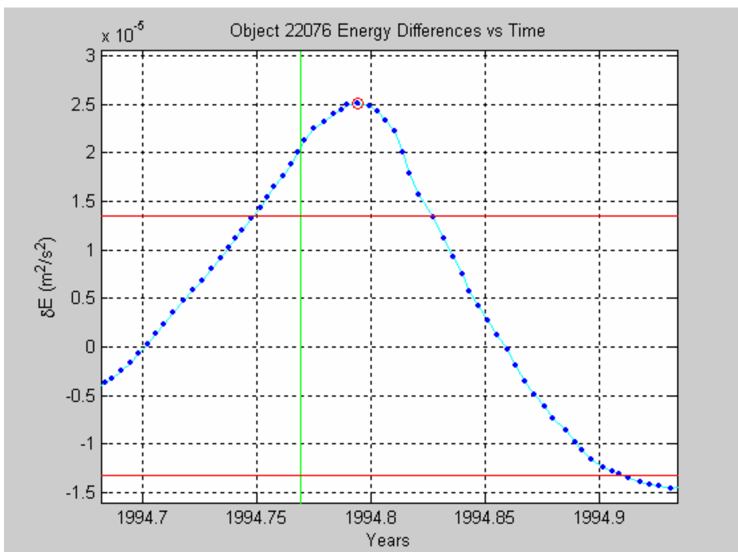

Fig. 6.b. Topex Filtered Energy Difference and Known Maneuver (green line);
Detection Limits are Red Horizontal Lines

4. ANALYSIS RESULTS

There are a variety of factors that can affect the maneuver detection performance using the technique just described such as the magnitudes of the maneuvers, the TLE data duration and density, the time or amount of data between maneuvers, and the factors that contribute to the quality of the data (e.g. noise and biases due to observational and environmental effects). Given the characteristics of the test data sets available for this work, the algorithm performance is examined as a function of sensitivity to algorithm parameters: filtering window length, the order of the filtering polynomial and the n-σ detection level. This analysis can not possibly to cover all variations in environmental factors, much less all of the combinations of the algorithm parameters. It must suffice to illustrate what can be learned about the performance sensitivity to the algorithm settings. In the course of this, what is feasible with the current configuration of tools will be demonstrated, and a “first-order” assessment of performance established.

Several cases are examined which illustrate the effect of the various algorithm parameters. The first cases will be illustrated using the Topex data which includes only fine-control maneuvers occurring in the in-plane direction. Furthermore, this data set has relatively sparse maneuver occurrences over the period of data availability, and so can be viewed as an "easy case" data set for testing and validating the maneuver detection algorithm performance. The analysis then follows up with additional results processed from the Envisat data set which has both a much denser maneuver history as well as inclusion of orbit control maneuvers that occur in the out-of-plane direction, and hence presents a more "challenging case" scenario.

4.1 Topex Analysis Results

The approach will be to establish a "baseline" case that can be used to compare the sensitivity of the maneuver detection performance to the various parameters. The baseline does not necessarily reflect the best that can be done, but establishes a baseline from which relative performance can then be gauged by varying the maneuver detection limits, filter window length, and polynomial fit order. A "trial-and-error" approach is used to establish the baseline cases for each satellite.

Baseline Case: Perfect Detection and No False Detections

This "baseline" case examines a 3-year segment of the Topex data running from 1993-1996. Six fine control maneuvers were executed over this period. Significantly, no orbit control maneuvers were executed during this time. Through trial-and-error, a parameter configuration was determined that resulted in 100% maneuver detection with zero false detections.

Figure 7.a shows the orbital energy time-history with green vertical lines indicating the times of the 6 maneuvers, where the data have been thinned to include data with time intervals no smaller than 24 hours. Maneuver events appear obvious in this raw (un-filtered) data, though close inspection reveals that the maneuver-induced energy changes lag by several data points the actual time of each maneuver.

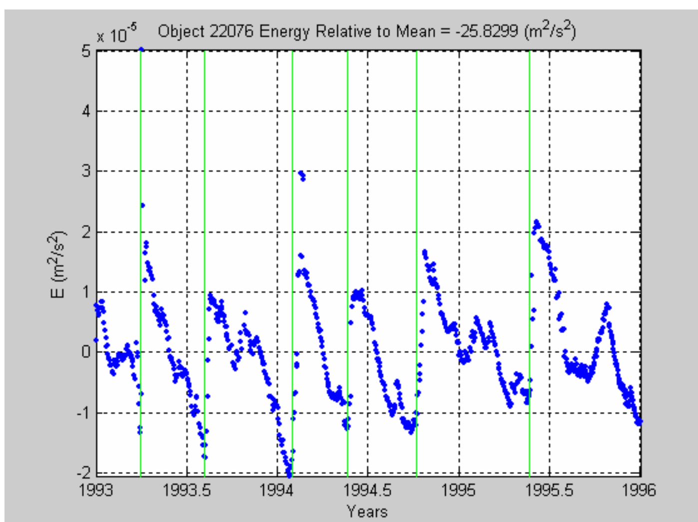

Fig. 7.a. Topex (22076) Orbital Energy: 1993 to 1996

The parameter configuration that results in the perfect detection performance is to fit trailing and leading data windows having a "length" of 60 data points (approximately 60 days) to first-order polynomials (linear fit) where detection threshold of 1-σ was used. Figure 7.b shows the resulting smoothed energy differences, with detection "peaks" depicted as red circles. In this case a time lag parameter of 10 days was used. Recall that this parameter accounts for the time lag present in the maneuver events as manifested in the filtered TLE data difference. The detection 1-σ limits are shown by the red horizontal lines. Note that negative limit detection is not exercised in this implementation.

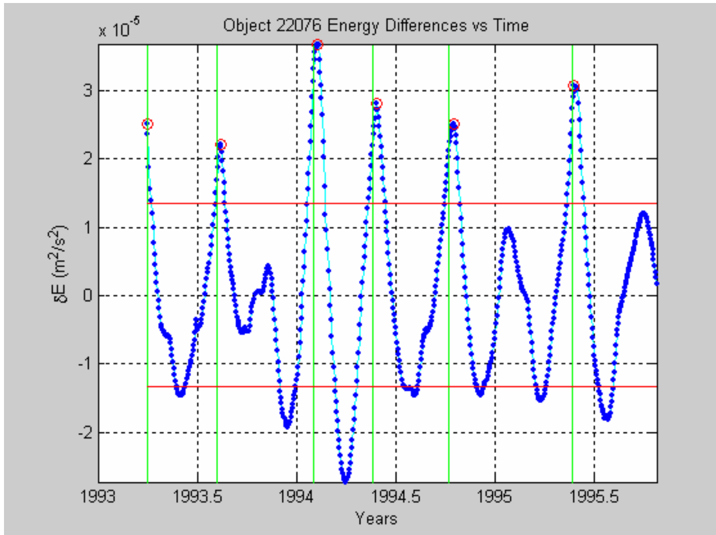

Fig. 7.b. Topex (22076) Energy Maneuver Detection: 1993 to 1996

Case 1: Detection Limit Increased to 2-σ Relative to Baseline 1-σ Case

Figure 7.c illustrates the effect of raising the detection threshold from 1-σ to 2-σ. The consequence is 3 of the 6 maneuver events being missed. This is expected, as the limit can always be raised high enough to the point where no maneuvers are detected. This example had no false detections, though, as illustrated in the next example, altering the limit can influence the number of false detection occurrences.

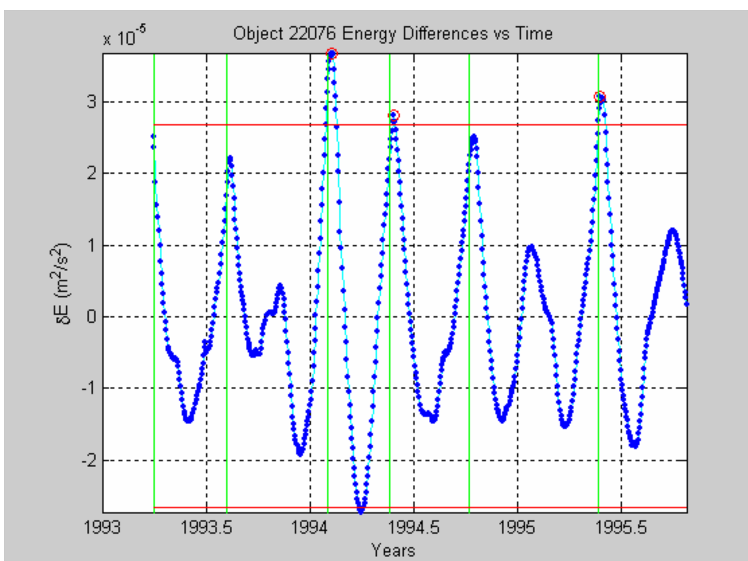

Fig. 7.c. Topex (22076) Energy Maneuver Detection: 1993 to 1996

Case 2: Detection Limit Lowered to 0.5-σ Relative to Baseline 1-σ Case

Figure 7.d illustrates the effect of lowering the maneuver detection limit from 1-σ limit to 0.5-σ. In this case, the algorithm detected all known maneuvers, but also 2 false detections. This and the previous example illustrate the trade-off between the detection limit, the number of maneuver detections versus number of false detections. The sensitivity will depend on the data at hand, and the settings of the other parameters that are assessed in some of the following examples.

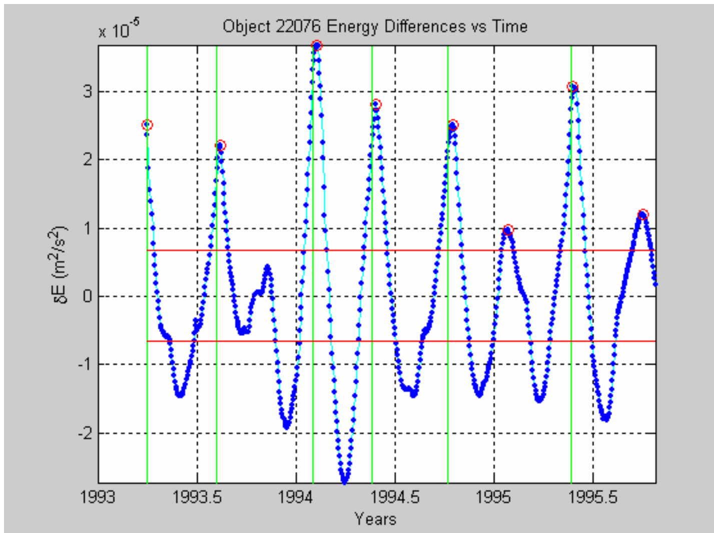

Fig. 7.d. Topex (22076) Energy Maneuver Detection: 1993 to 1996

Case 3: Data Windows Shortened Relative to Baseline Case

Figure 7.e illustrates the effect of shortening the window length. In this case, the baseline trailing and leading window lengths of 60 data points each were shortened to 10 data points each (approximately 10 days in time units). As with the baseline case, a linear polynomial filter was used. The filtered differences seen in Figure 7.e take on a noisy characteristic, the result being that 2 of the 6 maneuvers which were detected in the baseline configuration are now missed, likely due to an expanded time lag pushing those 2 cases outside of the 10 day detection threshold. Moreover, there are more false detections resulting from the noisier data.

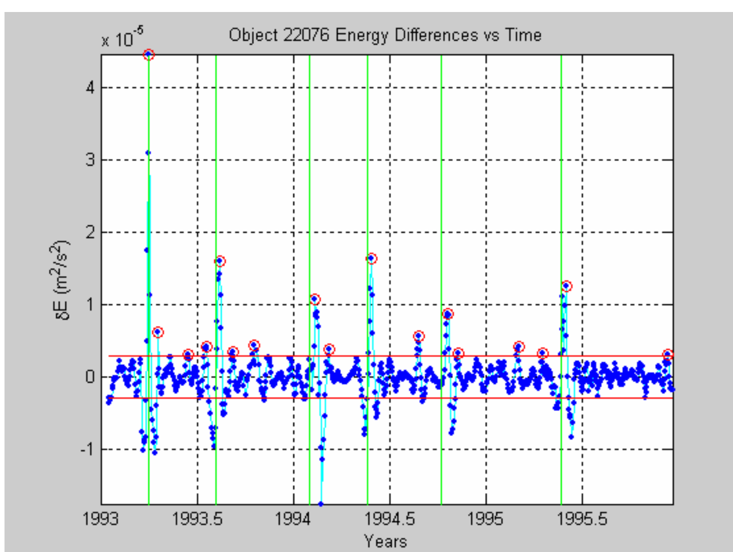

Fig. 7.e. Topex (22076) Energy Maneuver Detection: 1993 to 1996

Case 4: Polynomial Order Changed Relative to Baseline Case

Figure 7.f illustrates the case of changing the polynomial order. In this case, the filter trailing and leading window lengths were kept at 60 data points each, while the polynomial order was reduced to “0” (a bias fit). As can be seen in Figure 7.f, this flattens the peaks somewhat, so that although there are no false detections, 2 of the 6 known maneuvers are not detected. It should be cautioned not to extrapolate the specifics of these and previous results, as the data quality and density are factors to be considered when selecting filter window lengths and polynomial orders.

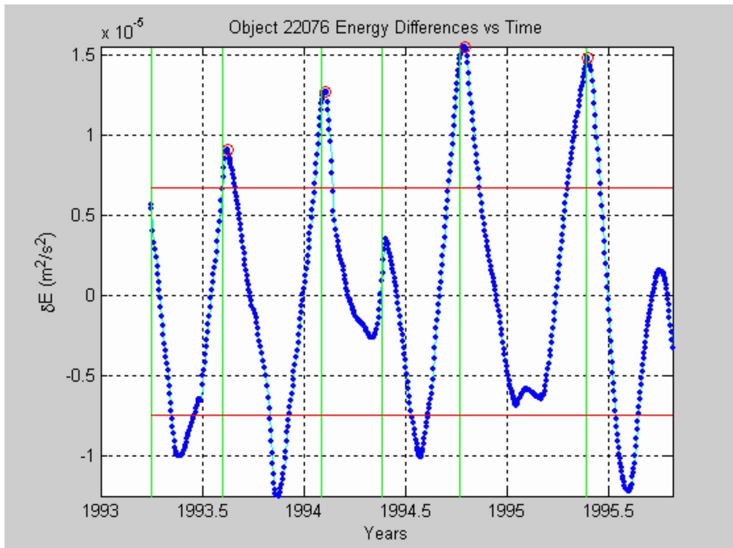

Fig. 7.f. Topex (22076) Energy Maneuver Detection: 1993 to 1996

Case 5: Full Data Set Used Relative to Baseline Parameters

Figure 8.a illustrates the final example for the Topex data, in which the baseline parameter settings are used, but now includes all of the data – the 14 year period from 1992 through 2006. The energy time-history is shown in Figure 8.a, along with the known maneuvers in green.

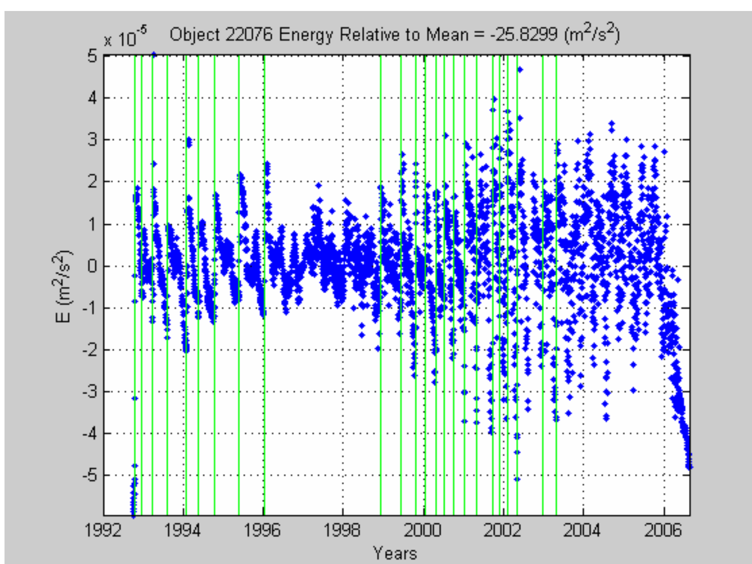

Fig. 8.a. Topex (22076) Orbital Energy: 1993 to 2006

Figure 8.b shows the data and maneuver history, and maneuver detection performance. It turns out that the "ideal" setting for the period between 1993-1996 does not accommodate the increased "noise" level of the data later in the data set, the result being both more missed known maneuvers, and more false detections. In fact, the maneuvers appear to end near the end of 2003, yet there are numerous maneuvers detected over that period. It is not known if there were actually maneuvers that occurred but which were not logged on the maneuver website, or that increased noise simply caused more false detections. If the filter is run using the baseline parameters, but only on the tail 2-year section (2004-2006) of the data after no more maneuvers are known to have occurred, the detection limit would need to be raised to around 2-σ in order for no false detections to be flagged. This is the result of both the higher detection limit factor as well as a higher noise σ for that portion of the data.

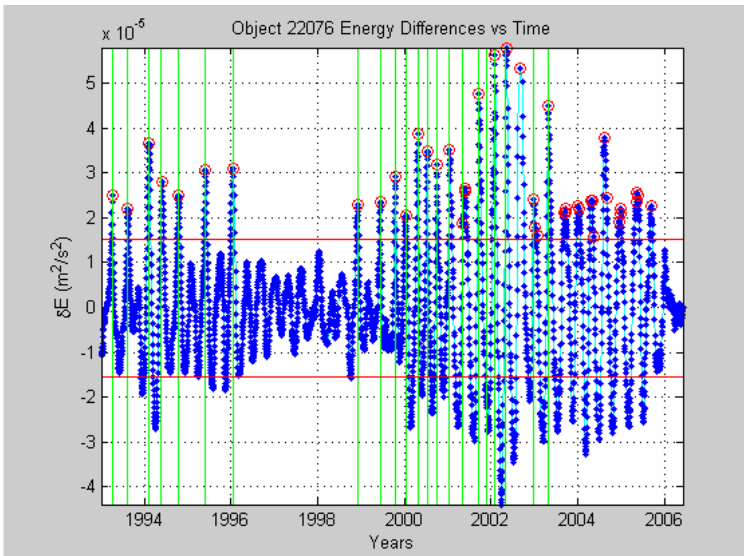

Fig. 8.b. Topex (22076) Energy Maneuver Detection: 1993 to 2006

4.2 Envisat Analysis Results

The previous Topex maneuver detection analysis results demonstrated the viability of detecting maneuvers from TLE data, and some of the trade-offs between algorithm parameters and maneuver and false detection performance results. The approach with the Envisat data, though not as comprehensive, will be similar, but also include the orbit control (out-of-plane) maneuver detection results.

<u>Baseline Case: Best Case Detection and No False Detections</u>

This case examines a 3-year segment of the Envisat data running from 2003-2006. The maneuver information available for this object indicates that of the total of 64 fine-control maneuvers, 40 are found to occur over this 3-year period. Similarly, of the 14 orbit control maneuvers in the data set, 9 are found over this period.

Figure 9.a and 9.b show the orbital energy and inclination time histories derived from the TLE data, respectively, with the green vertical lines indicating the times fine trim maneuvers, and the black vertical lines indicating the times of the orbit trim maneuvers.

The parameter configuration that resulted in the best-case maneuver detection was to fit trailing and leading data windows having a "length" of 8 data points to zero-order polynomials (bias fit). The parameter summary for this case is listed below, where a detection threshold of 0.1-σ was used for the energy change detection, while 2-σ was used for inclination change detection. The resulting smoothed energy and inclination differences, with detection "peaks" depicted as red circles, are shown in Figures 9.c and 9.d. In this case a time lag parameter of 10 days was used. The detection limits are shown by the red horizontal lines in both figures.

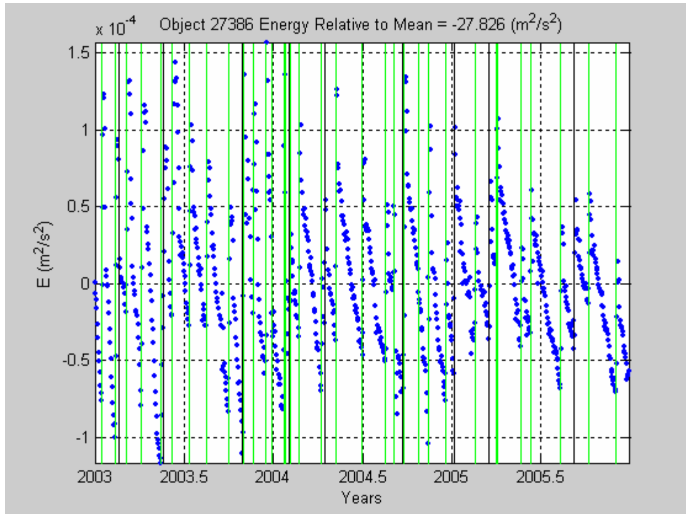

Fig. 9.a. Envisat (27386) Orbital Energy: 2003 to 2006

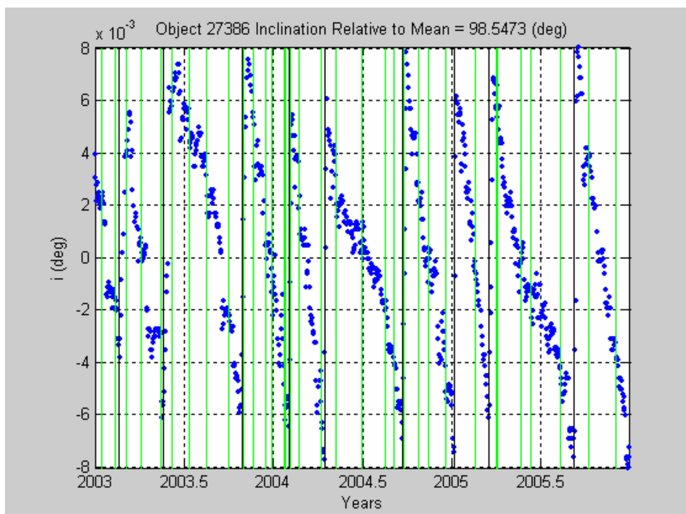

Fig. 9.b. Envisat (27386) Orbital Inclination: 2003 to 2006

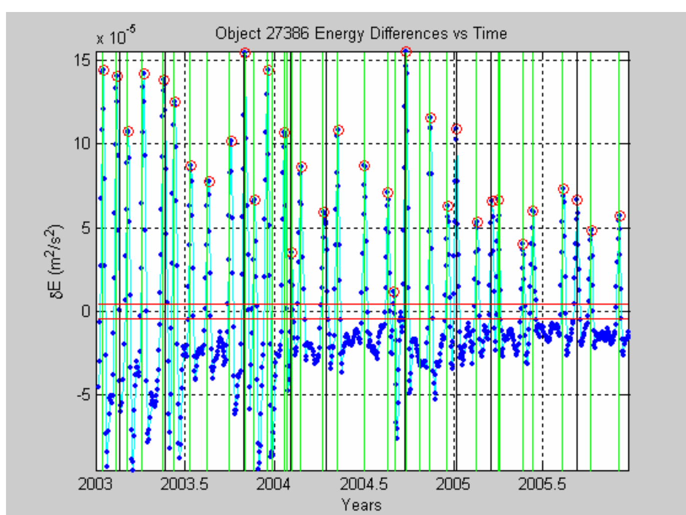

Fig. 9.c. Envisat (27386) Energy Maneuver Detection: 2003 to 2006

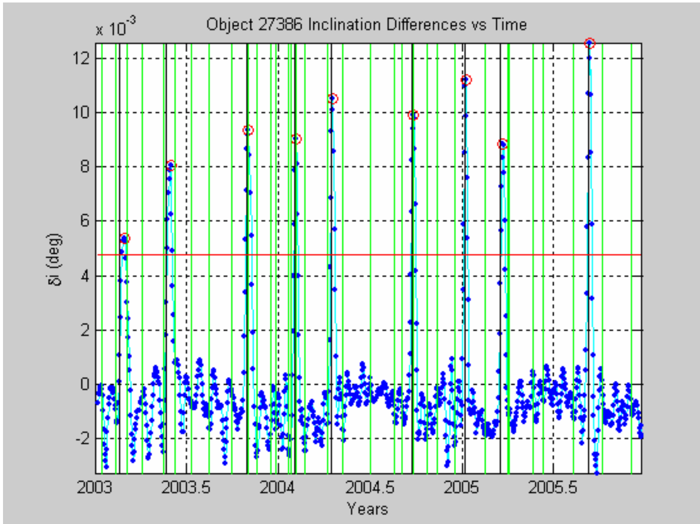

Fig. 9.d. Envisat (27386) Inclination Maneuver Detection: 2003 to 2006

As can be seen in these results, the inclination maneuver was easily detected at the 100% level with no false detections. In the case of the energy maneuver, 95% was the best-achieved detection reliability with a false detection level of a little over 6%. Assuming the maneuver history is correct, the cases of missed maneuvers appear to be the result of maneuver magnitudes that fall below the detection threshold as shown in Figure 9.e which is expanded from Figure 9.c. Another possibility is that the recorded maneuver was, for what ever reason, aborted. Unfortunately, there is not way of knowing for sure. The performance of the orbit-control maneuvers might, at least in part, be attributed to the larger magnitudes of those maneuvers (on the order of meters-per-second). In fact, a 1-σ detection threshold could have been used to detect all of the maneuvers, in this case, without the penalty of any false detections.

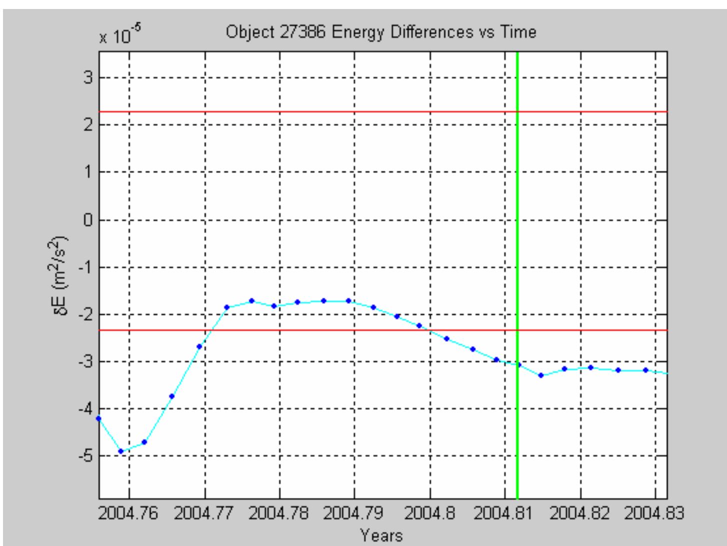

Fig. 9.e. Envisat (27386) Energy Maneuver Detection: Expanded

<u>Case: Full Data Set is Used Relative to Baseline Parameters</u>

Repeating the detection level, polynomial window length and fit order cases examined for the Topex data on the Envisat data merely re-enforces the performance sensitivities. The parameter settings used in the 3 year Envisat data were then run on all of the data. The results, shown below, show an energy (fine-control) maneuver detection performance of 95% and a false detection rate of 6%. The process results in an inclination (orbit-control) maneuver performance of 85% and a false detection rate of 7%. Figures 10.a and 10.b show the graphical results for the energy and inclination maneuvers, respectively.

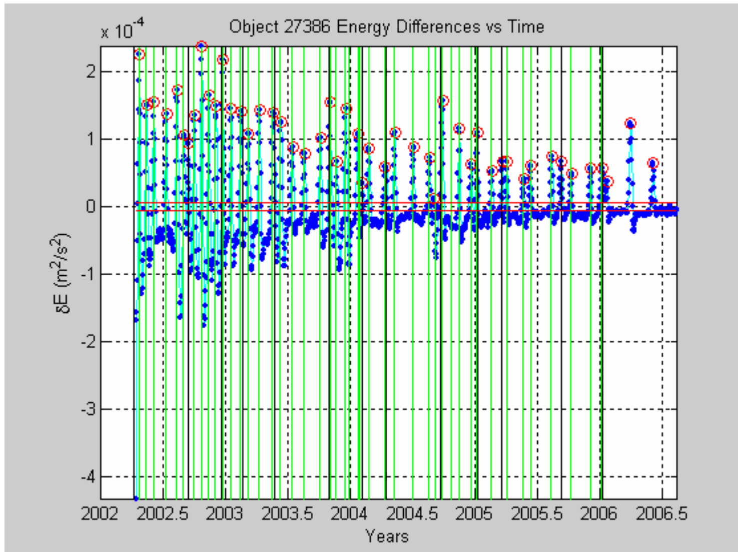

Fig. 10.a. Envisat (27386) Energy Maneuver Detection: 2002 to 2006

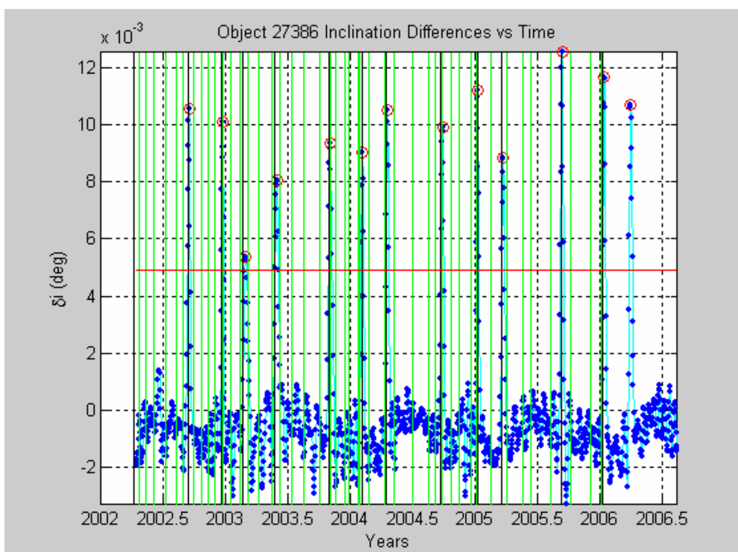

Fig. 10.b. Envisat (27386) Inclination Maneuver Detection: 2002 to 2006

5. SUMMARY AND CONCLUSIONS

The results of this study show that analysis of TLE data provides reasonably reliable detection of satellite thrust maneuvers down to the centimeter-per-second level or even less, provided algorithm parameters are "tuned" appropriately. The 95% detection reliability in the "challenging-case" Envisat data is noteworthy. The noise at the end of the Topex data presented more of a challenge, skewing the noise statistics, and causing several false detections. Though only two of the four test objects were presented in detail here, the results are representative. All of these data sets are candidates for mass determination analyses to follow-up this study, though ERS-1 is attractive in that it contains a multi-year segment with no known maneuvers that can be used to calibrate the mass determination process.

There is a sensitivity trade-off between the maneuver detection algorithm parameters. The σ detection threshold, for example, can be tuned to maximize maneuver detection reliability, but at the cost of a greater frequency of false detection occurrences. The manner in which the detection events are manifested in the data is a function of the data quality, density, and the maneuver geometry. Given these attributes, the filtered maneuver events can be optimized for detection by appropriate selection of the smoothing polynomial order and window length. The maneuver event "peaks" can be exaggerated, squashed, broadened or narrowed.

It is not surprising that no single best set of algorithm parameters exists for all satellites under all conditions. However, analyses of satellites with known maneuver histories can yield optimized parameters which can then be applied to similar objects–of-interest. The alternative is to take data for the object of interest and develop the parameters on segments of the data where the maneuver history might be known.

The time lag that appears to be intrinsic to the raw TLE data – believed to be an artifact of the TLE processing – is a limiting factor. However, if maneuver events can be characterized for a particular object, the uncertainty in the lag can be reduced to determine a more accurate estimate of the time of the maneuver. Analysis showed that the average offset is around 2-3 days, and has a standard deviation of around 2.4 days for a total of 657 detected maneuvers. This provides a bound on the timeliness for which maneuvers can be detected using these techniques Unfortunately, there is no way to exactly accommodate the lag since adequate post-maneuver data is needed to conclusively determine whether or not a maneuver has occurred using the TLE data.

Maneuver detection reliability and accuracy would likely be improved by using Special Perturbations (SP) vectors instead of TLE data. These SP vectors afford a significant improvement in orbital accuracy, and hence in the orbital histories of the objects. If the appropriate SP vectors can be acquired around some of the maneuver events for the objects, the maneuver detection performance can be measured and compared with that of the TLE derived maneuver events.

Finally, any effort to implement real-time or near real-time maneuver detection and mass determination systems would benefit immensely from further research and algorithm development. An *a priori* knowledge of both maneuver characteristics and mass properties might readily be incorporated into a real-time change detection process.

6. AKNOWLEDGEMENTS

This paper supports work done under the Maui Space Surveillance System (MSSS) Project Plan No. M011SOMD, "Satellite Orientation - Mass Determination," under IROSS Contract FA9451-05-C-0257.

7. REFERENCES

1. Hall, Doyle T., et al., "AMOS Measurements of the Physical Properties of Orbiting NaK Droplets," AMOS Technical Conference Proceedings, Wailea, HI, September 2004.

2. The TLEs were downloaded from the Space-Track web site (password protected) found at http://www.space-track.org/perl/login.pl

3. The maneuver history for each of the satellites was retrieved from the NASA "Maneuver History" web site found at http://ilrs.gsfc.nasa.gov/products_formats_procedures/predictions/maneuver/maneuver_history/

4. Patera, Russell A., "Space Event Detection Method," AIAA/AAS Astrodynamics Specialists Conference (AIAA 2006-6513), Keystone, CO, August 21-24, 2006.