VALIDATING SHORT PERIODICS CONTRIBUTIONS IN A DRAPER SEMI-ANALYTICAL SATELLITE THEORY IMPLEMENTATION: THE OREKIT EXAMPLE

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ABSTRACT

Abstract: *Among existing orbital propagation techniques, semi-analytical methods are of great interest: by separating the computation of long-term evolution from one side and the short-term variations from the other side, they tend to be significantly faster than classical numerical methods while keeping similar accuracy. The implementation of the Draper Semi-analytical Satellite Theory (DSST) into the free OREKIT library offers to the astrodynamics community one of the most mature and versatile semi-analytical propagator. This paper focuses on the validation process of this implementation covering a large panel of orbits, from LEO to HEO. Comparison with legacy Fortran 77 software demonstrated a great consistency.*

Keywords: *Draper Semi-Analytical Satellite Theory, OREKIT, Validation*

1. Introduction

This paper presents the implementation and validation of the Draper Semi-analytical Satellite Theory (DSST) model as an orbit propagator into the free OREKIT library.

The project, funded by the European Space Agency (ESA), was carried out by CS Romania with the support of CS Systèmes d'Information (France) and Paul J. Cefola.

The technical objectives were threefold:

1) validation of the DSST mean equations,
2) addition of short-periodic variations to improve accuracy,
3) handling of attitude models in the OREKIT DSST.

The complete implementation of the DSST propagator is now publicly available through the OREKIT library, as of release 7.0, freely downloadable at www.orekit.org.

2. Background

2.1. The OREKIT library

OREKIT is a low level space dynamics library written in Java. It provides basic elements (dates, frames, orbits, attitude …) and various algorithms to handle them (conversions, propagation, pointing, etc.).

OREKIT main features concern:

- Time: high accuracy absolute dates, time scales, transparent handling of leap seconds,
- Frames: reference and user-defined frames hierarchy supporting fixed and time-dependent frames,
- Orbits: Cartesian, circular, equinoctial and Keplerian representations, with transparent conversion between them, Two-Lines Elements,
- Attitude: extensible attitude evolution models and predefined laws,
- Propagation: analytical propagators, semi-analytical (DSST) and numerical propagators with customizable force models, ephemeris handling,
- Handling of discrete events during propagation.

Distributed under the Apache License Version 2.0, OREKIT is freely available both in source and binary formats, with all related documentation and tests [1].

2.2. The Draper Semi-analytical Satellite Theory

Semi-analytic propagators combine the speed of analytical propagators to the accuracy of numerical propagators by computing the orbital state as the sum of two different parts: one has very slow dynamics while the other corresponds to fast variations. The slowly varying part is akin to a centred or mean model including secular and long period terms, its rate of change is long with respect to the orbital period and it can be numerically integrated with very long steps (several orbits per step). The fast varying part is akin to short period terms that correspond to the difference between mean and osculating parameters. These terms are either computed analytically or represented as Fourier series. Fast computation is achieved because numerical integration can be done with long steps and short period terms are closed-form evaluations. High accuracy is achieved because the averaging and variations computation can be done for a wide range of perturbation types and only the zero-mean part of these perturbations needs to be handled (the non-zero-mean part being handled in the numerical integration).

Paul Cefola & al developed the DSST (Draper Semi-analytical Satellite Theory) model from the mid 70’s at the Draper Laboratory. The DSST model, widely used and validated, is characterized by its great flexibility: taking into account a large set of perturbations (gravity field of a central body, including zonal and tesseral harmonics, third body attraction, atmospheric drag and solar radiation pressure), it can handle any kind of elliptical orbits.

Many papers presenting parts of the mathematical model are publicly available, the most complete enabling the implementation being [2].

3. Validation of the equations of motion of the mean equinoctial elements

At the beginning of the project, in mid-2013, the implementation of the DSST model into the OREKIT library (release 6.0) was limited to the equations of motion of the mean elements. Thus, the first goal was the analysis of the current implementation, to identify and correct the bugs reported on the issue tracker of the OREKIT forge, and its validation through various test cases.

Therefor a comparison between the results of the OREKIT DSST propagator and those of the original Fortran DSST propagator, provided by Paul Cefola, was carried out.

A set of 29 test cases was completed for various perturbation and orbital configurations:

- 5 basic tests with only J2 zonal harmonics (to set-up the testing process) ,
- 4 LEO tests with realistic force models,
- 4 MEO tests,
- 2 GTO tests,
- 10 GEO tests,
- 2 "exotic" orbits tests,
- 2 backward propagation tests.

Each test was configured with:

- the mean orbital elements (Keplerian, equinoctial or Cartesian representation alike),
- the epoch of the orbital elements,
- the considered frame (mainly TOD frame to be coherent with Fortran DSST)
- the satellite characteristics: mass, cross sectional area
- the perturbations taken into account, which can be combined:
    - geopotential: order and degree for zonal and tesseral harmonics,
    - 3rd body: Sun and/or Moon,
    - atmospheric drag,
    - solar radiation pressure,
- the propagation duration: mainly 7500 days (~20 years),
- the choice of the integrator: Dormand-Prince (adaptive step) or Runge-Kutta (fixed step).

For each test, the evolution of all the Keplerian elements as computed by the two DSST propagators was plotted along with the differences between them.

Most of the tests show extremely small differences between the OREKIT DSST and the original Fortran DSST. The only noticeable discrepancies appear for LEO cases exhibiting final decay that can be explained by a small difference in the implementation of the Harris-Priester atmospheric model used by the two propagators, but also by the choice of the Dormand-Prince integrator for the OREKIT DSST, the use of the Runge-Kutta integrator lowering the gaps.

A few tests with propagation over 75000 days (~200 years) have also been run, but, because of a limitation in the environment data embedded into the original Fortran DSST, the results of the OREKIT DSST were compared with those of the OREKIT numerical propagator. Neglecting the short periodic effects, the trend for all the orbital elements appeared to be very satisfactory.

The figure below shows an example of the results for one of the GEO cases with 8x8 potential, Sun and Moon attraction and solar radiation pressure.

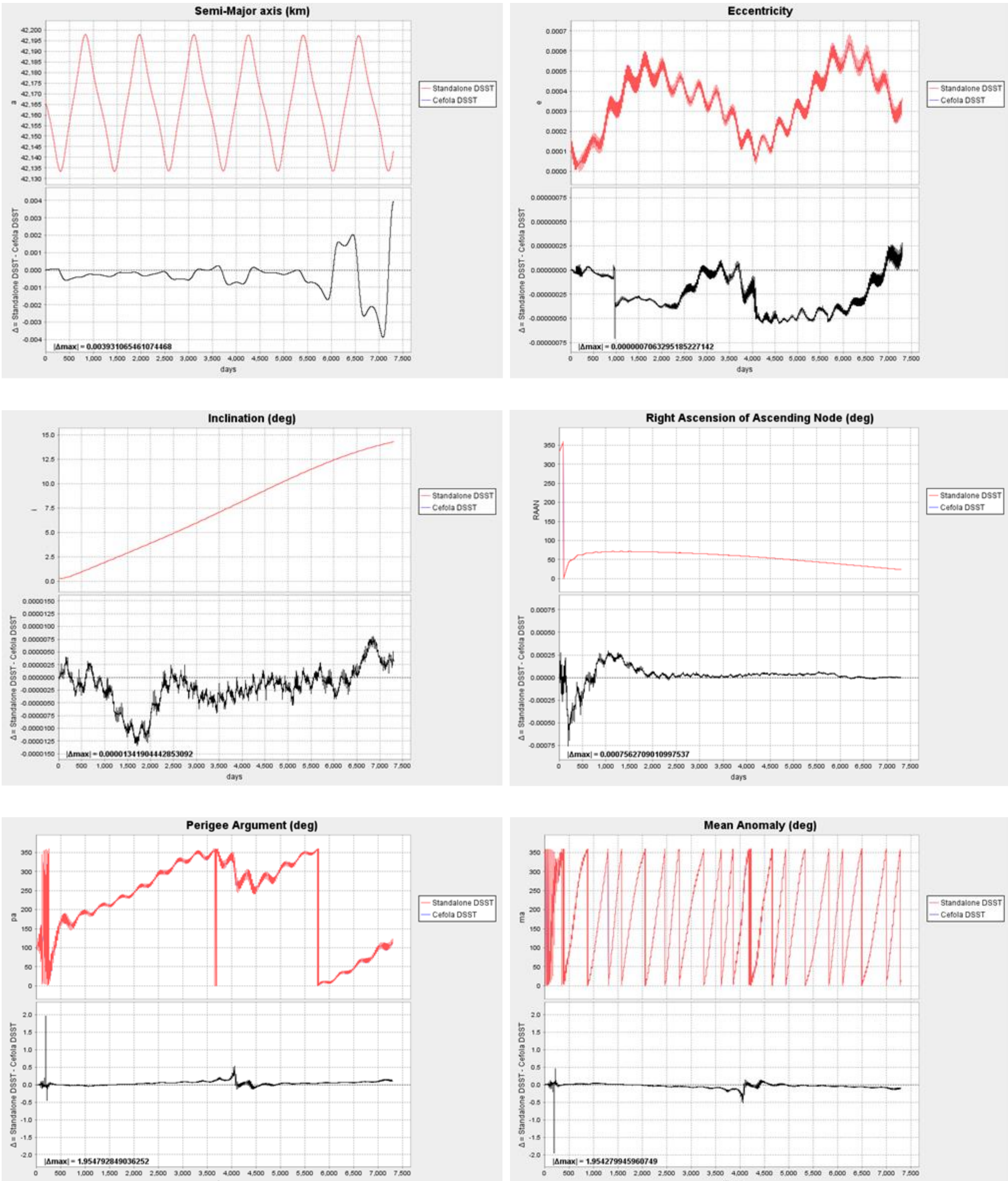


Figure 1 Meteosat-9 test case

After this first validation step, it was decided to improve the computation of the Hansen coefficients, their derivatives and the Jacobi polynomials, used in the formulas of the functions approximating the mean disturbing forces, in order to speed-up performances. The same tests were carried out and the results compared to the previous run: no significant numerical difference has been observed, but the execution time has been improved in any case, from a few percent up to 50 % for tests where tesseral and 3rd body contributions are important.

5. Short periodic variations

The second task of the project was the implementation of the short periodic variations for all perturbing forces into the OREKIT DSST propagator and its validation.

A set of 24 test cases was completed for various perturbation and orbital configurations:

- 5 basic tests with only J2 zonal harmonics,
- 5 LEO tests with realistic force models,
- 4 MEO tests,
- 2 GTO tests,
- 2 GEO tests,
- 6 “exotic” orbits tests.

The propagation duration was limited to 7 days for all tests since the validation is focused on accuracy in this case.

But the original Fortran DSST only handles a limited set of short periodic variations for some specific orbits:

- Low altitude, near circular orbit
    - Zonal Harmonics (up to degree 12)
    - Tesseral Harmonics (up to 8x8 potential)
    - Tesseral m-daily harmonics (up to 12x12 potential)
- 12 Hour high eccentricity Molniya Orbit
    - J2 Zonal Harmonics
    - Tesseral m-daily harmonics (up to 12x12 potential)
    - Lunar-Solar contribution
- 24 Hour Geosynchronous Orbit
    - J2 Zonal Harmonics
    - Lunar-Solar contribution

Thus, when test cases were not supported by the Fortran DSST, comparisons were made with the OREKIT numerical propagator.

For each test, the evolution of all the Keplerian elements as computed by the two propagators was plotted along with the differences between them. The differences between position and velocity were also plotted because they better compare the accuracy of the propagators.

In all cases, the comparison between the position and the velocity computed over the time span by the two propagators, OREKIT DDST on one side and Fortran DSST or OREKIT numerical propagator on the other side, show small differences: less than a few meters for position and a few mm/s for velocity.

So, the implementation of the short-periodic variations into the OREKIT DSST has been successfully validated against the original Fortran DSST and the OREKIT numerical propagator.

Some typical test cases are presented hereafter.

5.1. LEO equatorial (HETE-2)

Orbit characteristics:

- a = 6944.68005365 km
- e = 0.00222270824
- i = 1.86438067644°
- Ω = 281.661404104°
- ω = 230.123714157°
- M = 230.123714157°

Forces model:

- potential 15x15
- tesseral m-daily only (short periodic contribution)

OREKIT DSST is compared to Fortran DSST.

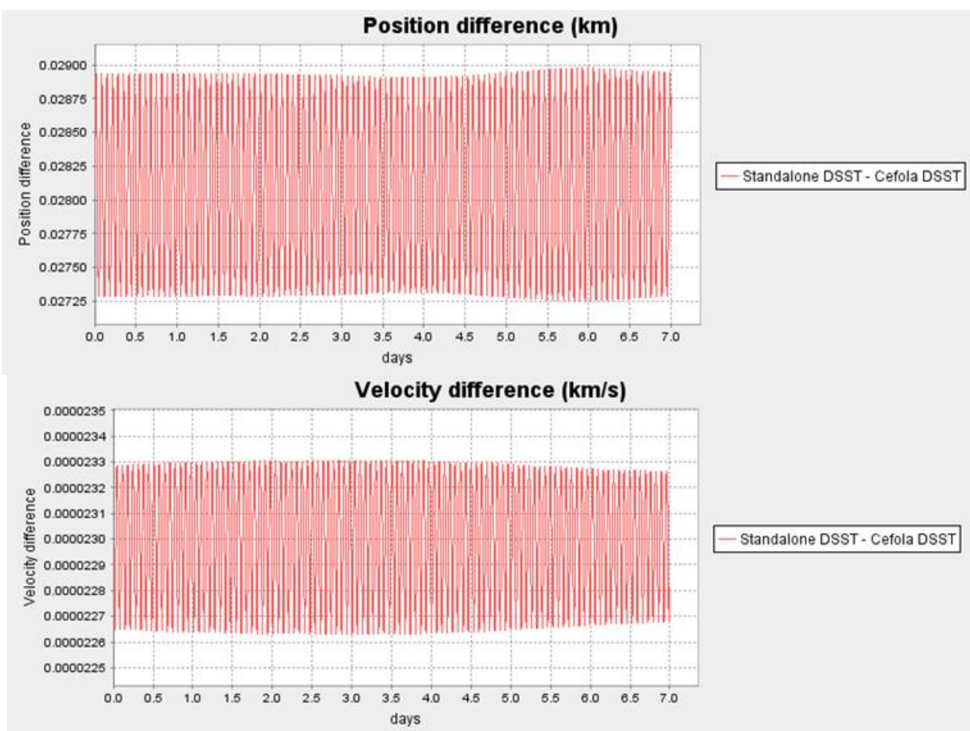


Figure 2 LEO equatorial (HETE-2)

5.2. MEO (Galileo-like orbit)

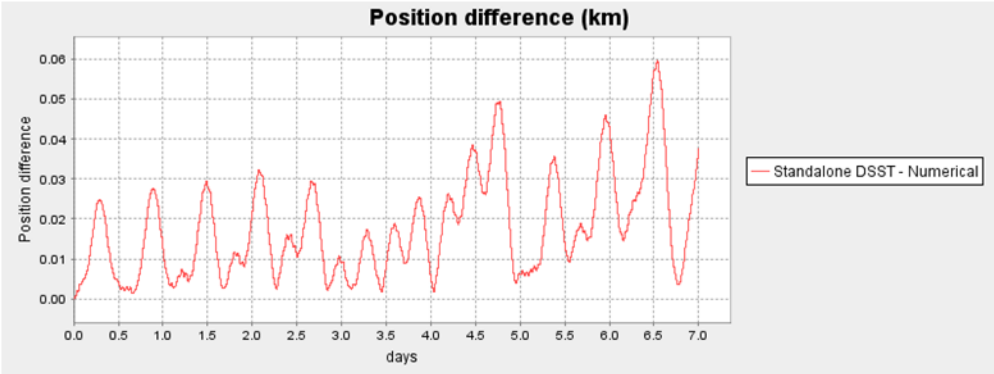
Orbit characteristics:

- a = 29600.0 km
- e = 0.001
- i = 56.0°
- Ω = 240.0°
- ω = 120.0°
- M = 0.0°

Forces model:

- potential 8x8
- 3rd body attraction: Sun & Moon
- solar radiation pressure

OREKIT DSST is compared to OREKIT numerical.



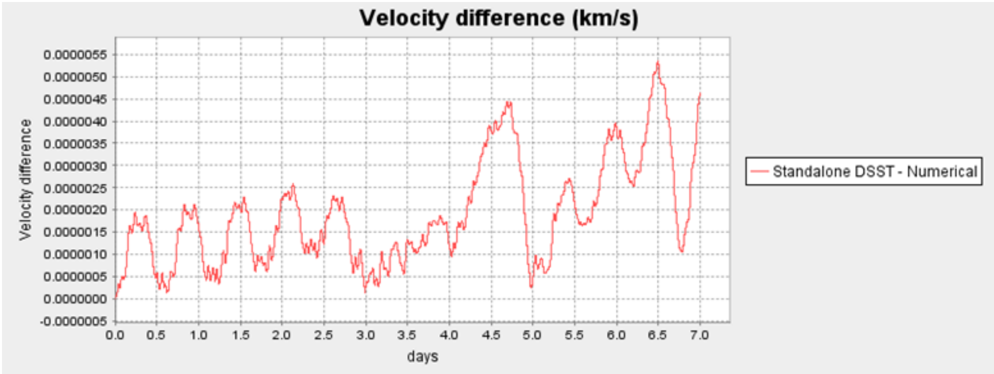


Figure 3 MEO (Galileo-like orbit)

5.3. GEO (METEOSAT-9)

Orbit characteristics:

- a = 42162.0364137 km
- e = 0.00016452266

- i = 0.30813281366°
- Ω = 331.126193309°
- ω = 112.076361788°
- M = 335.866955746°

Forces model:

- potential J2 only
- 3rd body attraction: Sun & Moon

OREKIT DSST is compared to Fortran DSST.

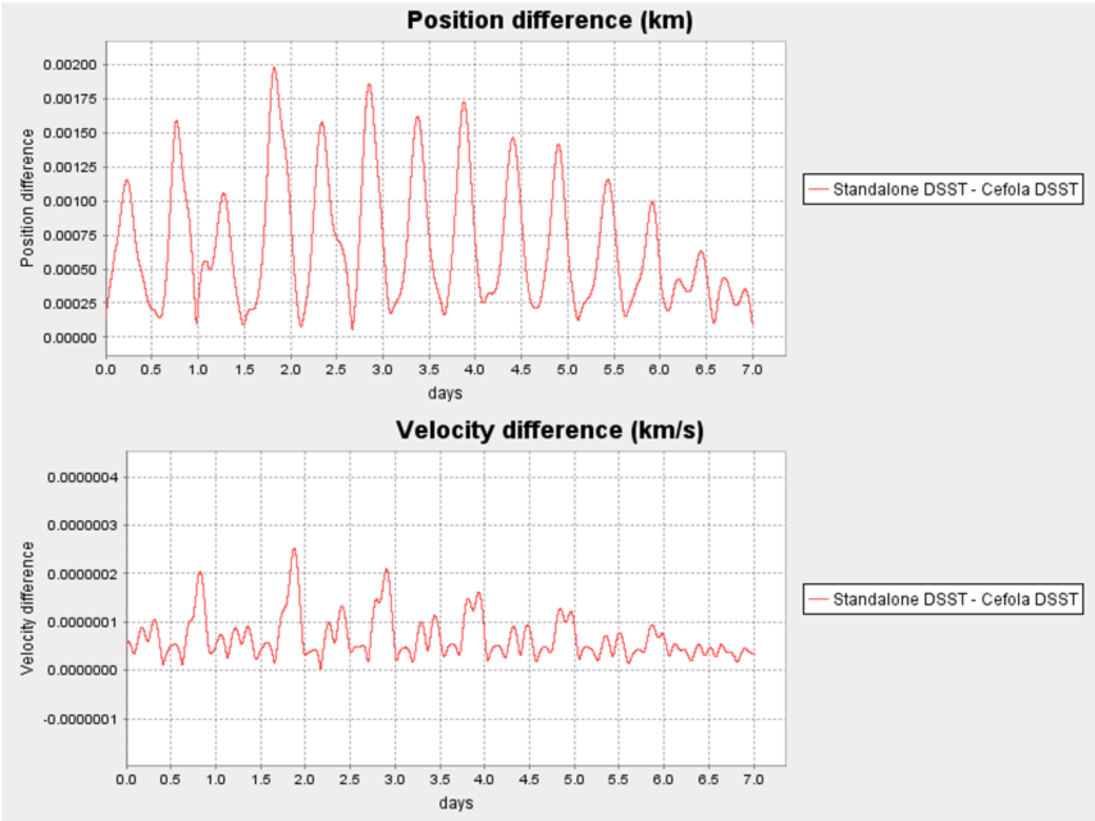


Figure 4 GEO (METEOSAT-9)

6. Attitude handling

The last objective of the project was to find a way to handle periodic attitude models in the OREKIT DSST propagator.

6.1. Analysis

Thanks to the documents provided by Paul Cefola about the 2Π periodic attitude handling for mean elements, the analysis concluded that, despite DSST constraints on either slow or periodic dynamics are very stringent and don't correspond to regular attitude laws for operational space missions, it was possible to compute accurately the mean elements for any force model that can be defined by sampling accelerations and therefore short periodic variations for periodic acceleration-based models can also be computed.

A close analysis of Fortran DSST implementation has leaded to improve the spacecraft shape modeling and to reuse the computation of the accelerations for surface force models (atmospheric drag and solar radiation pressure) that already exists in the OREKIT numerical propagator.

6.2. Implementation

Several modifications have been made in order to handle properly periodic attitude:

- Use of a numerical force model to compute accelerations,
- Addition of attitude handling in the OREKIT DSST propagator, allowing the user to set up attitude laws in order to compute the attitude of the satellite during the propagation,
- Update of the computation of accelerations used in the quadrature process for numerical averaging, so that attitude changes over the orbit could be taken into account.

Some parameters were added to the testing process:

- Design of the spacecraft shape: spherical, simple box, box with solar array,
- Choice of specific attitude laws:
    - Local Orbital Offset: attitude of the satellite fixed in the local orbital frame,
    - Nadir Pointing: satellite pointing towards the nadir,
    - Celestial Body Pointing: satellite pointing towards the Sun
- Enabling/disabling attitude handling for comparison purposes.

As the original Fortran DSST doesn’t handle attitude, the validation has been done by comparing the results of the OREKIT DSST propagator with the OREKIT numerical propagator, which already handles a wide set of attitude laws together with various spacecraft shapes.

Attitude handling only affects non-conservative forces, whose strength depends on the type of the orbit. Thus, two kinds of tests have been run:

1) GEO cases for solar radiation pressure validation, with various shapes and attitude laws,
2) LEO cases for atmospheric drag validation, with various shapes and attitude laws.

In both cases, the results produced by the OREKIT DSST propagator show significant sensibility to changes on the spacecraft shape and on the attitude law and appear to be consistent with those produced by the numerical propagator for short-term evolutions, of the order of one day. For long-term evolutions, above one week, the comparison is less satisfactory and, more importantly, the computation time degrades significantly.

As a conclusion, attitude handling with the DSST propagator is relevant on quite short time span to get an accurate estimation of the orbit evolution. For long term evolution, because of the performance issues and the lack of consistency, one should stay on a simpler modeling for drag and SRP contributions.

7. Conclusions

All the technical objectives of the project were successfully reached.

An almost complete DSST propagator has been fully validated and is now freely available from the OREKIT library, as of release 7.0.

Its accuracy could be slightly improved by implementing some lesser perturbation forces:

- Second order perturbations, such as J2 squared and J2-drag
- Weak-time dependent models for 3rd body short periodic variations,
- Tides.

7. References

[1] OREKIT home page, https://www.orekit.org/

[2] Danielson D., Sagovac C., Neta B. and Early L., "Semianalytic Satellite Theory", Naval Postgraduate School Department of Mathematics Monterey, CA 93943, 1995.