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Detection and orbit determination of a satellite executing low thrust maneuvers

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ABSTRACT

Concern for the safety of (and risk to) valued space assets has motivated the interest in processes and procedures that enable timely detection of maneuvers for satellites tracked by current and future surveillance systems. The timely detection of maneuvers provides for responsiveness in follow-up tracking, which is crucial for post-maneuver orbit characterization. However, availability and location of surveillance resources may not always allow timely detection and follow-up. Real tracking data for a maneuvering satellite, operated by the Air Force Research Laboratory (AFRL), were used for detection and process performance evaluation. This Low Earth Orbiting (LEO) satellite carried a small thruster that was used for routine orbit maintenance. Range and angles tracking data were obtained over the year 2007. In addition, burn logs for all executed maneuvers were obtained from the satellite operations to support validation of analysis done for this study. Periodic finite burn maneuvers were performed throughout the mission lifetime, sometimes in a sequence separated by hours, providing reference data for use in addressing a variety of maneuver scenarios. The ability to detect and assess maneuvers assuming no a priori maneuver information is examined for single and multiple maneuver scenarios. Batch least-squares (BLSQ) and extended Kalman filter (EKF) orbit determination strategies are applied, analyzed and compared to determine the performance sensitivity to maneuver knowledge. The comparisons examine the reliability in detecting specific maneuvers, the orbit determination performance in processing over the maneuvers, and the subsequent prediction performance resulting from the state estimates. In addition, the techniques presented can also be applied to detecting and supporting resolution of on-board anomalies that might occur on cooperative space assets.

1. Motivation and background

There are over 9000 objects orbiting the earth that are tracked and cataloged on a regular basis [1]. A smaller percentage of these are resident space objects, many of which have the capability to maneuver to accommodate mission objectives and/or orbit maintenance.

Accurate knowledge of the orbits and the ability to accurately predict object locations is crucial for safety and collision avoidance. The increasing number of nations, military, scientific and commercial users of space creates an added challenge to the tracking and surveillance community where the times/locations and characteristics of planned maneuvers might not be known in advance.

Large thrust maneuvers on the order of meters per second, though relatively easy to detect, can present challenges when follow-up observations are not immediately available [2]. Re-acquiring the maneuvered object and re-constructing the maneuver and orbit are

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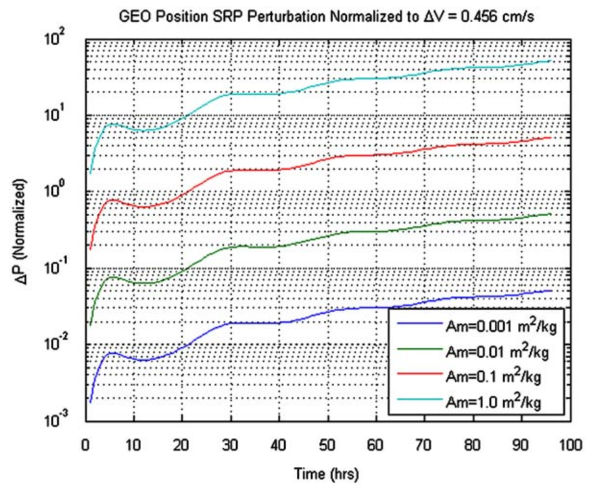

Fig. 1. Maneuver normalized solar radiation pressure perturbations on a GEO object vs. time.

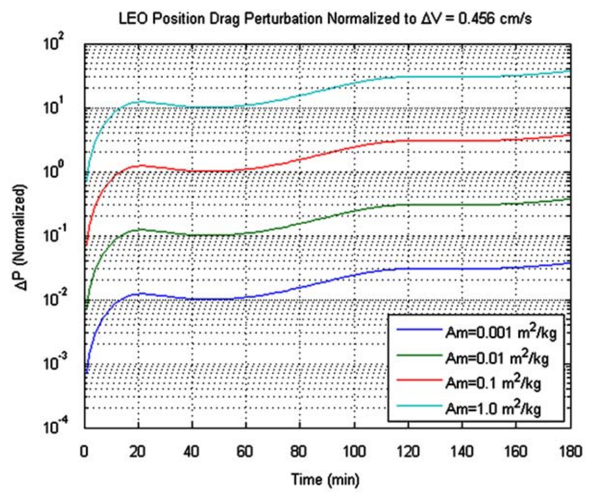

Fig. 2. Maneuver normalized atmospheric drag perturbations on a LEO object vs. time.

sometimes a matter of chance, with involvement of time-consuming search and correlation processing.

Low thrust maneuvers, however, present a different set of challenges. Though tracking of a low thrust maneuvering object may be maintained through the maneuver event, the problem is detecting that a low thrust maneuver has occurred, discriminating it from the other non-conservative perturbation effects. These subtle maneuvers can either be the result of attitude maneuvers or deliberate orbit change maneuvers, which if gone unaddressed, can result in degraded orbit determination and prediction of the object.

Low thrust maneuvers can be indistinguishable from natural dynamic perturbations. Fig. 1 illustrates how a single low thrust maneuver (0.46 cm/s) for a geosynchronous orbit (GEO) object can be interpreted as a solar radiation pressure perturbation. Similarly, Fig. 2 illustrates a similar relationship between a low thrust maneuver and the atmospheric drag perturbation on a LEO object. The figures reflect natural dynamic perturbations (for various object area-to-mass ratios), normalized by those associated with a low thrust ΔV=0.46 cm/s. A value of 1 represents a point where the magnitudes of each perturbation (natural vs. propulsive) are equal to each other. It can be seen that propulsive effects are indistinguishable from natural non-conservative perturbations for objects having nominal area-to-mass ratios on the order of 0.01 m^2/kg.

This paper presents analysis results for detection and reconstruction of a low thrust maneuvering LEO satellite. In this scenario, a single finite burn maneuver is examined. Though the focus is on detection and reconstruction of low thrust in-track maneuvers (cm/s or less), prediction performance is also examined.

2. Finite burn maneuver scenario

An experimental LEO satellite that performed periodic low thrust in-track maneuvers was used for this analysis. The semi-major axis history, along with maneuver times, is shown in Fig. 3 for most of the year 2007. The thruster force magnitude had a nominal value of 13 mN, and the burn durations ranged on the order of 10–100 s. The burns were performed either separated by several to many days, or in a sequence separated by hours. The executed maneuvers were for orbit maintenance purposes to counter the effects of atmospheric drag (i.e., in the in-track direction).

Radar based tracking data were used for the orbit determination and prediction. This included range, range-rate and angles measurement tracks throughout each orbit cycle. In addition, the validated maneuver histories and planned maneuver schedule were obtained from the satellite operators to allow accurate modeling and prediction. This also enabled analysis of performance of the detection, orbit determination and prediction in the presence of maneuvers when these were assumed to be unknown or un-modeled.

3. Un-modeled finite burn maneuver detection

A single, 129-second finite burn maneuver was conducted on 3 June 2007 at 15:40:26, resulting in a nominal ΔV of 0.46 cm/s in the in-track direction. The pre- and post-maneuver normalized[1] data residuals are shown in Fig. 4 with the maneuver time indicated. The maneuver occurred approximately centered in between a 90-min tracking gap, and any artifact of the maneuver in the residuals after the maneuver is minimal. Hence, small maneuvers may go undetected if residuals are used as the primary means for detection.

The challenge of separating small maneuvers from environmental phenomena is underscored in Fig. 5 where

[1] Normalized residuals refer to the ratio of the actual measurement residual and the measurement sigma derived from the current estimate.