DETERMINATION OF ORBIT CROSS-TAG EVENTS AND MANEUVERS WITH ORBIT DETECTIVE

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Cross-tag and orbit maneuver events can often be detected using a low-pass filter based upon pre- and post-event statistics accumulation. In this paper, we examine the implementation of such a filter in the Orbit Detective tool, and we apply the filter to the Galaxy 15 mission to determine cross-tag frequency of occurrence. Maneuver detection and calibration using such a low-pass filter are also discussed.

INTRODUCTION

The space operations community depends daily upon Non-Cooperative Tracking (NCT) data (e.g., radars and optical sensors). NCTs are the only tracking data source for debris objects, and they generally provide very functional information and services.

Certain orbit regimes offer a challenge to the NCT community. As shown in Figure 1, the GEO belt is very crowded, and satellite flybys are a common occurrence. Radar and optical sensors can have difficulty associating observations with the correct object during flyby periods, resulting in a "cross-tag" condition.

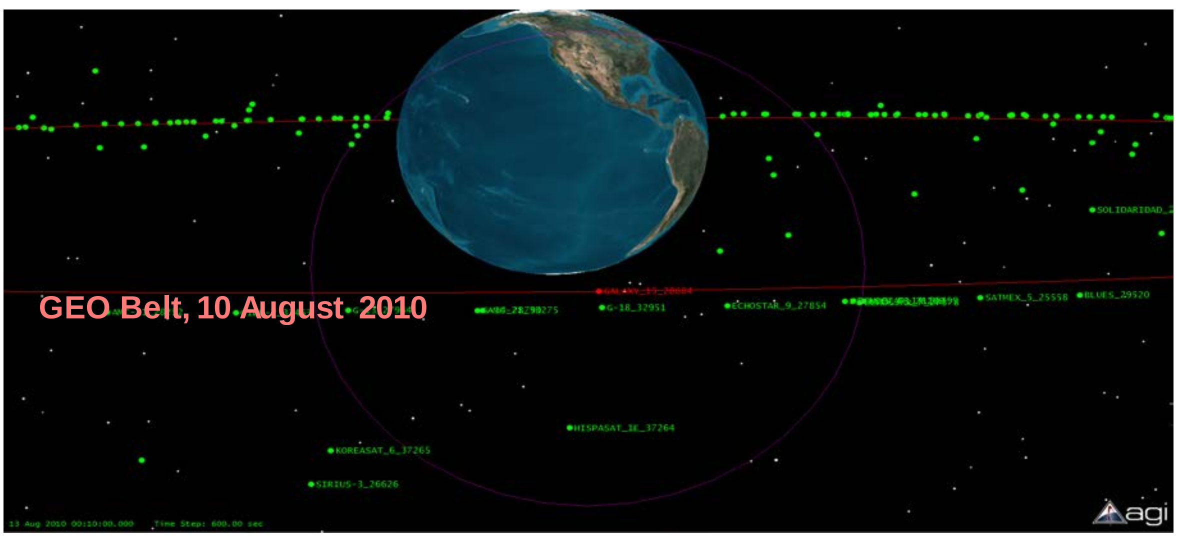

Figure 1. GEO Belt Population as of 10 August 2010 (www.CelesTrak.com)

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Although NCTs are the only reliable source for debris positional and metric data, it is essential for space operators to characterize the performance of such NCT data on an on-going basis. To help characterize this performance, AGI's Center for Space Standards and Innovation (CSSI) has created the "Orbit Detective" tool. This effort was undertaken on behalf of the Space Data Association (SDA), a non-profit association that brings together satellite operators who value the controlled, reliable, and efficient data-sharing that is critical to the safety and integrity of the space environment and the RF spectrum. The SDA was founded by Inmarsat, Intelsat and SES — three leading global satellite communications companies. By collecting definitive SDA Member RF, CA, ephemeris data, and points-of-contact information in the SDA's Space Data Center (SDC) analysis repository, Space Situational Awareness and threat mitigation analyses can now be completed to levels of previously unachievable accuracy and realism.

CROSS-TAGGING

As defined above, cross-tagging occurs when NCT observations are tagged to the wrong satellites. Unfortunately, such cross-tag events can have a large impact on the accuracy of orbit solutions for both Resident Space Objects (RSOs) during a transit of two satellites. The situation is often further aggravated because the most likely time for cross-tagging to occur is during flyby events, which is precisely when satellite owner/operators require the most accuracy. Unfortunately, the application of a higher-accuracy orbit propagation scheme (e.g. numerical integration instead of semi-analytic theory) does not significantly help reduce cross-tagging events.

Cross-tagging is not a result of using low-quality space surveillance hardware or employing unknowledgeable space analysts; rather, it is a direct result of the NCT method, which lacks active ranging and telemetry-based tracking.

ORBIT MANEUVER DETECTION AND CALIBRATION

The detection and removal of cross-tagged orbital data permits the remaining orbital state vectors and/or ephemerides to be used to detect potential maneuvers and determine overall NCT orbit solution and prediction accuracy. As with cross-tagging occurrences, NCTs are typically unaware of RSO maneuvers and can easily fit orbit solutions through the maneuver, resulting in degraded orbit estimation accuracy. This is especially prevalent among a number of GEO satellites that use low-thrust, long-duration burns to accomplish stationkeeping. Again, the use of higher-accuracy orbit propagation schemes does not reduce orbit solution degradation due to fitting through satellite maneuver events.

ANALYSIS OF TIME SEQUENCES OF ORBIT DATA VIA "ORBIT DETECTIVE"

In order to examine cross-tag and maneuver effects, a low-pass filter approach was implemented in the "Orbit Detective" tool. This basic approach is shown in Figure 2. By propagating both forward and backward from the epochs of a sequence of ephemerides or orbit solution states, distribution statistics may be generated for each orbit solution epoch. By examining the standard deviation, mean and median values at each epoch, an assessment can be made whether: (a) the orbit solution state in question is outside of the population bounds by more than a user-selectable 'N'-sigma value, indicating a potential cross-tag event; or (b) the orbit solution is within the bounds of the pre- or post-event statistics, but outside of the other statistics, indicating a potential maneuver.

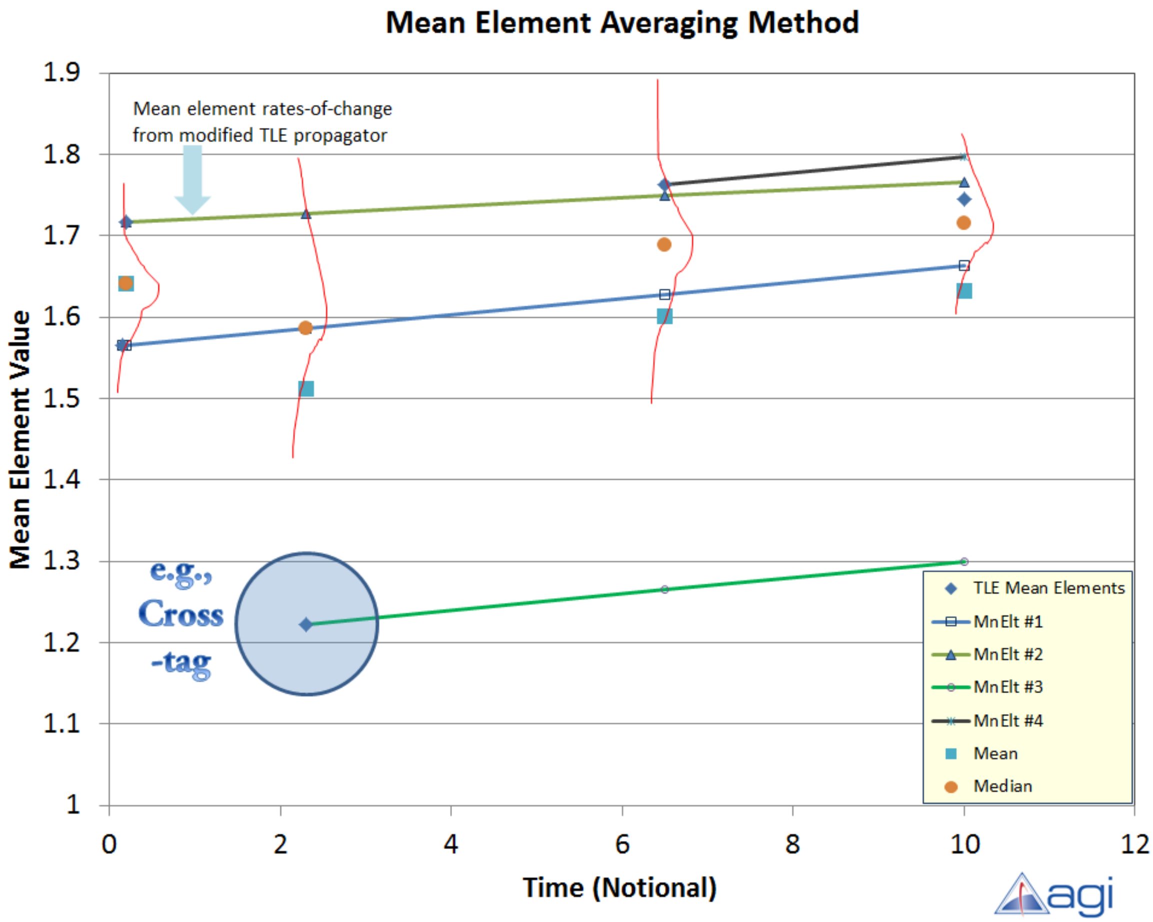

Figure 2. Time Sequence of Orbit Solutions Propagated to Epochs of Bounding Cases

APPLICATION OF "ORBIT DETECTIVE" TO GALAXY-15 CASE

As a test case, we now apply this low-pass filter approach to the Galaxy 15 mission to determine cross-tag frequency of occurrence. Two-Line Element (TLE) data from the CelesTrak site[1] is used exclusively for all TLE data products in this paper. A likely solar flare-induced Galaxy-15 satellite anomaly, which occurred on 5 April 2010, yielded a satellite that was unable to maneuver or respond to commands yet was able to continue to broadcast. Because the Galaxy-15 satellite hosts a GPS Wide Area Augmentation System (WAAS) transponder, the operations team was able to maintain very precise orbit solutions for Galaxy-15. This Galaxy-15 anomaly is a very good test case for cross-tagging investigations because (a) an eastward drift was initiated due to the lack of stationkeeping; (b) the location of the satellite is precisely known by the operator but not in the public catalog; and (c) no maneuvers occurred. Control of Galaxy-15 by the ground operations team was reestablished on 23 December 2010.

Examination of classical orbital elements for the year 2010 (Figure 3 - Figure 7) shows the 8.5-month anomaly period. The difference in the signature of the classical orbit elements is readily apparent during this period. In addition to this signature difference, discrete step functions in the orbit elements may be observed.

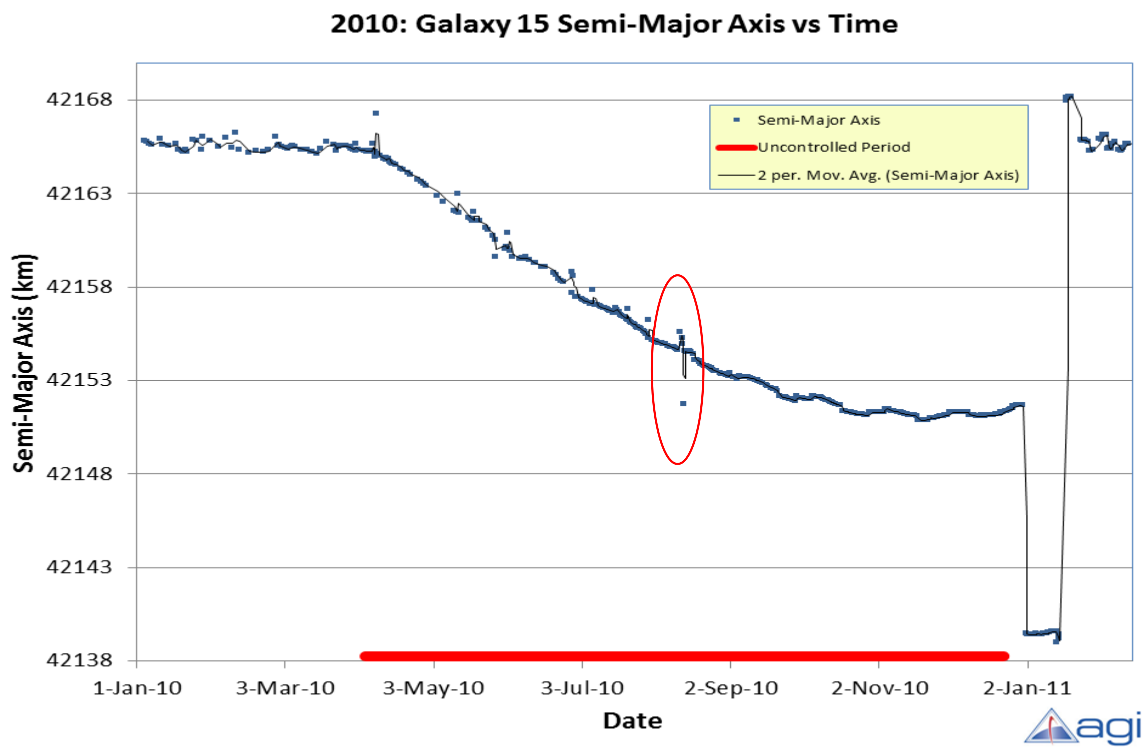

Figure 3. RSO Semi-Major Axis Versus Time in 2010

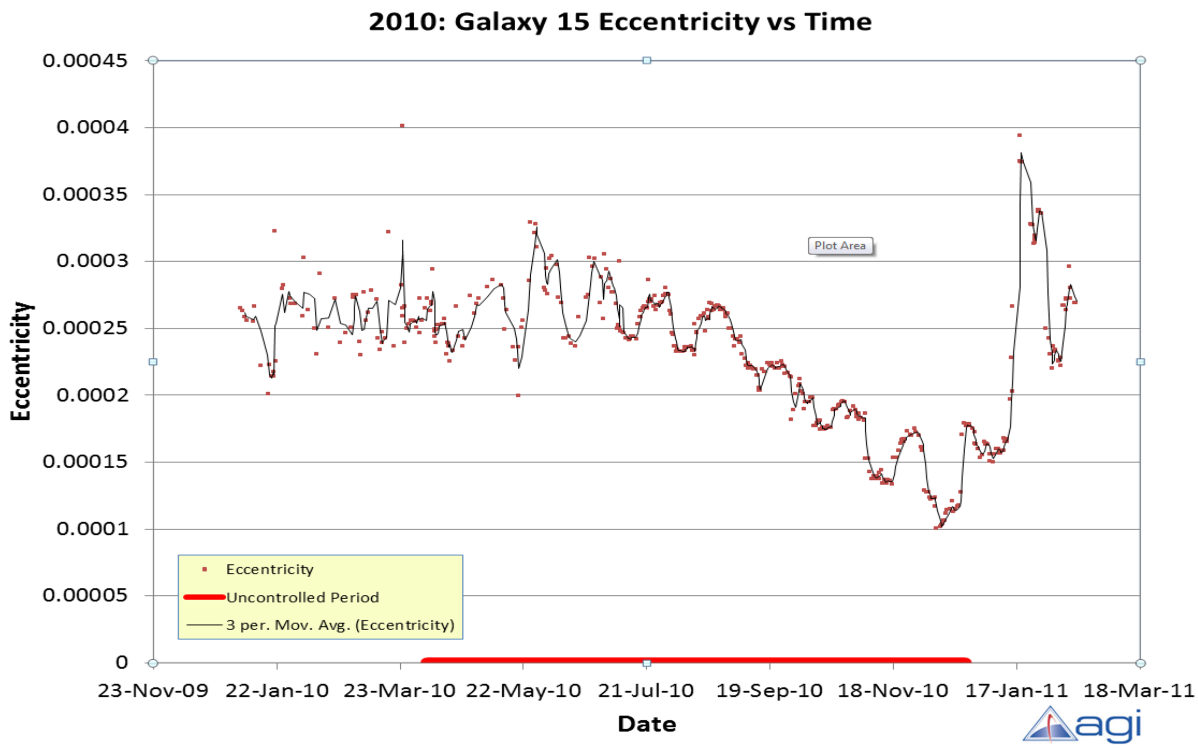

Figure 4. RSO Eccentricity Versus Time in 2010

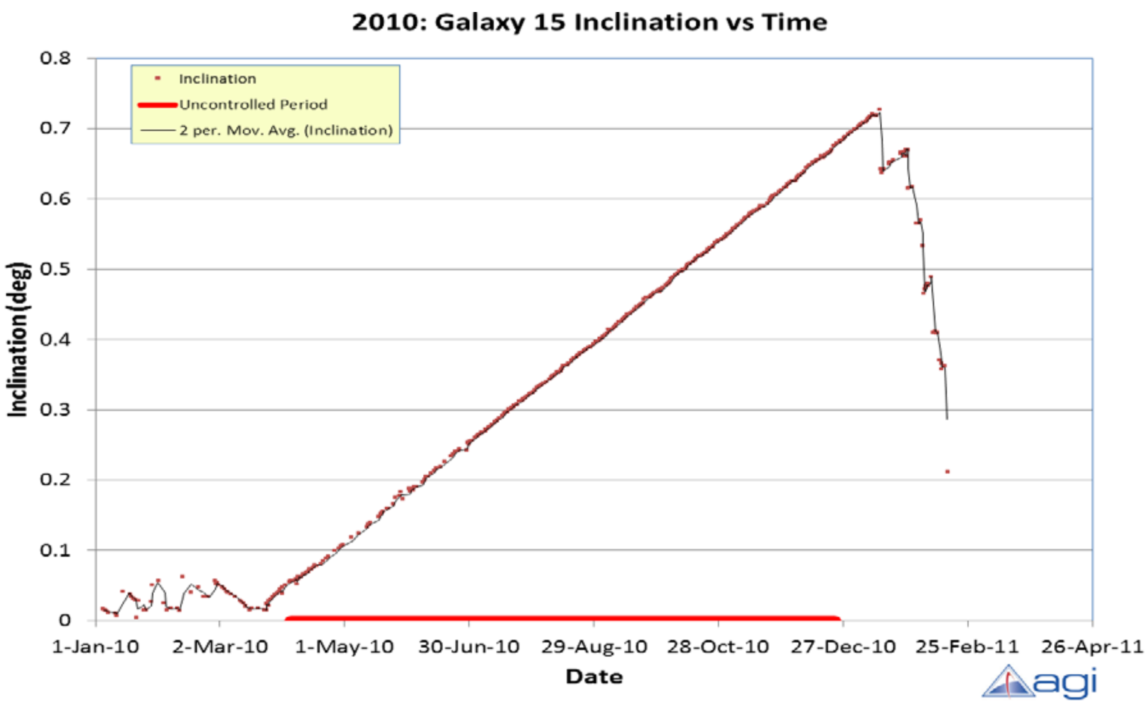

Figure 5. RSO Inclination Versus Time in 2010

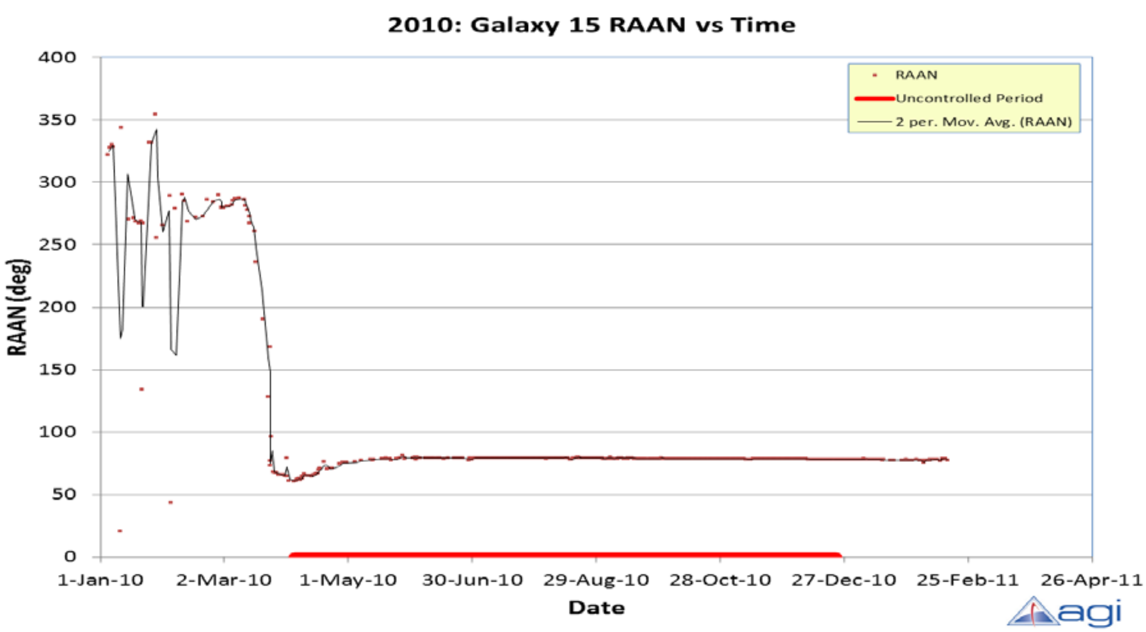

Figure 6. RSO Right Ascension of the Ascending Node Versus Time in 2010

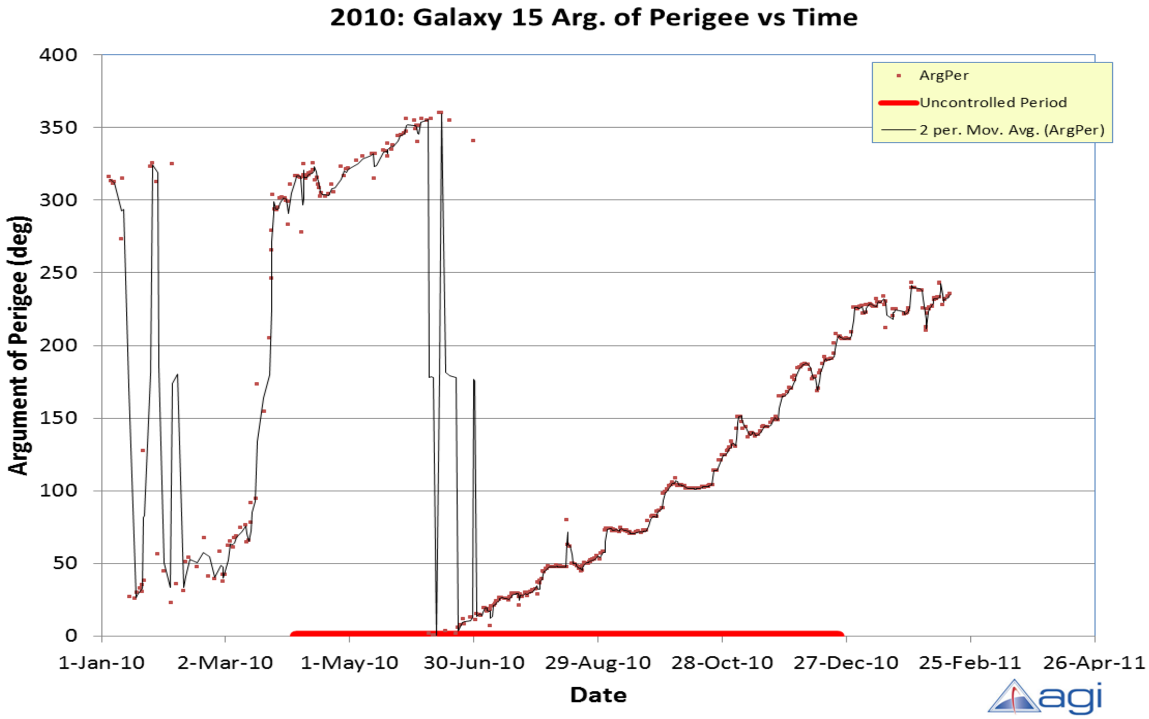

Figure 7. RSO Argument of Perigee Versus Time in 2010

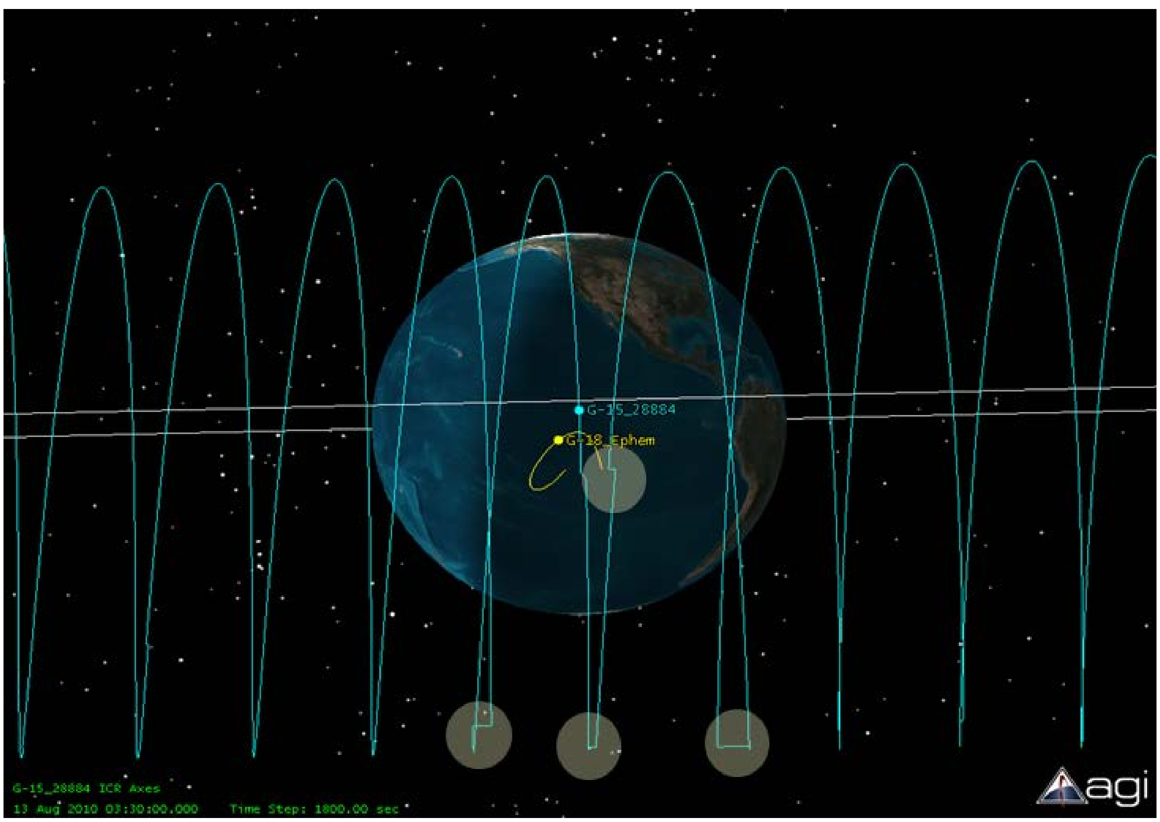

Figure 8. Galaxy-15 and Galaxy-18 Earth-Relative Paths During Flyby Encounter

Note the ellipse-encompassed step function in semi-major axis that occurred for multiple TLE vectors on approximately 13 Aug 2010. Examination of Earth-relative orbit paths during this time period reveals that these TLE step functions occurred at the approximate time of Galaxy-15's flyby of Galaxy 18, as shown in Figure 8. The figure also shows distinct step functions in the Earth-relative orbit paths for Galaxy-15 during this period.

The "scallop" pattern shown in Figure 8, coupled with what seems likely to be track mis-association problems, indicates that observations taken by NCT sensors are not taken at times that are designed to avoid mis-association problems. An NCT should predict upcoming transit or "fly-by" events occur and prioritize tasking/observation times which avoid the immediate transit event. Taking Galaxy-18 observations when Galaxy-18 is most to the north or most to the south from Galaxy-15 would likely minimize such cross-tagging. Yet it is not clear that such prioritization can be accommodated in the "contributing and collaborating sensors" framework that comprises, for example, the US Space Surveillance Network.

Using the 2.5σ filter mentioned above with recursive excision, such step functions in the orbit elements may be either removed or replaced by new elements produced by the low-pass filter distribution statistics. Note that while the current low-pass filter employs symmetric standard deviation limits about the mean value, we have not as yet demonstrated that the distribution is actually symmetric. In the future, a simple replacement of the selected 2.5σ value with equivalent percentile values (+2.5σ corresponding to a percentile of 98.76% and -2.5σ a percentile of 1.24%) will remove any assumptions on skewness, kertosis, etc. that the current approach makes.

That said, it appears that the applied 2.5σ filter worked very well in identifying and replacing equinoctial element outliers as shown in Figure 9. The figure shows that this approach identifies time periods when orbit element inconsistencies have occurred. Again, this is a non-maneuvering satellite, so any observed inconsistencies are solely caused by NCT tracking methods and susceptibilities. An interesting statistic from this figure is that out of 348 Galaxy-15 TLEs obtained during the uncontrolled period, 52 of them (15%) were found to contain cross-tag or equivalent data inconsistencies. Such inconsistencies cause overall accuracy degradation in predicted positional knowledge.

AGI is currently working on an automated approach to studying each one of these potential cross-tag periods. For now, a somewhat manual procedure using the STK deck access tool for Galaxy-15 was employed to determine when major GEO flyby events occurred. The results are shown in Figure 10. As is evident, the potential cross-tag periods are strikingly similar to the detected flyby event times.

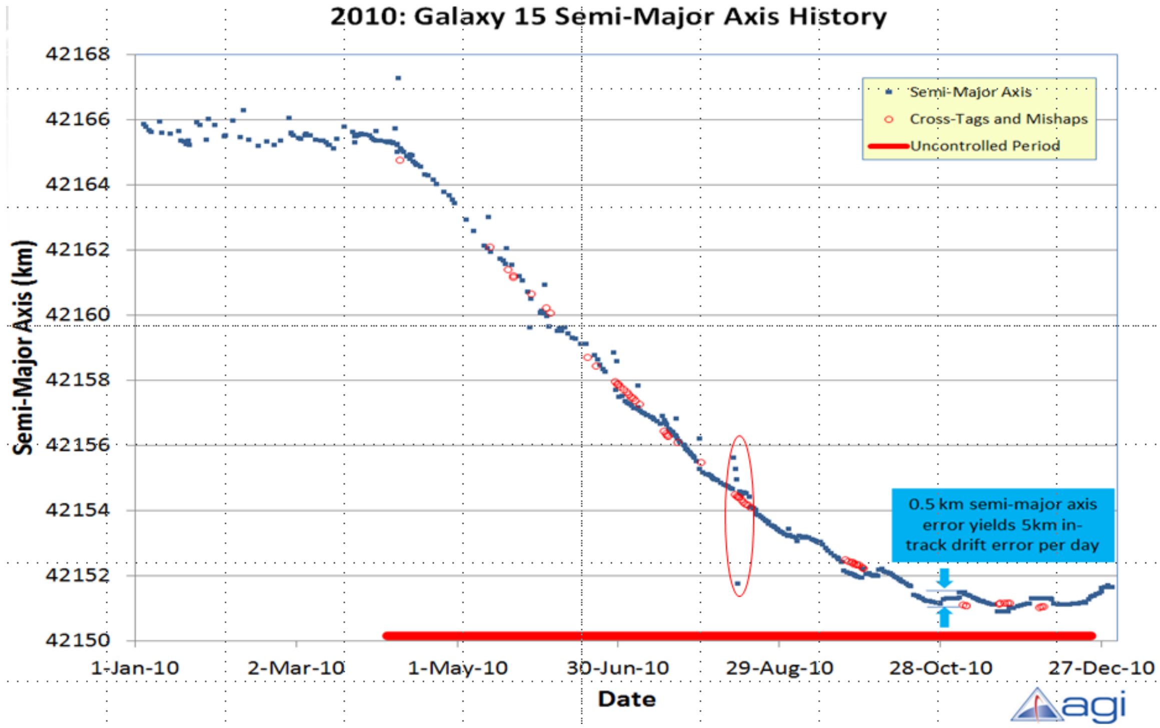

Figure 9. Orbit Element Replacement Using Orbit Detective Low-Pass Filter

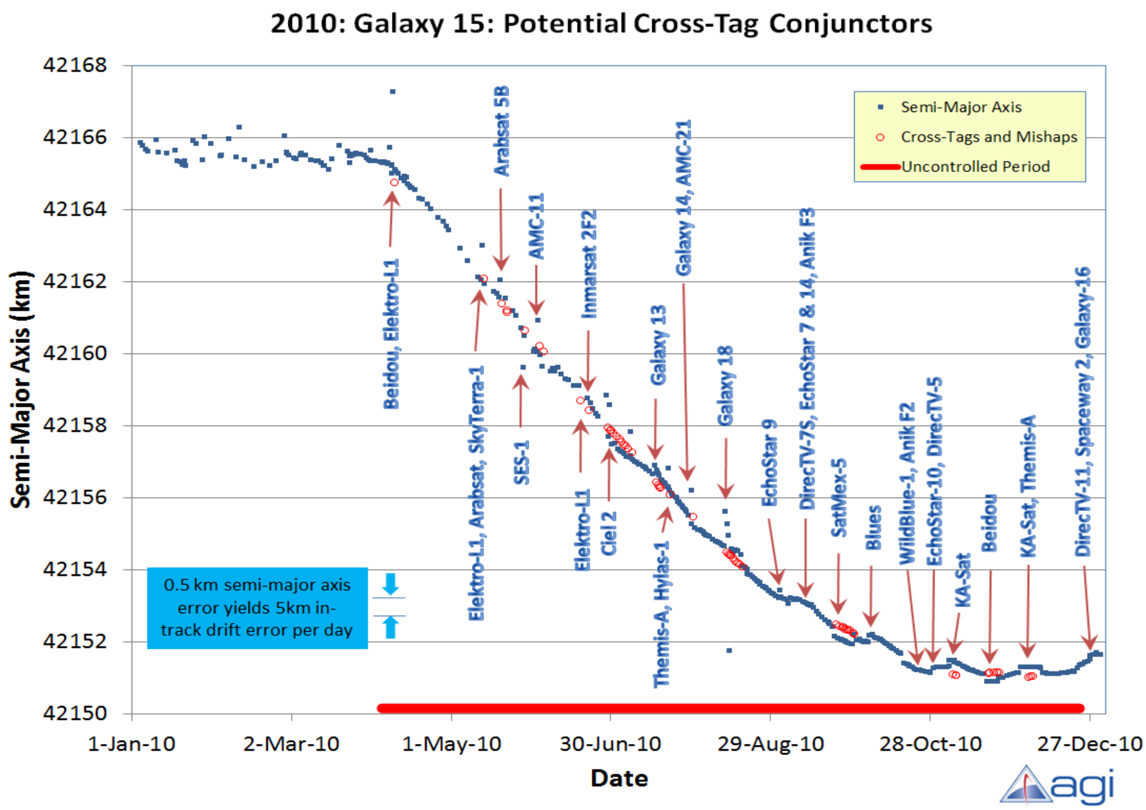

Figure 10. Correlation of Potential Cross-tag Events with Galaxy-15 Flybys

APPLICATION OF FILTER TO ENTIRE GEO POPULATION

Upon completion of the Galaxy-15 analysis, the same low-pass filter was applied to the remaining GEO regime RSOs. Distributions of the percentage of TLEs that showed such data inconsistencies were generated as a function of orbital period, longitude, and orbit update frequency.

CORRELATION OF POTENTIAL CROSS-TAGGING WITH ORBIT PERIOD

It was anticipated that objects that are nearly, but not quite, rotating at Earth's rotation rate would experience more cross-tagging data inconsistencies, because the relative drift could lead to frequent observation association problems. However, as shown in Figure 11 - Figure 13, there is not a strong correlation, and for a given percent cross-tagging/degradation, super-sync and sub-sync orbits are equally likely to experience that percentage.

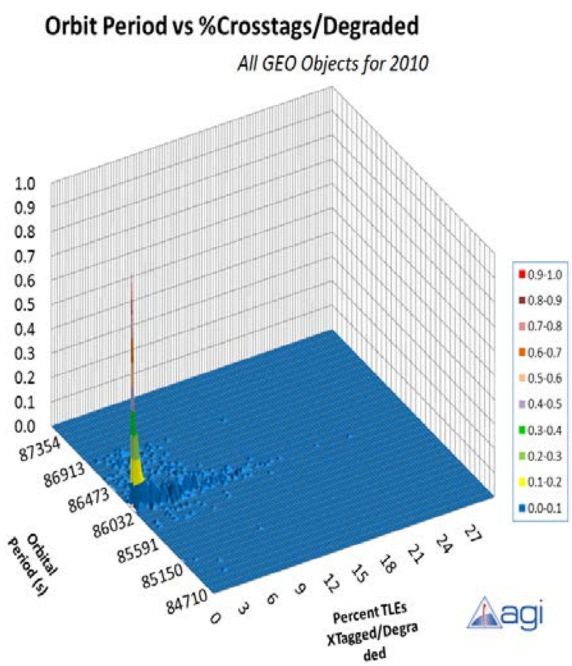

Figure 11. Distribution of Potential Cross-tag Percentage versus Orbital Period (3D)

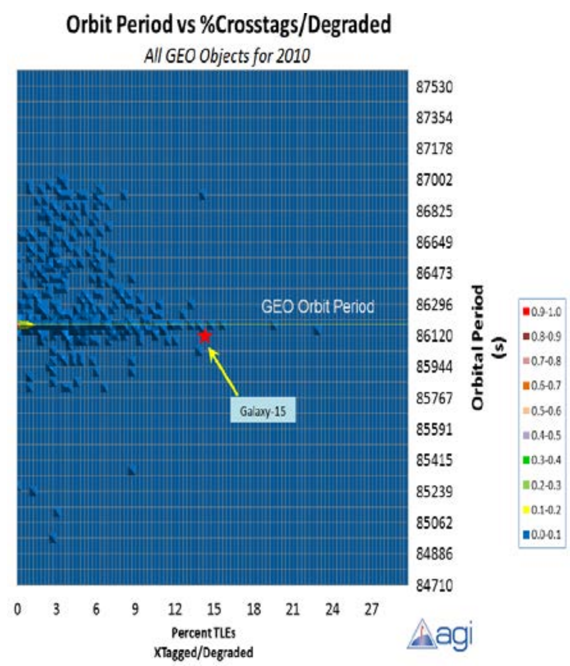

Figure 12. Distribution of Potential Cross-tag Percentage versus Orbital Period

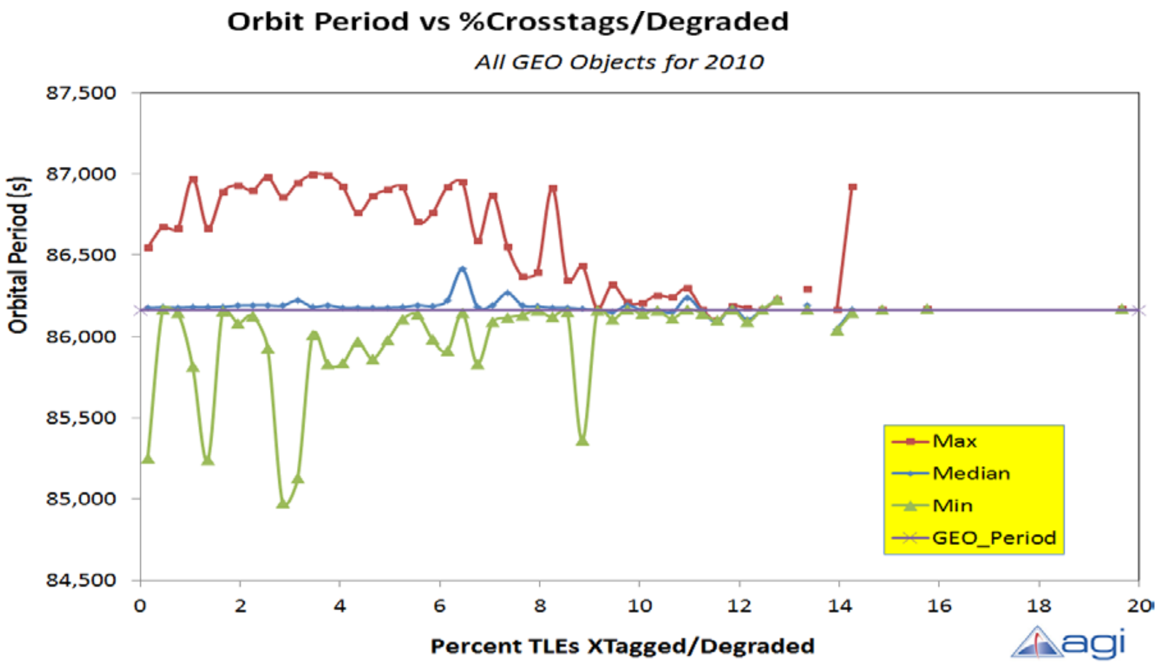

Figure 13. Distribution of Potential Cross-tag Percentage versus TLE Update Frequency

The correlation between GEO longitude and percent cross-tagging/degradation are examined next. Factors that may lead to such a correlation include the longitudinal distribution of NCT sensor placement, GEO longitude population, and GEO gravitational stability points. Figure 14 and Figure 15 show such a correlation to gravitational stability point location.

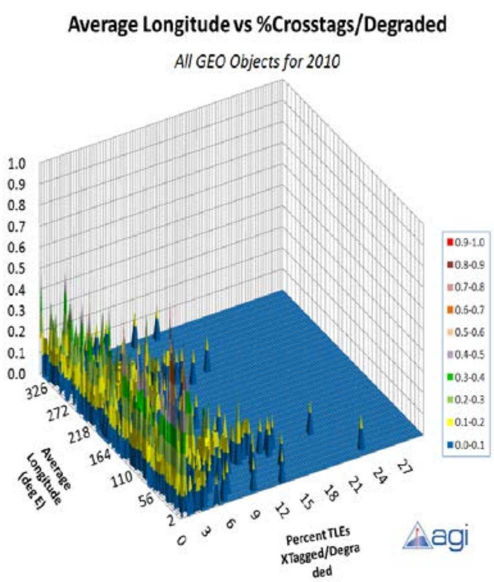

Figure 14. Distribution of Potential Cross-tag Percentage versus TLE Update Frequency (3D)

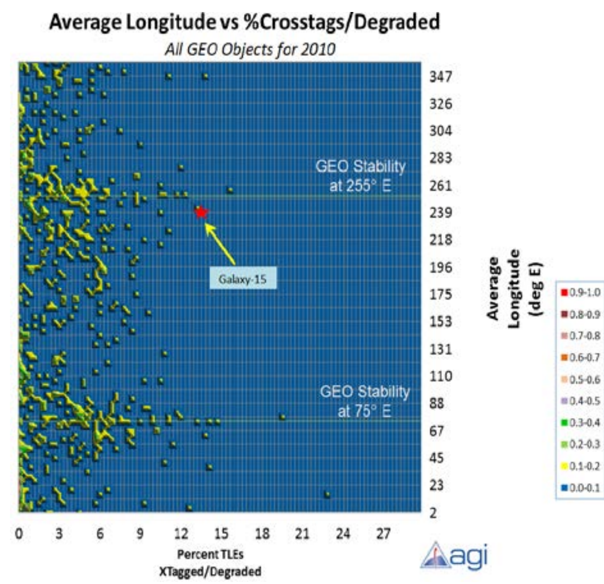

Figure 15. Distribution of Potential Cross-tag Percentage versus TLE Update Frequency

It was also thought that perhaps those objects that were tracked at a higher frequency (based upon their TLE update or publication frequency) might be less susceptible to cross-tagging. But as shown in Figure 14 through Figure 18, frequently-tracked objects are just as susceptible to potential cross-tagging events.

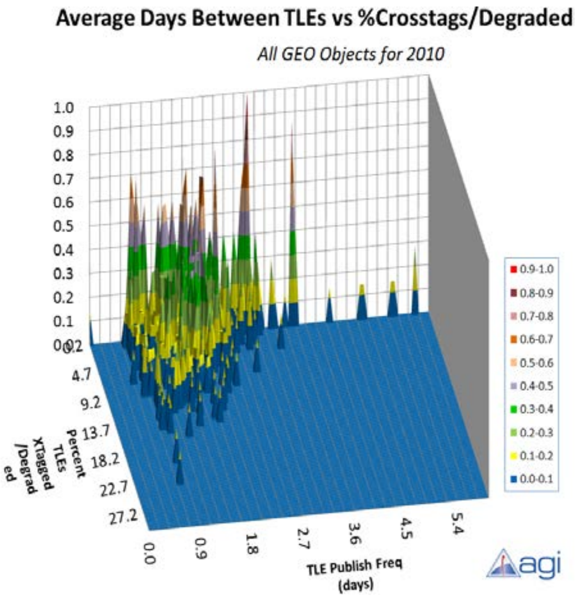

Figure 16. Distribution of Potential Cross-tag Percentage versus TLE Update Frequency (3D)

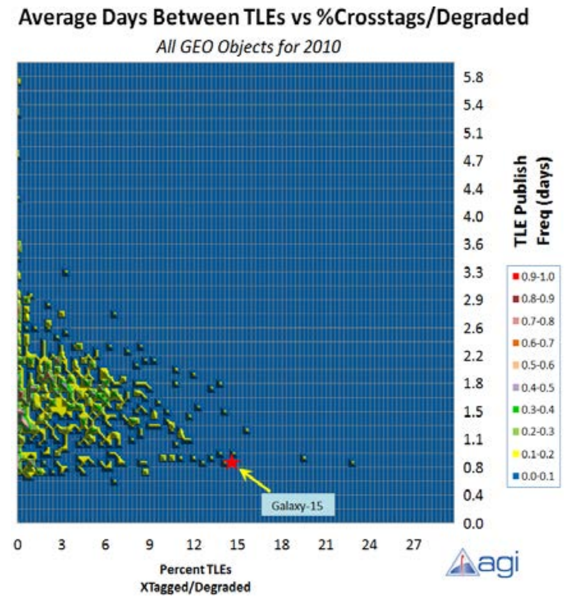

Figure 17. Distribution of Potential Cross-tag Percentage versus TLE Update Frequency

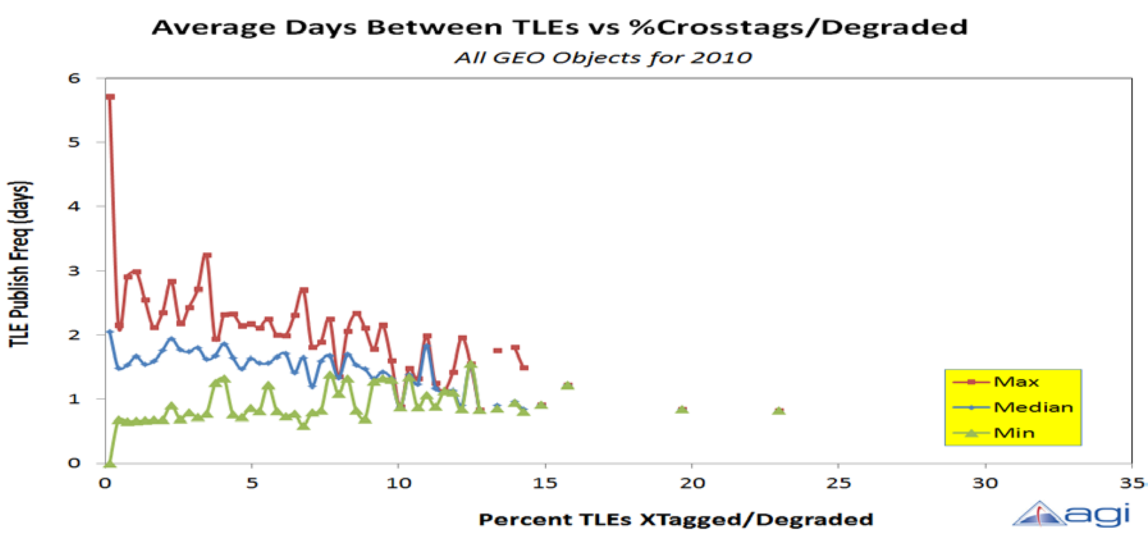

Figure 18. Distribution of Potential Cross-tag Percentage versus TLE Update Frequency

INCORPORATION OF MANEUVER DETECTION

Once outlier NCT has been removed from the orbital time history, our next step will be to incorporate maneuver detection into the Orbit Detective tool. Details of this capability are presented at this conference in a separate session[2]. A sample output from the maneuver detection capability is shown in Figure 19. The figure shows the maneuver optimization topology for a sample in-track maneuver, as well as the detected maneuver conditions shown by the red star.

The performance and capabilities of this tool are detailed in Ref. 2.

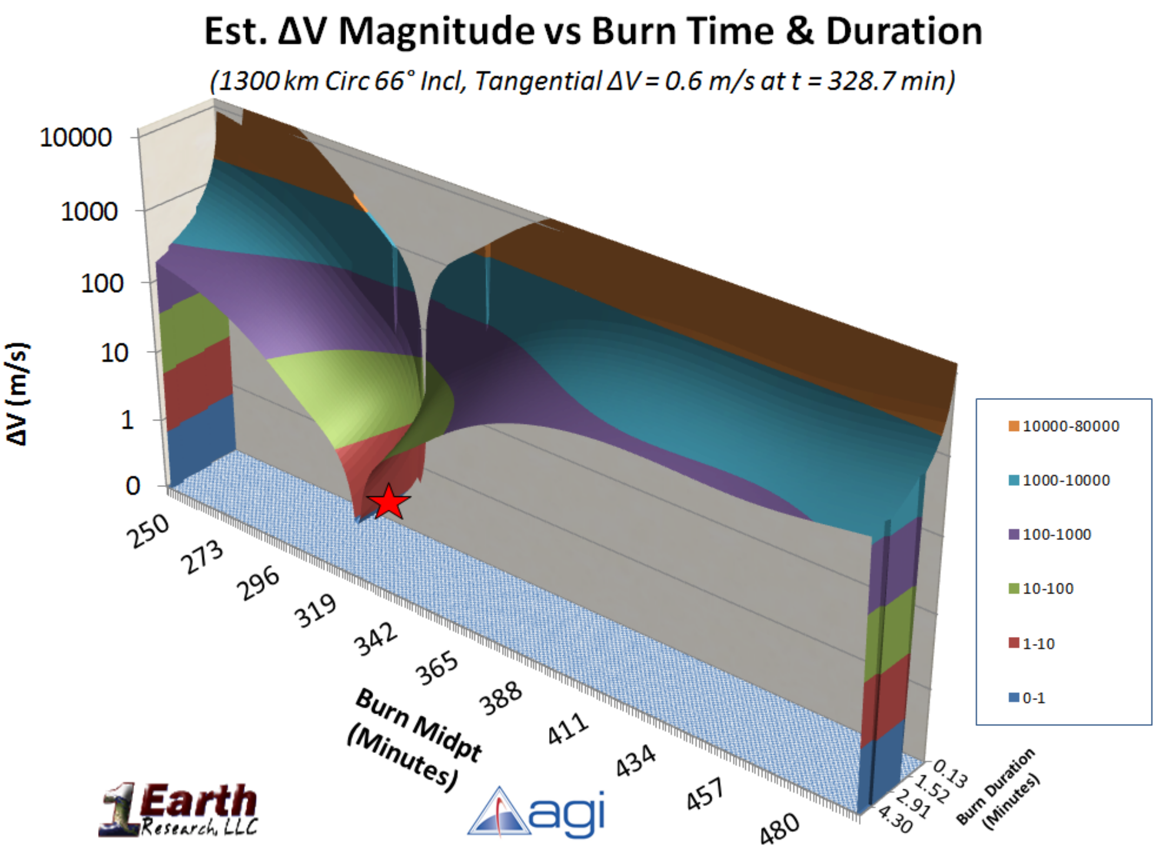

Figure 19. Sample Output from the 1Earth/AGI Maneuver Detection & Calibration Tool

CONCLUSIONS

A low-pass orbit elements filter method has been shown to be an effective approach to identifying potential cross-tagged or similarly-degraded orbit solution accuracy events. The cross-tags can be identified by rapid short-term spikes in orbital elements, which return rapidly to 'nominal' values after the event. Maneuver events can be similarly identified, but with orbital elements taking a step-function in time.

FUTURE WORK

Additional work is planned to apply these low-pass filtering techniques to the RSO catalog on an on-going basis. The current standard deviation-based low-pass filter will also be modified to rely on percentile filtering limits to remove any assumptions on distribution symmetry or Gaussian distribution. Following that, it is planned to incorporate an on-going maneuver detection capability into the Orbit Detective tool.

ACKNOWLEDGMENTS

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REFERENCES

[1] CelesTrak site, www.CelesTrak.com

[2] Oltrogge, D.L., "Maneuver Event Detection and Reconstruction Using Body-Centric Acceleration/Jerk Optimization," AAS 11-578, August 2011 AIAA/AAS Astrodynamics Specialist Conference, Girdwood, AK.