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Application of Semi-analytical Satellite Theory orbit propagator to orbit determination for space object catalog maintenance

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Abstract

Catalog maintenance for Space Situational Awareness (SSA) demands an accurate and computationally lean orbit propagation and orbit determination technique to cope with the ever increasing number of observed space objects. As an alternative to established numerical and analytical methods, we investigate the accuracy and computational load of the Draper Semi-analytical Satellite Theory (DSST). The standalone version of the DSST was enhanced with additional perturbation models to improve its recovery of short periodic motion. The accuracy of DSST is, for the first time, compared to a numerical propagator with fidelity force models for a comprehensive grid of low, medium, and high altitude orbits with varying eccentricity and different inclinations. Furthermore, the run-time of both propagators is compared as a function of propagation arc, output step size and gravity field order to assess its performance for a full range of relevant use cases. For use in orbit determination, a robust performance of DSST is demonstrated even in the case of sparse observations, which is most sensitive to mismodeled short periodic perturbations. Overall, DSST is shown to exhibit adequate accuracy at favorable computational speed for the full set of orbits that need to be considered in space surveillance. Along with the inherent benefits of a semi-analytical orbit representation, DSST provides an attractive alternative to the more common numerical orbit propagation techniques.

Keywords: Semi-analytical Satellite Theory; Orbit propagation; Orbit determination; Space Situational Awareness

1. Introduction

Space around the Earth is increasingly crowded, posing computational problems with accurately predicting the positions of a large numbers of space objects. This prediction is required not only for the correct operation of the satellites, but also for preserving the integrity of space assets and the services they provide to citizens. The present international concern with Space Situational Awareness (SSA) has produced a renewed interest in analytical and semi-analytical theories to propagate orbits fast and accurately, for the maintenance of a space object catalog. In addition, the mean elements in an analytical or semi-analytical theory can be governed by nearly linear differential equations and this impacts the error analyses associated with SSA.

Typical SSA tasks which involve orbit determination and/or orbit predictions are

- observation processing: object correlation, track association and updating of cataloged objects (orbit determination)

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- object maneuver detection and maneuver processing
- object conjunction assessment: covariance propagation and uncertainty propagation
- sensor tasking
- lifetime predictions

Among these, the first three tasks typically demand an accurate orbit propagation technique, whereas a statistical assessment of approximate predictions is sufficient for lifetime predictions and less accurate propagations will also suffice for sensor tasking. Methods for sensor tasking and lifetime predictions are presented in Miller (2007), Goodliff et al. (2006) and Dell'Elce and Kerschen (2009).

The aim of this study is to find a propagation method that can be used for all cataloging tasks and offers favorable trade-off between accuracy and computational effort. Morton and Roberts (2011) estimate that the US Joint Space Operation Center (JSpOC) performs about 40,000 track and object correlations per day to maintain their catalog and provide collision warnings. This system requires a few hundred thousand orbit predictions and determination runs per day. On the other hand, Boikov et al. (2009) states that the Russian Space Surveillance Center performs about ten million orbit propagations every day to maintain their catalog. In order to compute 10^5 to 10^7 orbit predictions per day, the chosen orbit propagation technique for SSA must be computationally efficient and at the same time accurate.

Additionally, the theory should fulfill the following requirements:

- Force modeling for different orbital regimes: the theory should be based on non-singular orbital elements and capable of handling both conservative and non-conservative perturbations.
- Flexibility of choosing force models at run time and having the option to propagate orbits with different spacecraft area to mass ratios and altitudes.
- Facilitate modular implementation: the theory should provide flexibility to update or upgrade the constants and models used within the propagator.
- Fast and accurate state transition matrix computation: the theory should be flexible with respect to the choice of solve-for variables for the orbit determination methods and covariance propagation.
- Ability to generate closely spaced ephemerides without increasing the computational effort: to have an interpolation procedure in order to process dense and closely spaced observations.

Special Perturbations (SP) methods using numerical integrator with high fidelity force models provide space operators with accurate predictions of the positions and velocities of space objects. However, the high accuracy of these methods and the flexibility to employ force models of varying complexity and sophistication comes with the disadvantage of a strictly sequential, step-wise processing when propagating from one epoch to another.

On the other hand, computationally lean General Perturbations (GP) methods exist, that provide analytical solution of the equations of motion. They can be used to compute orbital positions at "arbitrary" times and the computational effort does not grow with the time between the epoch of the orbital elements and the epoch of the computation. However, the formulations are often based on restrictive assumptions (Brouwer, 1959; Kozai, 1959); the modeling of the dynamic forces is limited relative to the accuracy requirements of space operations (Vallado, 2001). This concern is specifically true for the analytical SGP4 orbit model (Hoots and Roehrich, 1980), which provides the basis for propagating "2-line" orbital elements in the catalog of space objects made available by the US Spacecommand.

Kozai (1974) describes the physical effects that need to be included in an analytical formulation for prediction accuracies compatible with current SSA observation accuracies. Efforts to develop advanced analytical theories with improved modeling accuracy have, for example, resulted in the 'A' and 'AP' analytical satellite theories, which are claimed to offer high propagation accuracy (Boikov et al., 2009) but are not accessible for the general public. Other theories worth mentioning in this context include the works of Wnuk (2002) and Bezdek (2006) which offer second-order solutions for the full Earth gravity field, simplified solutions for atmospheric drag, as well as special formulations suitable for high eccentricities. However, despite considerable complexity, these theories remain limited in the underlying physical models and the achieved overall accuracy.

To summarize, SP provides the best solutions for realistic problems at the cost of speed, while GP is fast but only acceptable when seeking approximate solutions, of reasonable accuracy, for approximate problems. An ideal choice for the SSA application would be to have an approximate solution of reasonable accuracy for realistic problems, such that a balance exists between propagation accuracy and speed. That is to have accuracies better than GP and computational burden less than SP.

This goal can in fact be achieved by Semi-analytical Satellite Theories (SST). In a semi-analytical approach, the highest frequencies of motion are separated analytically via averaging procedures (Herriges, 1988) allowing the numerical integration of the averaged system to proceed with very long step sizes of half a day to one day. Later, the short-period terms are recovered analytically. Both the mean elements and the Fourier coefficients in the short periodic expressions may be recovered by an interpolation technique.

Following an initial review of available SST formulations including those of Golikov (2012), Sang and OBrien (2004), Bezdek and Vokrouhlicky (2004), Yurasov (1996) and Kaufman (1981), the Draper Semi-analytical Satellite