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Testing of the Java Astrodynamics Toolkit Propagator

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The Java Astrodynamics Toolkit (JAT) is an open source software library of reusable software components for mission design, trajectory optimization, and simulation of navigation, guidance and control systems. This paper provides results of comparing various Earth orbit ephemerides created with JAT with those created using Analytical Graphics Inc.'s Satellite Tool Kit/High Precision Orbit Propagator (STK/HPOP) and a.i. solutions, Inc.'s FreeFlyer. Ephemerides produced using STK and FreeFlyer are also compared to each other. With careful attention to parameters and models, results show agreement of millimeter to meter level over several days. Differences are discussed including potential sources of error.

I. Introduction

The Java Astrodynamics Toolkit (JAT) is an open source library of reusable software components written in the Java programming language to support rapid development of spacecraft simulations including 2-D and 3-D visualization capabilities. JAT is distributed under the GNU General Public License and is available at http://jat.sourceforge.net. Potential applications of JAT include:

- Simulations of autonomous spacecraft navigation, guidance and control
- Space mission design and analysis including trajectory optimization
- Operational orbit determination and orbital events generation

This paper provides results of comparing ephemerides created by propagating various Earth orbits using JAT with those created using Satellite Tool Kit/High Precision Orbit Propagator (STK/HPOP) from Analytical Graphics, Inc. (AGI) and FreeFlyer (FF) from a.i. solutions, Inc. Ephemerides produced using STK and FreeFlyer are also compared to each other. FreeFlyer is a spacecraft simulation package currently in use at the NASA Goddard Space Flight Center. Version 5.5, build 5.5.0.25 of FreeFlyer and STK version 6.1 were used for comparison in the propagator validation.

II. Initial State Vectors

The following orbits were selected for testing: Sun-Synchronous, Geostationary (GEO), Molniya, International Space Station (ISS) and the Global Positioning Satellite System (GPS) orbit. The initial epoch was chosen to be June 1, 2004, 12:00:00. The initial conditions which were used for the test case orbits are presented in Table 1. The corresponding osculating orbital elements at the initial epoch are presented in Table 2. The orbit naming convention is based on the approximate altitude of the orbit and does not follow the exact path of any particular orbiting body. For example, ISS refers to an orbit which approximates that of the International Space Station, but does not refer to the actual location of the International Space Station.

The integrator step size, propagation length and output frequency were varied for the different test cases as shown in Table 3. The propagation length and output frequency were chosen based on a previous study performed by The Aerospace Corporation to validate STK/HPOP.[1]

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Table 1. Initial Conditions

Category	Orbit Type	X (km)	Y (km)	Z (km)	Vx (km/s)	Vy (km/s)	Vz (km/s)
LEO	ISS	-4453.783586	-5038.203756	-426.384456	3.831888	-2.887221	-6.018232
LEO	Sun-Sync	-2290.301063	-6379.471940	0	-0.883923	0.317338	7.610832
MEO	GPS	5525.33668	-15871.18494	-20998.992446	2.750341	2.434198	-1.068884
HEO	Molniya	-1529.894287	-2672.877357	-6150.115340	8.717518	-4.989709	0
GEO	GEO	36607.358256	-20921.723703	0	1.525636	2.669451	0

Table 2. Initial Osculating Orbital Elements

Orbit Type	a km	e	i Deg	Arg of Perigee Deg	RAAN Deg	True Anomaly Deg
ISS	6747.414767	.001646462	51.667871	151.908712	45.649594	32.718375
Sun-Sync	6778.137291	.000000046	97.034619	337.556006	250.251300	22.443994
GPS	26558.859022	.015930402	56.286490	33.142451	52.707850	216.676430
Molniya	26553.376213	.740969399	63.4	270.000001	330.214160	359.999998
GEO	42164.165718	.000000135	0	103.882708	0	226.368596

Table 3. Step Size, Propagation Length and Output Frequency

Orbit Type Type	Integrator Step Size (s)	Propagation Length (days)	Output Frequency (mins)
ISS	5	1	1
Sun-Sync	5	1	1
GPS	60	2	2
Molniya	5	3	5
GEO	60	7	10

Twelve test cases were performed for each orbit type. Test cases were run to verify JAT's ability to perform accurate propagation of Earth orbits using various force models. The force models considered in this study were two-body Earth gravity, JGM2 and JGM3 spherical harmonic gravity models; Solar/Lunar third-body perturbation effects; atmospheric drag using the Harris-Priester density model, and the Naval Research Laboratory Mass Spectrometer and Incoherent Scatter Radar Exosphere (NRLMSISE 2000) atmospheric density model; and solar radiation pressure (SRP). Each of the force models was run independently to test their individual accuracy, using two-body Earth except for spherical harmonic cases. A final test case was run for each satellite orbit which included an atmospheric drag model, the SRP model, a spherical harmonic gravity model and third-body perturbations from both the Sun and the Moon. These last test cases were performed to validate the capability of JAT to accurately propagate satellite orbits with multiple models.

III. Earth Orientation Parameters

The use of spherical harmonic gravity models requires precise calculation of the Earth's orientation. Earth orientation involves parameters for the following transformations: Nutation, Precession, Pole Wander, and Sidereal Time, including the exact UT1 time obtained from the UT1-UTC correction in the International Earth Rotation Service (IERS) Bulletin A.[4] It is important to understand how the numerical integrators handle the rotation. FreeFlyer does not appear to update the perturbations in the Earth's orientation during a propagation run. Our testing seemed to indicate that STK/HPOP is updating some information less frequently than every time step. Currently, JAT updates the Earth orientation every time the integrator calls for the derivatives. This was done to ensure that JAT was at its highest accuracy.

JAT implements the conventions established by the International Astronomical Union (IAU), in the Explanatory Supplement to the Astronomical Almanac[6] ,[7] and by the IERS 1996 conventions[8] . Exhaustive comparisons were conducted between the Almanac, and IERS 96 conventions for Nutation, Precession, and Greenwhich Hour Angle.

The Earth orientation computation in FreeFlyer, however, does not seem to implement pole wander, though it uses the UT1-UTC value from the IERS. Because of this discrepancy, pole wander was turned off for the purpose of validation between the three programs.

IV. Integrator

The JAT fixed step-size, 8th order Runge-Kutta numerical integrator was used. The Runge-Kutta 8th order integrator within FreeFlyer was utilized in fixed step size mode for all of the propagation comparisons. The Runge-Kutta-Fehlberg 7th order integrator with 8th order error control within STK/HPOP was used as a fixed step integrator with error control turned off.

V. Atmospheric Drag

Currently, JAT contains two high fidelity atmospheric drag models: NRLMSISE2000 and Harris-Priester. The NRLMSISE2000 model was adapted from code developed by the Naval Research Laboratory.[13] The Harris Priester Model is based on the model in *Satellite Orbits*.[14] STK/HPOP also has both the NRLMSISE2000 and Harris-Priester models available in version 6.1 and later. FreeFlyer does not have the NRLMSISE2000 model, but it does have the Harris-Priester model. The value used for the F10.7 cm solar flux was 150 W/m^2/Hz and a_p was 14.918648166.

A. Ap/Kp Indicies

When using the NRLMSISE 2000 in STK, the geomagnetic index (k_p), was set to 3 for this study. STK allows the user to input k_p (the planetary index) and F10.7 values in the force model. However, STK does not allow the user to enter in an a_p (planetary amplitude) value. The NRLMSISE 2000 model in JAT requires the a_p value in order to calculate the density in the drag model. Therefore a correlation between the k_p value and the a_p value was needed. Wertz presents the equation for the correlation as:[12]

$$a_p = \mathrm{e}^{\frac{k_p+1.6}{1.75}} \tag{1}$$

As previously mentioned, a k_p value of 3 was used for the test cases, which according to Equation 1 above results in an a_p value of 13.85396. However, when this value is entered into JAT the error in position is approximately 500 meters for the LEO satellite orbits. Therefore, it was determined that the a_p was incorrect. In order to validate the value of a_p which should be used in the JAT, other sources were investigated.

According to NOAA, for a k_p value of 3, the corresponding value of a_p is 15.[5] Since the nature of atmospheric density is empirical, there are several different analytical approaches which disagree slightly on the exact value which should be used in the calculation of density for atmospheric drag. When a value of 15 is used for the a_p in JAT, the position error is approximately 51 meters for the ISS case and 28 meters for Sun-Sync.

NOAA presents the following equation for the correlation: [5]

$$28 * k_p + 0.03 * \mathrm{e}^{k_p} = a_p + 100 * 1 - \mathrm{e}^{-0.08 * a_p} \tag{2}$$

When a k_p value of 3 is used in Equation 2 the a_p value is 14.918648166. A position error of approximately 1 meter over a day is found when this value of a_p is used with the ISS orbit.

VI. Third Body Perturbations

Models for Solar and Lunar perturbations have been created in JAT. These models use the JPL DE405 ephemerides for the Sun and Moon. FreeFlyer and STK/HPOP were also set to utilize Sun and Moon positions obtained from the DE405 ephemeris.

VII. Gravity Models

JAT and STK/HPOP contain both JGM2 and JGM3 spherical harmonic gravity models. FreeFlyer only contains the JGM2 model. For all cases using the JGM2 and JGM3 models, the degree and order were both set to 20 for all three programs. STK/HPOP has the ability to model solid and ocean tides. JAT currently does not have this ability and so this was option turned off in STK/HPOP. STK/HPOP was also set to not include relativistic accelerations. In STK/HPOP, JGM2 and JGM3 gravity files were applied with a zero degree and order for the two-body cases.

VIII. Solar Radiation Pressure

A solar radiation pressure (SRP) model is also included in JAT. The SRP model assumes a uniform spherical spacecraft with a given cross-sectional area. The SRP model has a discontinuity at the boundary between full illumination and entering the shadow of the Earth. To handle this, a cylindrical partial illumination model is implemented to provide some continuity in the derivatives as the radiation component becomes zero. The vector to the sun is computed using the JPL DE405 ephemeris. In FreeFlyer, a basic solar radiation pressure model is available, although documentation on this model is not very detailed. The settings for the altitude of the atmosphere for the Earth's shadow were set to zero in STK/HPOP and JAT.

IX. Ephemeris Comparison Results and Discussion

The ephemerides produced by JAT, STK/HPOP and FreeFlyer were compared with each other. Table 4 presents the maximum position and velocity differences for the ISS orbit. In all cases, JAT agrees well with STK/HPOP. The largest differences in this set of tests was between JAT and FreeFlyer when using the Harris-Priester model, however, it is interesting to note that STK/HPOP and FreeFlyer also do not agree well in these cases.

Table 4. Position and Velocity Differences for ISS Orbit

Description	JAT-STK Position (m)	JAT-STK Velocity (m/s)	JAT-FF Position (m)	JAT-FF Velocity (m/s)	FF-STK Position (m)	FF-STK Velocity (m/s)
2-body	0.000829	0.000808	0.000048	0.0000008	0.000838	0.000809
2-body+Moon	0.000830	0.000815	0.000329	0.000001	0.000996	0.000815
2-body+Sun	0.000827	0.000838	0.000037	0.0000008	0.000826	0.000838
2-body+NRL	0.269426	0.000995	–	–	–	–
2-body+HP	1.031710	0.001802	2.33001	0.002665	5.495820	0.006752
2-body+SRP	0.103515	0.000875	0.069386	0.000071	0.136046	0.000885
JGM2	0.368138	0.001085	0.500248	0.000552	0.836881	0.001576
JGM3	0.368124	0.001076	–	–	–	–
All+JGM2+NRL	0.857388	0.001496	–	–	–	–
All+JGM2+HP	1.053890	0.001723	4.39748	0.005034	5.441040	0.006492
All+JGM3+NRL	0.857146	0.001572	–	–	–	–
All+JGM3+HP	1.053360	0.001730	–	–	–	–

Table 5 presents the maximum position and velocity differences for the Sun Synchronous orbit. JAT and STK/HPOP agree well for all cases except for the cases that include atmospheric drag as would be expected based on the previous discussion on the difficulties in matching atmospheric density models.

Table 5. Position and Velocity Differences for Sun-Sync Orbit

Description	JAT-STK Position (m)	JAT-STK Velocity (m/s)	JAT-FF Position (m)	JAT-FF Velocity (m/s)	FF-STK Position (m)	FF-STK Velocity (m/s)
2-body	0.00081	0.00080	0.00003	0.0000008	0.00082	0.00080
2-body+Moon	0.00083	0.00083	0.00028	0.0000009	0.00093	0.00083
2-body+Sun	0.00082	0.00082	0.00003	0.0000008	0.00081	0.00082
2-body+NRL	8.66478	0.01035	–	–	–	–
2-body+HP	3.33383	0.00439	1.61195	0.00181	1.77066	0.00261
2-body+SRP	0.09203	0.00083	0.03162	0.00003	0.09110	0.00083
JGM2	0.17022	0.00096	0.27362	0.000296	0.37380	0.00111
JGM3	0.16998	0.00089	–	–	–	–
All+JGM2+NRL	8.22196	0.00970	–	–	–	–
All+JGM2+HP	3.53857	0.00461	1.8332	0.00209	1.70622	0.00258
All+JGM3+NRL	8.22146	0.00995	–	–	–	–
All+JGM3+HP	3.53792	0.00455	–	–	–	–

Table 6 presents the maximum position and velocity differences for the GPS orbit. All three programs have close agreement in this case due to the nature of the GPS orbit, which was chosen to minimize the effects of perturbations.

Table 6. Position and Velocity Differences for GPS Orbit

Description	JAT-STK Position (m)	JAT-STK Velocity (m/s)	JAT-FF Position (m)	JAT-FF Velocity (m/s)	FF-STK Position (m)	FF-STK Velocity (m/s)
2-body	0.00080	0.00083	0.000008	0.0000008	0.00080	0.00083
2-body+Moon	0.00080	0.00085	0.03287	0.000005	0.03298	0.00085
2-body+Sun	0.00084	0.00080	0.00064	0.0000008	0.00122	0.00080
2-body+NRL	0.00782	0.00083	–	–	–	–
2-body+HP	0.00080	0.00083	0.000008	0.0000008	0.00080	0.00083
2-body+SRP	0.08960	0.00084	0.72128	0.00008	0.72511	0.00088
JGM2	0.01950	0.00081	0.01660	0.000002	0.02076	0.00081
JGM3	0.01940	0.00081	–	–	–	–
All+JGM2+NRL	0.11936	0.00083	–	–	–	–
All+JGM2+HP	0.12493	0.00083	0.61088	0.00006	0.52284	0.00086
All+JGM3+NRL	0.11951	0.00085	–	–	–	–
All+JGM3+HP	0.12509	0.00085	–	–	–	–

Table 7 presents the maximum position and velocity differences for the Molniya orbit. The Molniya orbit is the most challenging for a number of reasons. JAT and STK/HPOP agree well for the cases that did not include atmospheric drag or a spherical harmonic gravity model. It is interesting to note that JAT and FreeFlyer did agree well in the cases with atmospheric drag.

Table 7. Position and Velocity Differences for Molniya Orbit

Description	JAT-STK Position (m)	JAT-STK Velocity (m/s)	JAT-FF Position (m)	JAT-FF Velocity (m/s)	FF-STK Position (m)	FF-STK Velocity (m/s)
2-body	0.00090	0.00084	0.00047	0.0000008	0.00082	0.00084
2-body+Moon	0.00082	0.00080	0.08194	0.000068	0.08180	0.00080
2-body+Sun	0.00085	0.00082	0.03110	0.000025	0.03129	0.00082
2-body+NRL	28.39440	0.02389	–	–	–	–
2-body+HP	15.16700	0.01287	0.02214	0.000018	15.18920	0.01289
2-body+SRP	0.63727	0.00092	2.77142	0.00229	2.13422	0.00190
JGM2	5.57807	0.00456	7.72931	.006160	2.30217	0.00184
JGM3	5.57807	0.00481	–	–	–	–
All+JGM2+NRL	27.86270	0.02052	–	–	–	–
All+JGM2+HP	7.57025	0.00460	5.43094	0.00417	12.97950	0.00862
All+JGM3+NRL	27.86160	0.02082	–	–	–	–
All+JGM3+HP	7.57107	0.00493	–	–	–	–

Table 8 presents the maximum position and velocity differences for the GEO orbit. In all cases, JAT agrees well with STK/HPOP. The largest differences in this set of tests was between JAT and FreeFlyer when including SRP, however, it is interesting to note that STK/HPOP and FreeFlyer also do not agree well in these cases.

Table 8. Position and Velocity Differences for GEO Orbit

Description	JAT-STK Position (m)	JAT-STK Velocity (m/s)	JAT-FF Position (m)	JAT-FF Velocity (m/s)	FF-STK Position (m)	FF-STK Velocity (m/s)
2-body	0.00070	0.00070	0.00009	0.0000007	0.00070	0.00070
2-body+Moon	0.00090	0.00081	0.07980	0.00005	0.07989	0.00081
2-body+Sun	0.00087	0.00081	0.05206	0.000004	0.05230	0.00081
2-body+NRL	0.00070	0.00070				
2-body+HP	0.00070	0.00070	0.00009	0.0000007	0.00070	0.00070
2-body+SRP	0.00080	0.00082	2.73497	0.00012	2.89851	0.00087
JGM2	0.07287	0.00081	1.58727	0.000116	1.65447	0.00083
JGM3	0.07276	0.00081				
All+JGM2+NRL	0.72280	0.00084				
All+JGM2+HP	0.72280	0.00084	2.99845	0.00014	3.41299	0.00090
All+JGM3+NRL	0.72298	0.00082				
All+JGM3+HP	0.72298	0.00082				

Plots for the Sun-Sync and Molniya cases can be seen after the tables showing the Root Sum Square (RSS) error profile over the length of the propagation. The Molniya orbit's high eccentricity causes a larger error in velocity during the perigee passage, amplifying small differences. The Sun-Sync drag error can be seen for the NRLMSISE2000 model, where small differences in the density accumulate quickly over time.

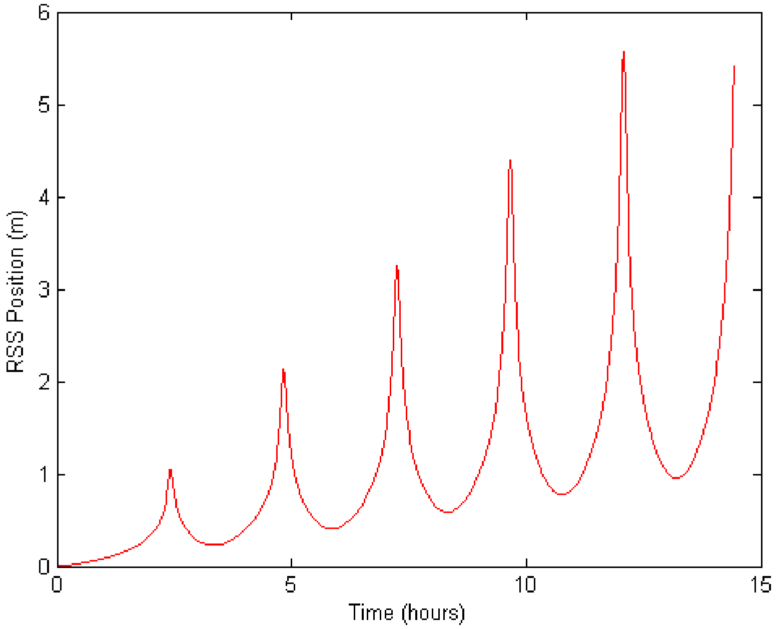

Figure 1. Molniya JGM3 Position Error

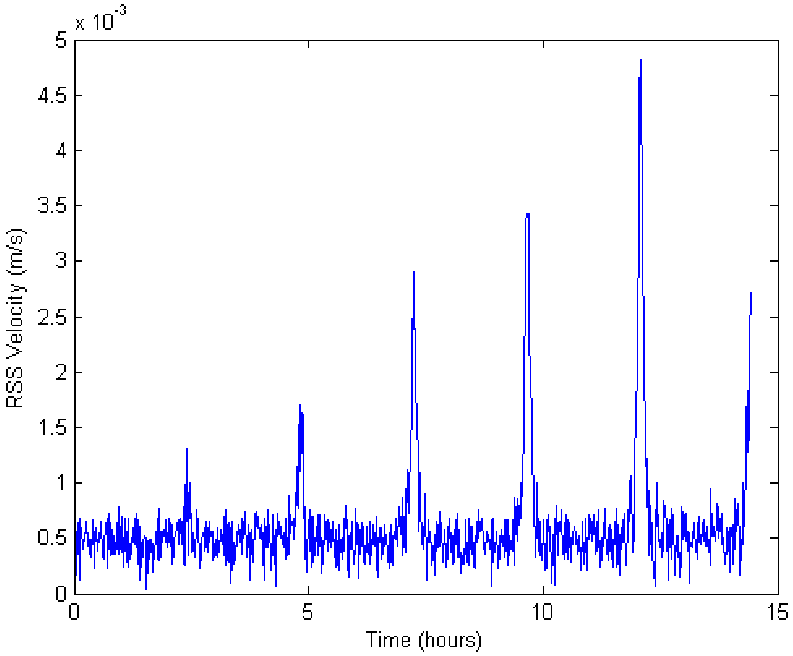

Figure 2. Molniya JGM3 Velocity Error

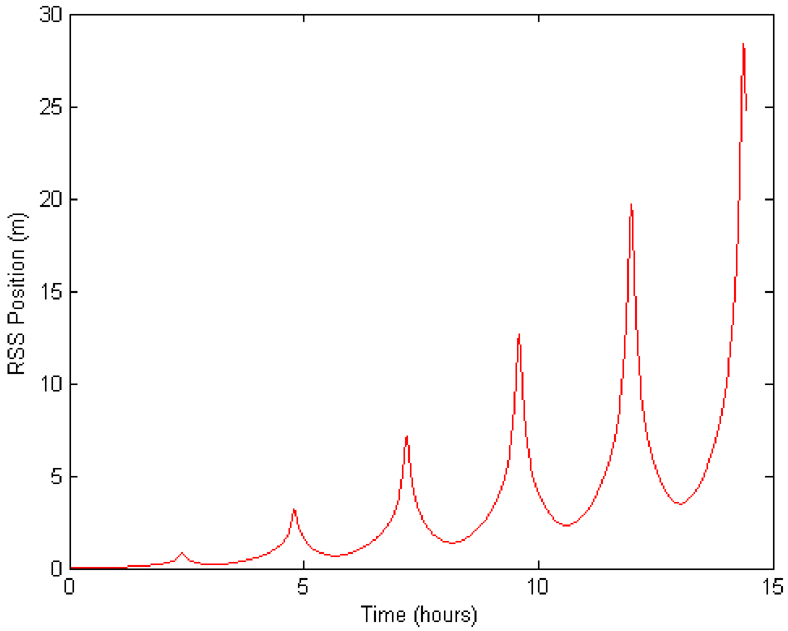

Figure 3. Molniya 2body+NRLMSISE2000 Position Error

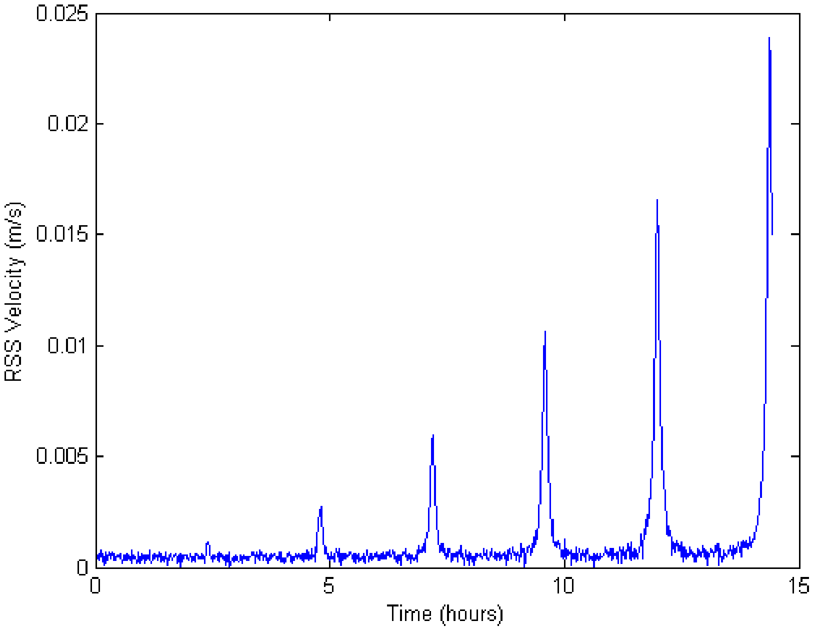

Figure 4. Molniya 2body+NRLMSISE2000 Velocity Error

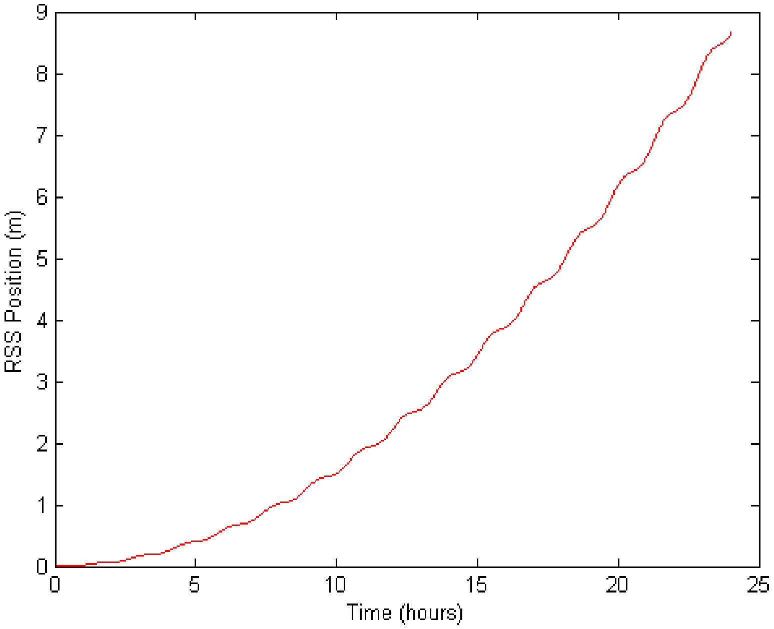

Figure 5. Sun-Sync 2body+NRLMSISE2000 Position Error

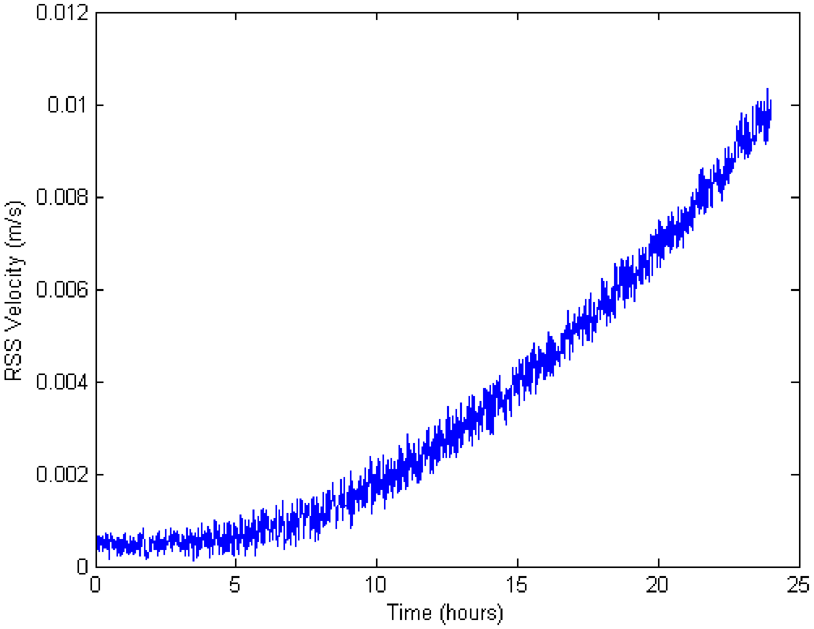

Figure 6. Molniya 2body+NRLMSISE2000 Velocity Error

X. Conclusions

JAT achieves agreement below meter levels for all cases except those with atmospheric drag. The sensitivity to differences in the density calculation make an exact match difficult. Atmospheric drag depends on proper modeling of geomagnetic and molecular behavior influencing atmospheric density. Care must be taken to model the geomagnetic index correctly. However, given that the range of modeling error can be on the order of kilometers or more for low Earth orbits, meters or tens of meters in the Molniya case is expected.

The verification of the spherical harmonic gravity models revealed ambiguities in which IERS convention and update procedure is used in the rotation from the Earth Centered Inertial frame to the Earth Centered Earth Fixed frame. Ultimately, due to the complexity of the IAU and IERS conventions and their subsequent corrections, it is extremely difficult to match algorithms exactly without knowledge of all equations and values used or access to the source code.

This study shows that JAT has the capability to closely match the ability of commercial packages. However, the uncertainty of the models for both spherical harmonic and atmospheric drag indicates that exact agreement does not necessarily correspond to accurate propagation. It is recommended that propagators seek to ensure the current, correct algorithms for Earth rotation from the IAU and IERS as well as the correct atmospheric data from NOAA in addition to validation against existing codes. Commercial packages such as STK/HPOP and FreeFlyer often implement different conventions and data sets in different versions, so care should be taken in determining the standards used.

XI. Future Work

The goal of JAT is to provide high-fidelity models for simulation of guidance, navigation, and control of spacecraft. As an open source project, the Java Astrodynamics Toolkit will continue to be updated with new conventions and updated data from the IERS, IAU, and NOAA. It will grow in both accuracy and functionality as the project progresses.

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