First tests of the C/C++ version of the Draper Semi-analytical Satellite Theory (DSST)

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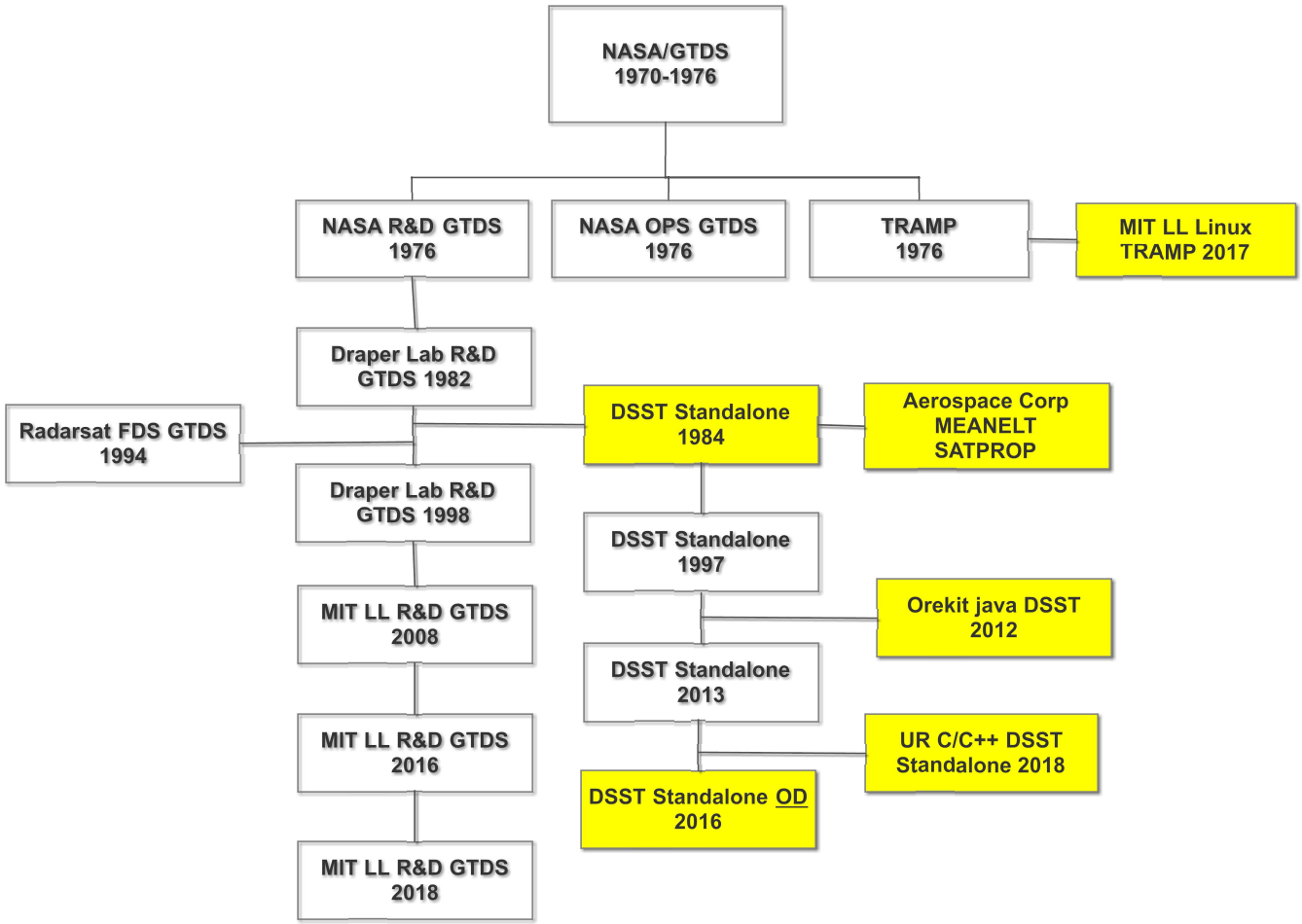
Outline

Draper Semi-Analytical Satellite Theory (DSST)

- DSST was created to be a low cost, long-term orbit propagator for the following applications:
  - Mission feasibility studies
  - Mission analysis (lifetime and geometry constraints)
  - Tracking station acquisition schedules
  - Dynamic modeling required for differential correction procedures
- DSST $\subset$ Goddard Trajectory Determination System (R&D GTDS)
- DSST Standalone

GTDS/DSST version histoy



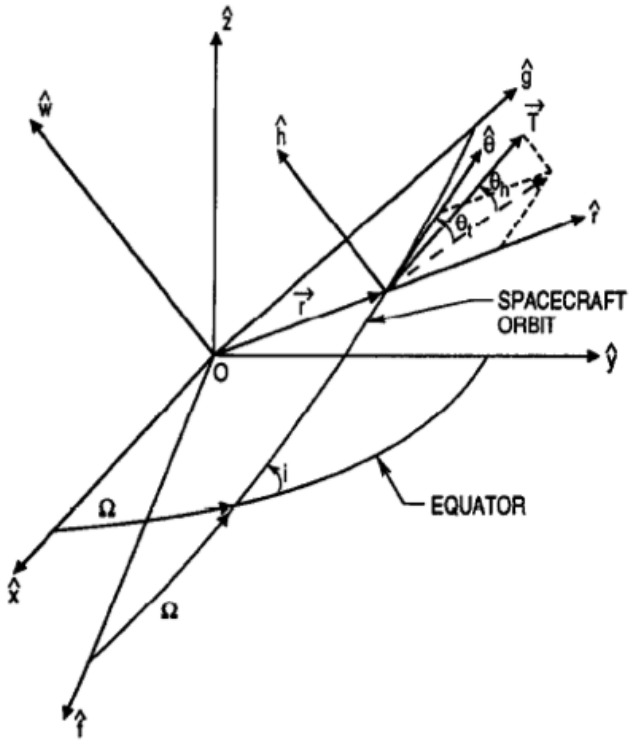
(Dr. Paul J. Cefola)

Equinoctial elements

$$
\begin{aligned}
a &= a \\
h &= e\sin(\omega + I\Omega) \\
k &= e\cos(\omega + I\Omega) \\
p &= \tan^I\left(\frac{i}{2}\right)\sin\Omega \\
q &= \tan^I\left(\frac{i}{2}\right)\cos\Omega \\
\lambda &= \ell + \omega + I\Omega
\end{aligned}
$$

(Nonsingular elements)

Equinoctial reference frame



Expansion of the Geopotential in Equinoctial Elements

- Expression in spherical harmonics relative to the ECI frame
  - radial distance, latitude, and longitude
- Rotation of the spherical harmonics to the equinoctial orbital frame
  - Jacobi polynomials replace the Kaula inclination functions
  - stable recursion formulas are available in the mathematical literature
- Products of radius to a power times sin or cos of true longitude (and multiples) are expanded as a Fourier series in the mean longitude
  - Modified Hansen coefficients replace the Kaula eccentricity functions
  - stable recursion formulas due to Hansen (1855) were rediscovered around 1978 in the astronomical literature
  - Jozef Van Der Ha translated the Hansen manuscript from German to English (1978)

Basic concepts of DSST Standalone

DSST Standalone: Mean element dynamics

Averaged VOP equations:

$$\frac{d\bar{a}_i}{dt} = \sum_{\substack{j=0 \\ (1\leq j+k)}}^{N} \sum_{k=0}^{M(j)} \epsilon^j \nu^k B_{i,j,k} + \mathcal{O}(\epsilon^{N+1}) \quad (i = 1 \ldots 5)$$

$$\frac{d\bar{l}}{dt} = n(\bar{a}_1) + \sum_{\substack{j=0 \\ (1\leq j+k)}}^{N} \sum_{k=0}^{M(j)} \epsilon^j \nu^k B_{6,j,k} + \mathcal{O}(\epsilon^{N+1})$$

Force model:

- Recursive zonals and J_2^2 (Folcik, 2012) in closed form
- Recursive tesseral resonance (e^n, $n > 20$) up to 50×50 geopotential
- Recursive Solar-Lunar single averaged (Time Independent, closed form) and double average
- Solid Earth tide in closed form
- Atmospheric drag and J_2-drag coupling terms via numerical quadrature
- Solar radiation pressure via numerical quadrature

Basic concepts of DSST Standalone

DSST Standalone: Mean to osculating

Short-periodic functions:

$$a_i = \bar{a}_i + \sum_{\substack{j=0 \\ (1 \leq j+k)}}^{N} \sum_{k=0}^{M(j)} \epsilon^j \nu^k \psi_{i,j,k} + \mathcal{O}(\epsilon^{N+1})$$

$$l = \bar{l} + \sum_{\substack{j=0 \\ (1 \leq j+k)}}^{N} \sum_{k=0}^{M(j)} \epsilon^j \nu^k \psi_{6,j,k} + \mathcal{O}(\epsilon^{N+1})$$

Force model:

- Recursive zonals and J_2^2 (Folcik, 2012) in closed form
- Recursive tesseral m-dailes and J_2 secular/tesseral m-daiy coupling in closed form. Recursive tesseral linear combinations (e^n, $n > 20$)
- Recursive Solar-Lunar in closed form
- Atmospheric drag numerical computation
- Solar radiation pressure numerical computation

DSST Standalone: Physical model data

- `epotfld` contains the Earth geopotential coefficients
- `timecoef` includes (A.1-UTC) and (A.1-UT1) time difference coefficients, as well as polar motion coefficients, and supports the SLP files
- `slp1950` is the solar-lunar-planetary (SLP) ephemeris file for Mean of 1950.0 coordinates. This file also supports the SLP ephemeris file for J2000 coordinates
- `slptod` is the solar-lunar-planetary (SLP) ephemeris file for tod coordinate system (compatible with Mean of 1950.0 coordinates). `slptod` also supports the SLP ephemeris file for tod compatible with J2000 coordinates
- `jacdat` supports the Jacchia-Roberts atmospheric density model
- `newcomb` is the file of the modified Newcomb operators, which supports the tesseral resonance and tesseral linear combination short-periodic terms

Testing, Reporting, and Maintenance Program (TRAMP) was developed to maintain the physical model data files (Folcik, 2017)

DSST C Project

The work that we are currently carrying out is based on maintaining the architecture of the Fortran 77 version of DSST as much as possible, and thus avoiding rewriting the C/C++ version from scratch. One of the main consequences of this choice implies that the new code is functionally equivalent to the original legacy code, thereby facilitating the use of existing test resources

The original Fortran 77 DSST version is a well-tested and validated tool

Current status of this project

- DSST Standalone is a collection of about
  - 50 include modules
  - 283 modular Fortran subroutines
  - approximately 25000 lines of code
  - more than 50000 lines of documentation
- Major problems:
  1. DSST Standalone uses `GO-TO` statements which usually leads to very complex programs, difficult to understand and maintain, and may be the cause of serious bugs (93/283). Ambiguity handling Fortran arrays
  2. A serious difficulty arises from the fact that the Fortran physical model data files are divided into records and stored in Fortran binary format

Current status of this project

Incremental development model

1. Fortran 77 code is being translated to C/C++ maintaining the `GO-TO` statements and the original code as much as possible
   - 50 include modules ✓
   - 283 modular Fortran subroutines (240 files have been migrated and in progress the rest)✓
   - Doxygen documentation ✓

   Validation and verification from the original code: Unit test and integration test ✓
2. Once the C/C++ version has passed all the test, the C/C++ code will be refactored for conformance with C/C++ style in successive iterations, thereby proceeding to convert old Fortran-style structures into new code that also passes the tests
3. Extend the facilities of DSST Standalone

Integration test

Low Earth Orbit (LEO)

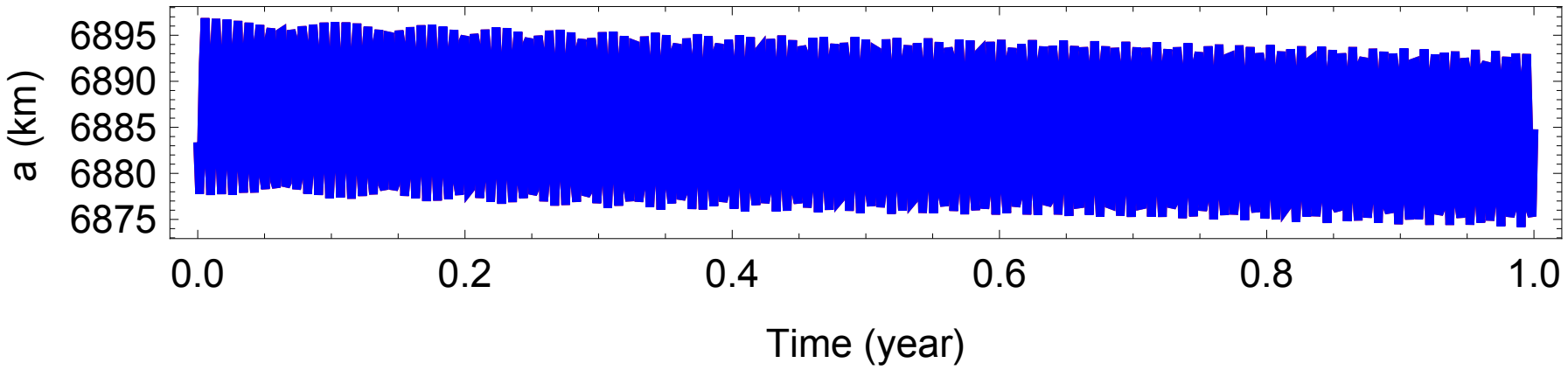
	Mean elements
Epoch	2014 January 01, 0 hrs 0min 0.0 sec
Semi-major axis	6887.30414km
Eccentricity	0.00113949
Inclination	87 deg
RAAN	82.6658693 deg
Argument of the perigee	132.3453611 deg
Mean anomaly	286.4508005deg

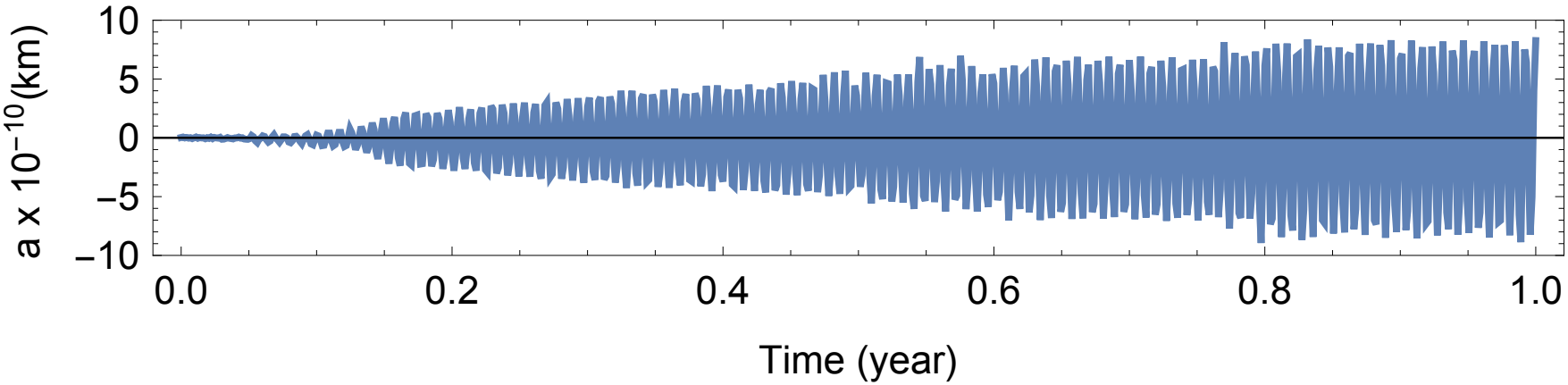
DSST C/C++ parametrization

- Force Models
  - Recursive zonals up to 50×50 geopotential and J_2^2 in closed form
  - Recursive Solar-Lunar single averaged
  - Solid Earth tide in closed form
  - Atmospheric drag and J_2-drag and Iszak J_2 effect
  - Short-period terms
- Propagation: 1 year

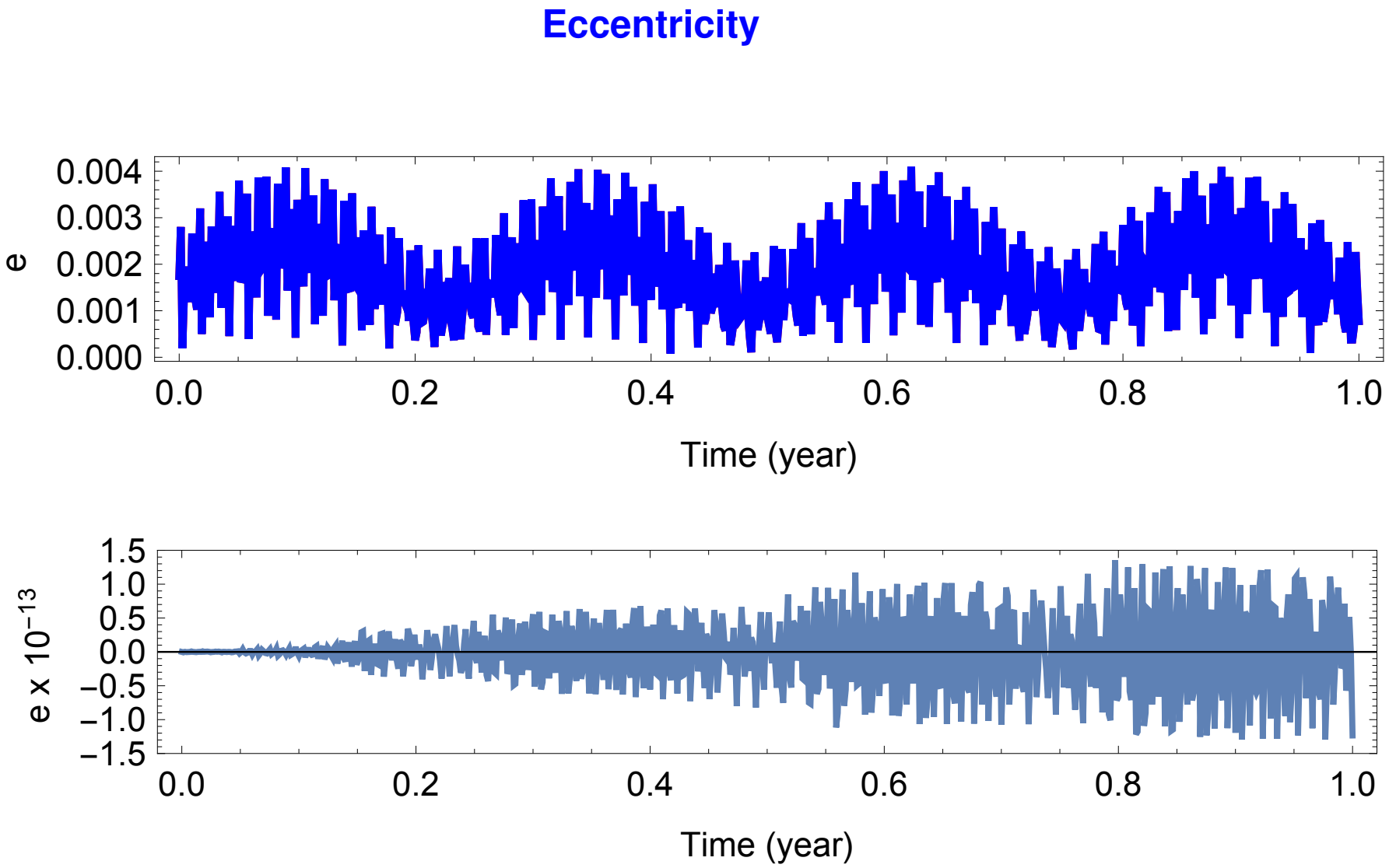
Integration test

Semimajor axis



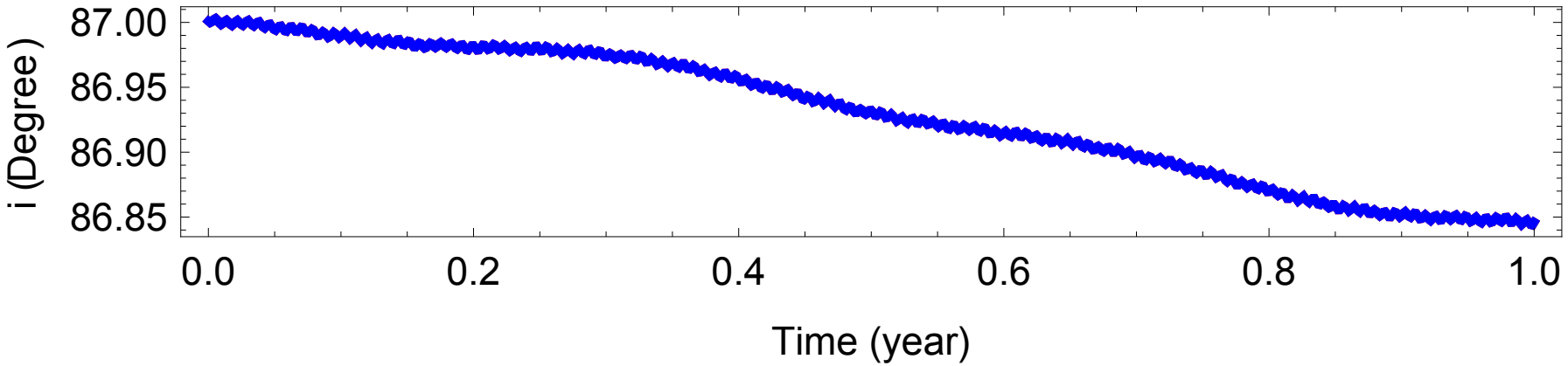


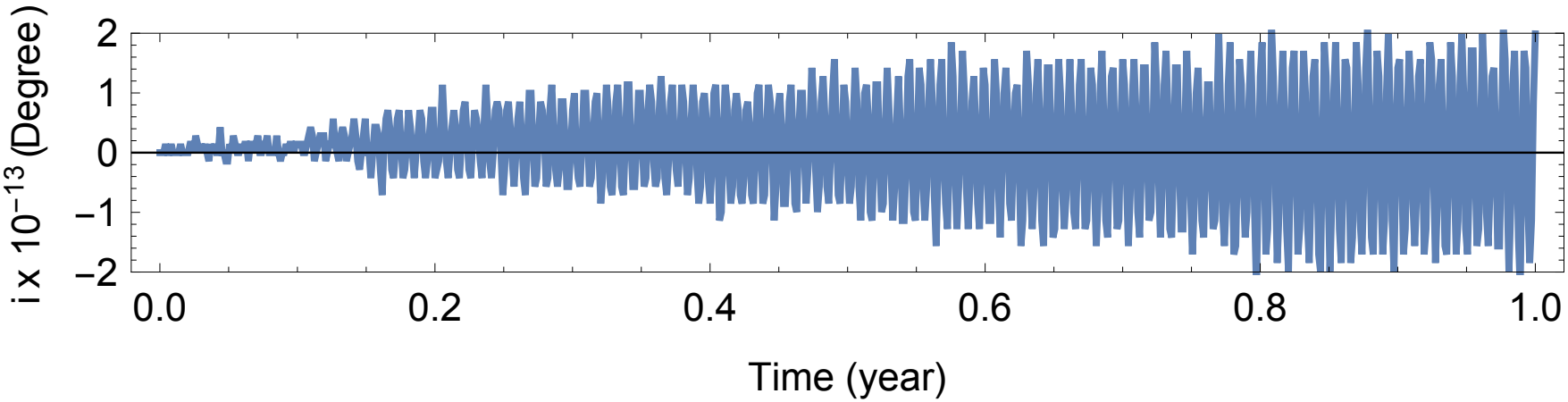
Integration test



Integration test

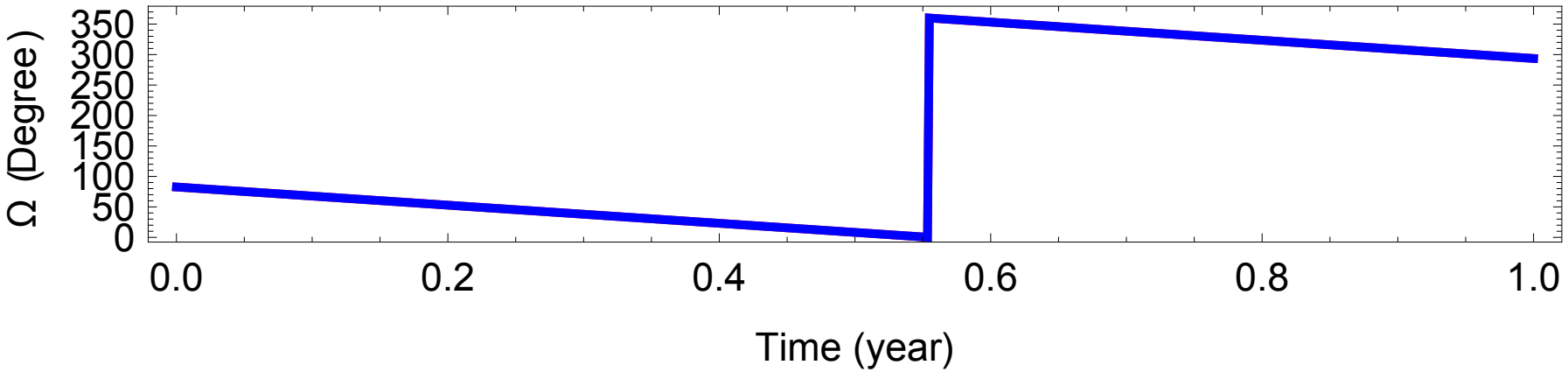
Inclination

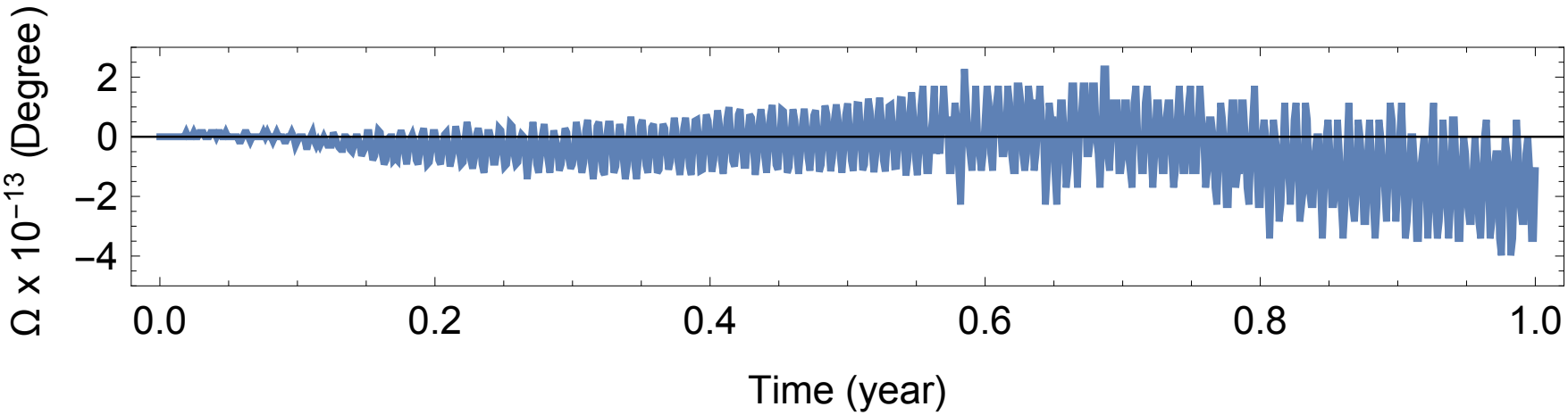




Integration test

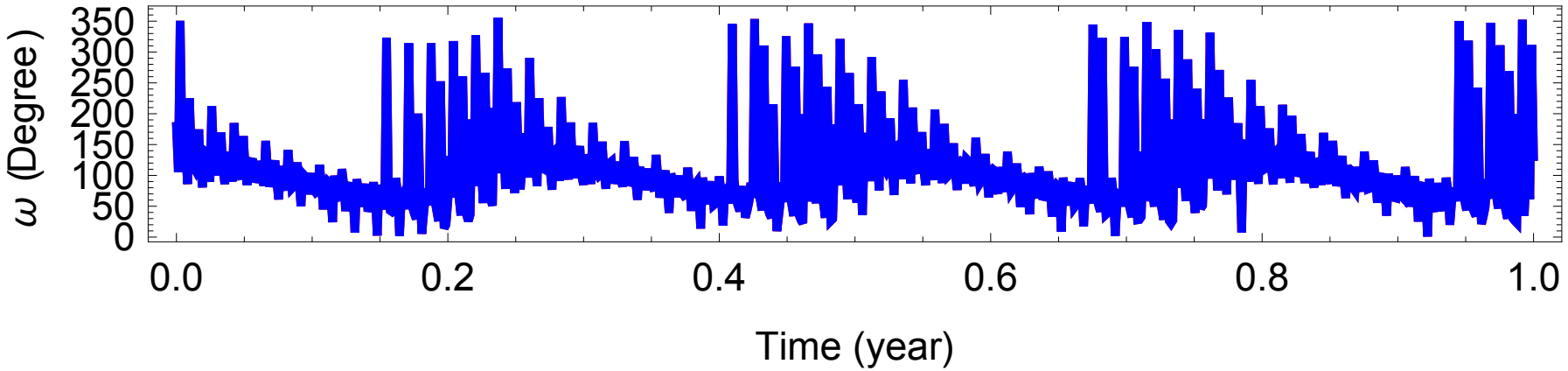
Right ascension of the node

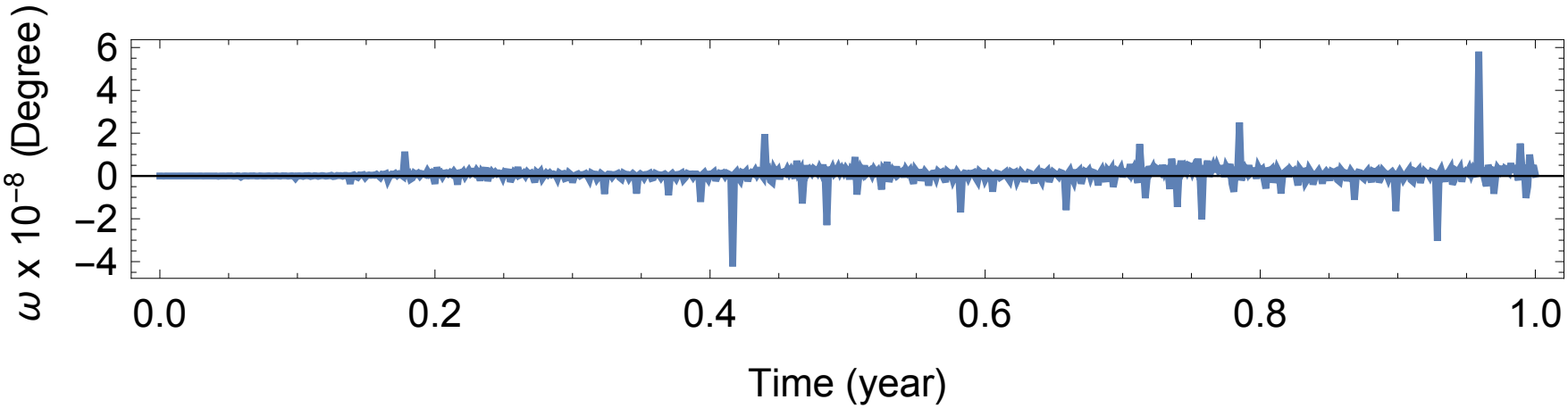




Integration test

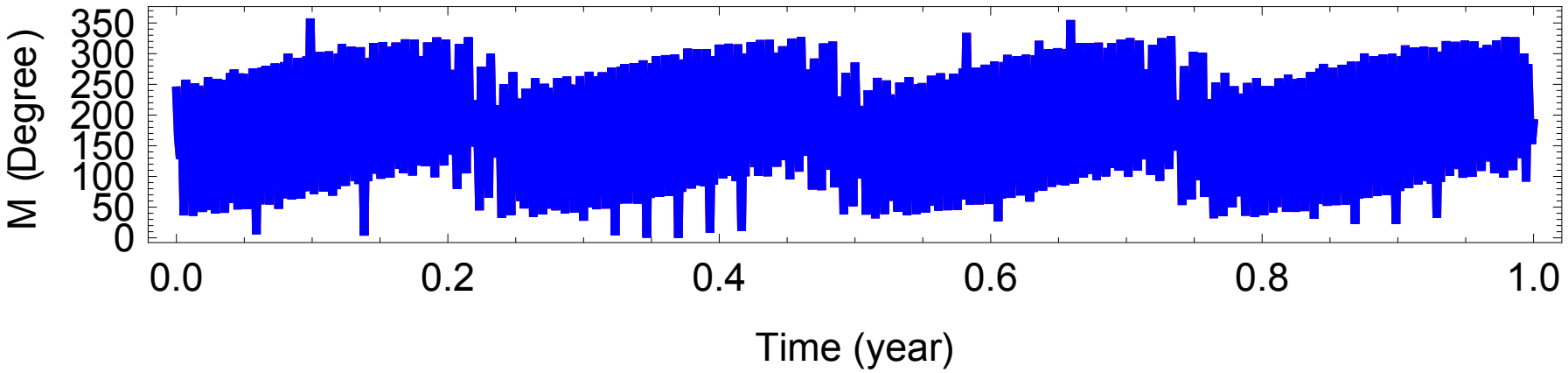
Argument of the perigee

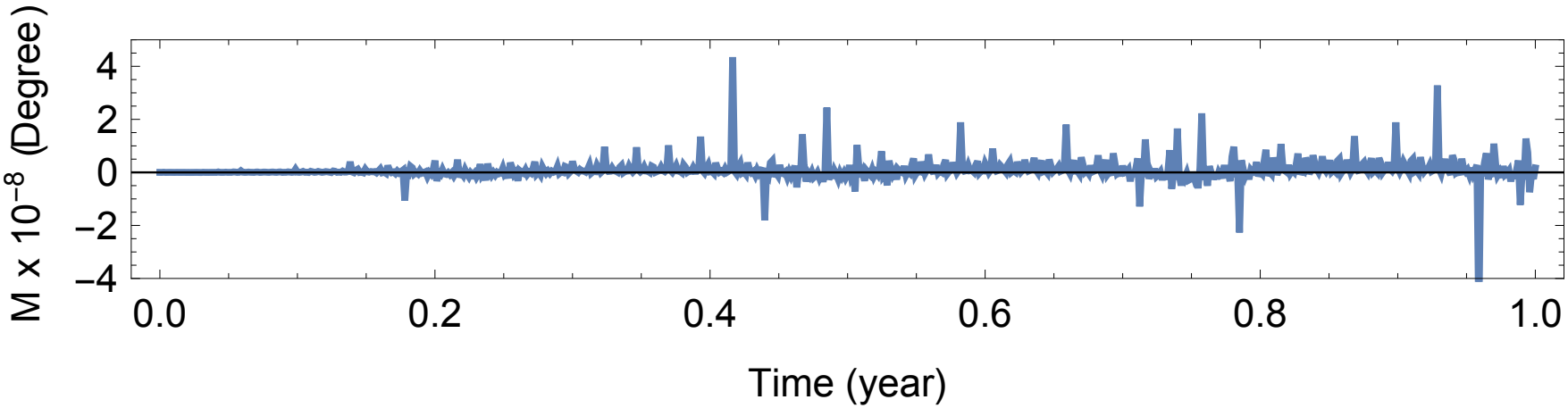




Integration test

Mean anomaly





Future works

- The development of a parallel DSST orbit propagator based on the Picard-Chebyshev concept using multicore and GPU technologies
- Normalized gravity-model coefficients, ideally for high degree and order fields
- Different atmospheric density models