

Do Open Source Tools Rival Heritage Systems?

A comparison of tide models in OCEAN and Orekit

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Open source software tools have been gaining acceptance in the astrodynamics community for some applications, though heritage tools still dominate precision orbit determination and propagation. This paper examines recent tide modeling improvements in the open source Orbit Extrapolation Toolkit (Orekit) and compares it with the US Naval Research Laboratory's (NRL) heritage Orbit Covariance Estimation And ANalysis (OCEAN) system. First, the two tools are compared directly against each other by propagating a given state vector for Stella, a geodetic satellite sensitive to tidal variations in the geopotential. Second, orbits were fit to International Laser Ranging Service (ILRS) laser ranging data using OCEAN and orbit determination software built around Orekit so that a more useful comparison could be made. Five days of data were used to solve for orbital parameters using OCEAN and Orekit. This solution orbit is then propagated forward 25 days and compared to subsequent five day orbit solutions. This comparison between predicted and fitted orbit solutions is used as a metric to compare the quality of each piece of software's dynamic modeling capability. Results from the direct orbit propagation comparison indicate the RSS of position difference between the OCEAN and Orekit propagated orbit grow to only 7 meters over 25 days. It is also seen that the difference between OCEAN's and Orekit's implementation of Earth tides are less than 3% of the total tidal effect. The results of the orbit determination analysis show that the Orekit orbit solution comparison is at worst on the same order of magnitude in accuracy as the OCEAN orbit solution comparison, and at best more accurate than the OCEAN orbit solution comparison. While OCEAN produces a more accurate orbit prediction than Orekit in the majority of the cases studied, more testing is needed to understand the origin of the difference.

I. Introduction

A recent trend in astrodynamics is the use and proliferation of open source software (OSS). Several recent papers have detailed the incorporation of OSS into a client-server architecture to deliver astrodynamics services, such as space situational awareness, conjunction analysis, and lifetime analysis.¹⁻³

This new breed of tools is suitable for design studies and manipulating orbit data, but has not yet been evaluated for high precision applications. High precision orbit determination requires accurately modeling numerous small effects in the satellite forces and frame transformations and has traditionally been the domain of heritage systems.⁴

Low altitude, geodetic satellites, such as Stella, provide a challenging test case with which to compare astrodynamics software because of their high sensitivity to tidal and temporal gravity perturbations. Additionally, Stella's simple shape and passive nature mean that errors can be attributed to the propagator's force models, and not mis-modeling the spacecraft shape or maneuvers.

This paper describes the OCEAN and Orekit propagators, and then first compares them directly for a given initial condition, and secondly compares their performance in determining Stella's orbit.

A. OCEAN

The Orbit Covariance Estimation and ANalysis (OCEAN) software was developed at the Naval Center for Space Technology at the US Naval Research Laboratory (NRL). It was developed not only to provide

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operational support to a range of satellite missions, but to also serve as a platform to enable astrodynamics related research and development.

Early history of OCEAN is given in Reference 5. References 6, 7 and 8 discuss further developments of OCEAN. Recently, it has been used to provide operational precision orbit knowledge for the NRL's MITEX UPPERSTAGE and TACSAT-4 missions.

OCEAN is a highly configurable, data-base driven software tool within which a number of high fidelity models can be applied to determine precise orbits. The latest release of OCEAN implements many of the models perscribed by the IERS 2010 Conventions.⁹ These include Earth orientation models, EGM2008 geopotential, FES2004 ocean tide models, solid earth tides, pole tides, relativity corrections, third-body perturbations, atmospheric drag and solar radiation pressure.

OCEAN may be used to propagate an orbit given an initial condition or to fit an orbit solution to a wide range of data types using either a Kalman filter-smoother or a batch Weighted Least Squares Orbit Determination (WLS-OD) process. Data are edited in these processes in a combination of user configurable absolute limit or standard deviation based methods.

B. Orekit

Orekit is a open source software library for space flight dynamics.^{10,11} It includes the ability to model standard astrodynamical elements such as orbits, time systems and reference frames. The algorithms necessary to make use of these elements, such as frame conversions, time conversion and various orbit propagation methods, are included as well. Orekit, including its dependencies shown in Figure 1, are freely available both in source and binary formats, with all related documentation and tests. It is distributed under the Apache License Version 2.0. This license allows anybody to build an application, including commercial applications, with no license restrictions or limitations from the use of Orekit.

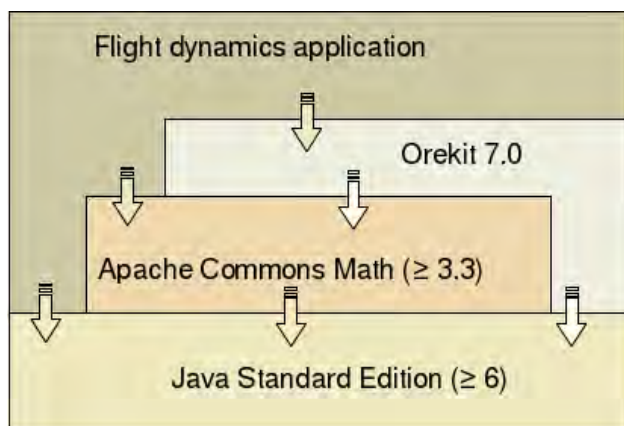


Figure 1: Orekit is a low level library, relying only on the open-source Apache Commons Math library (which provides the general-purpose mathematical algorithms). It can be used to build higher level complete applications.

Orekit development started in 2002 at CS Systèmes d'Information and was officially published as free software in 2008. The original team has since been extended to a global community including experts from different countries and background. Numerous external contributions have been included in the library. The governance of the project is now fully open, with a project management committee including representatives of government agencies, space manufacturers, academia, software companies, researchers and experts. The user community is also extended and the library is used for both operational or analysis purposes. As an example, Orekit has been successfully used during the real time monitoring of the rendezvous phase between the Automated Transfer Vehicle (ATV) and the International Space Station (ISS) by the Centre National d'Études Spatiales (CNES, the French space agency) and European Space Agency (ESA). Orekit has been selected in early 2011 by CNES to be the basis of its next generation space flight dynamics systems, including operational systems, study systems and mission analysis systems.¹²

Tide modelling is a recent Orekit feature, released in December 2013. It is based on the IERS conventions models.⁹ Both solid tides and ocean tides are supported. Ocean tides can use either the FES2004 model using

the data provided by IERS, or load a custom model provided by user. In this case, the Love deformation numbers can be either the IERS ones for degree up to 6, or numbers from the Gégout model up to degree 250. The inclusion of solid tides and ocean tides effects allows for high precision applications to be explored.

Using Orekit and the Java Commons Math library an orbit determination application was built in a few weeks in pure Java. The orbit determination application consisted of adding a measurement model, data management, and file I/O. Orekit and Commons Math provides all of the necessary astrodynamical and mathematical algorithms. This software uses the Levenberg-Marquardt algorithm to solve for orbital parameters, including the satellite's position, velocity, coefficient of drag and coefficient of solar reflectivity. The application is used to fit an Orekit orbit to Stella SLR data in Section B.

C. The Stella Satellite

Stella is a spherical satellite, 24 cm across, and 48 kg in mass, covered in retro reflectors. Launched in 1993 by CNES for gravity field recovery, it is in an 800 km circular orbit inclined at 98.6 degrees, which is sensitive to tidal forces.¹³ The International Laser Ranging Service (ILRS) maintains a database of Satellite Laser Ranging (SLR) data from a number of ground sites worldwide that regularly collect laser ranging data for Stella.¹⁴

Stella, along with other geodetic satellites, is particularly well suited to orbit determination studies since its motion is largely dominated by gravity forces. The satellite's simple shape and passive nature ensures that error sources are dominated by force mis-modeling rather than incorrectly modeling the spacecraft's attitude or maneuvers.

II. Methodology

A. Direction Propagation Comparison

In the direct propagation comparison of OCEAN and Orekit, each propagator is given the same initial condition for Stella and the resulting ephemerides are compared.

Both OCEAN and Orekit are used to propagate the same initial state vector for 25 days, using only Earth gravity forces. This time span was chosen to be sufficiently long such that trending can be observed. Modeled forces include EGM2008 gravity field to degree and order 90, with the correction recommended in IERS 2010 Conventions; solid tides due to the Sun and Moon; ocean tides to degree and order 20; and the pole tides.⁹ Orekit uses the Dormand-Prince 8(5,3) integrator with adaptive step size control.¹⁵ OCEAN uses a ninth order, multi-step predictor corrector.⁵

Because the inclusion of solid and ocean tides in Orekit enables high precision applications, Stella's orbit was propagated with Orekit including and excluding these tidal forces to demonstrate the magnitude of orbit difference due to these forces. This allows the orbit propagation difference between Orekit and OCEAN to be put into context.

B. Orbit Solution Predictive Capabilities

To determine OCEAN's and Orekit's predictive capability, ILRS laser ranging data is used to fit an orbit solution. The fitted orbit is generated using a five day fit span and then a predicted orbit is created by extrapolating for 25 days. The prediction span was chosen to be sufficiently long to observe longer term trends. Using new data, fitted orbits are generated for 5 days at a time over the 25 day prediction interval, and then compared to the predicted orbit. Differences between the predicted and fitted orbits indicate the accuracy of the each software's modeling of the physical forces on the vehicle. Figure 2 gives a visual representation of this methodology.

The comparison between fitted orbits and predicted orbits creates a metric that captures how effective each piece of software is at modeling the dynamics of each satellite. Often, the Root Mean Square (RMS) of the residual error is used in this fashion; however, RMS error is often controlled by the data editing and weighting scheme. Indeed, it can be seen that methods that yield lower RMS error residuals do not always yield the smallest difference between predicted and fitted orbit solutions.

The Orekit orbit determination software examined in this section uses the same configuration from the direct propagation comparison test case with the addition of cannonball drag and solar radiation pressure, third body gravity due to the Sun and Moon, and general relativity. The measurement model uses the

Mendes-Pavlis⁹ atmospheric correction, with the IERS specified center of mass offset for Stella. Additionally 5σ data editing is applied to the measurement residuals. The Levenberg-Marquardt optimizer is used to estimate Stella's position velocity, drag coefficient, and reflection coefficient.

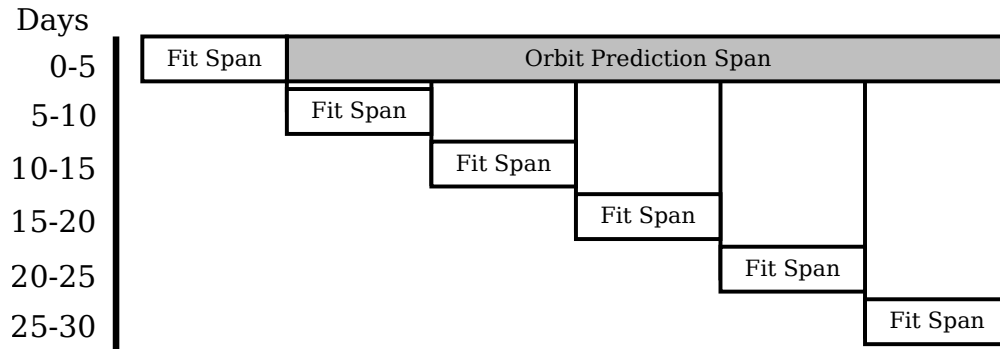


Figure 2: Depiction of Orbit Solution Comparison Methodology

III. Results

A. Direct Propagation Comparison

The differences between the two ephemerides are shown in Figure 3. Over 26 days the differences are less than 7 m RSS, and less than 1.6 m in-track. The cross track difference, at 6 m, is significantly larger than than the in-track difference.

The differences between the propagators could be due to small frame misalignments, different schemes for interpolating Earth orientation parameters, integrator error, or small differences in the force models. Another small source of the observed differences could be that Orekit uses JPL 406 ephemerides for the Sun and Moon positions when calculating solid tides, while OCEAN was configured to use analytical ephemerides. It is likely that several of these error sources combine to produce the observed result.

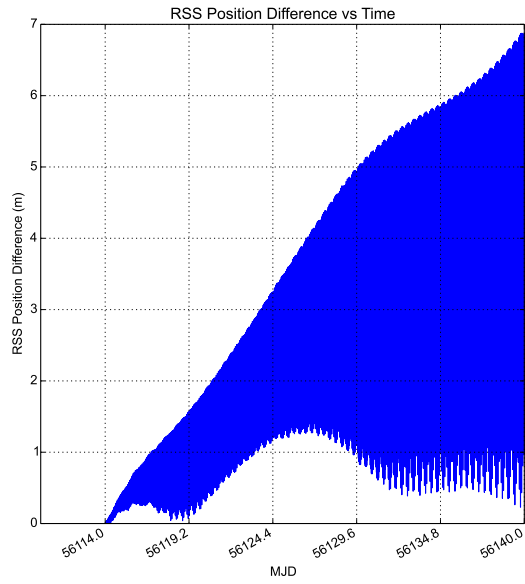
Figure 4 shows the orbit difference when propagating with Orekit from an initial condition including and excluding either the solid earth or ocean tides. The orbit difference from excluding solid Earth tidal effects grows to about 250 meters over 25 days. The orbit difference from excluding ocean tidal effects grows to about 25 meters over 25 days. It can be seen that the difference in tide models between the two propagators is less than 3% of the tidal effect, and likely even smaller. This demonstrates good agreement between Orekit's and OCEAN force models, including two independent implementations of IERS recommended tide models.

B. Orbit Solution Predictive Capabilities

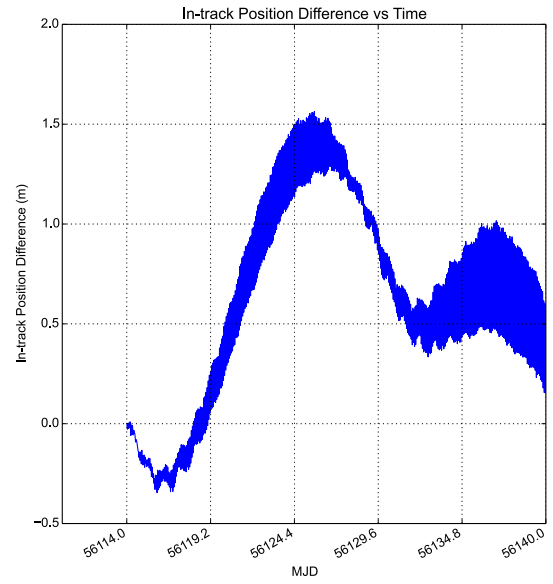
As shown in Figure 5 OCEAN's and Orekit's predictive accuracies are the same order of magnitude and the observation set determines which orbit determination application is more accurate. When using an orbit fit to SLR observations during July 1-5, 2012 OCEAN out-performs Orekit, and after 25 days of extrapolation the observed accuracies are different by 50m. Similarly, when using an fit to observations during July 6-10, 2012, OCEAN out performs Orekit to a greater degree (different by 260m after 25 days), though for 2 days Orekit is more accurate than OCEAN.

An interesting change is observed when extrapolating an orbit fit to data from July 11-15, 2012. For the first seven days OCEAN displays better predictive accuracy than Orekit. However, from the eighth day onward Orekit is more accurate than OCEAN and by the end of the fit span the difference between them is 330m. In this case the Orekit predicted ephemeris does not diverge exponentially from the fitted ephemerides. This suggests either that Orekit produced a very accurate extrapolation, or that Orekit's extrapolation contains multiple small errors that cancel each other out to produce the observed parabolic shape and close agreement between prediction and fit.

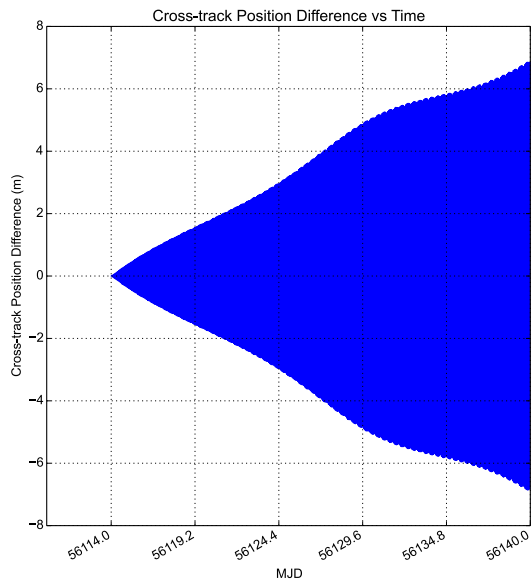
The difference between OCEAN and Orekit could be due to a variety of factors, including propagation differences detailed in the previous section, as well as measurement modeling and data editing differences. One known source of difference is the use of different atmospheric density models. Though OCEAN and



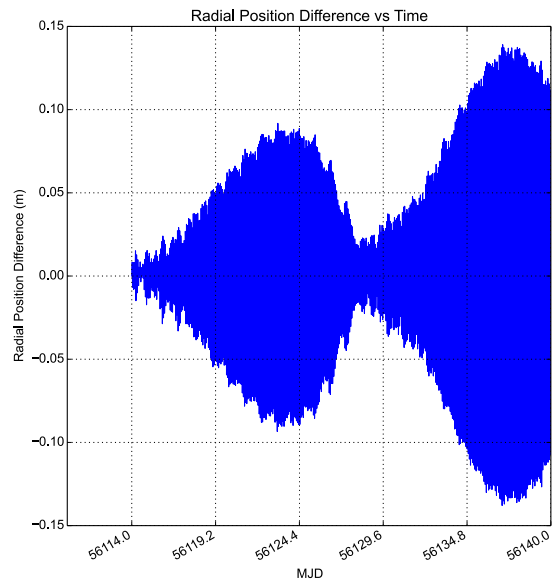
(a)



(b)



(c)



(d)

Figure 3: Comparison of the ephemerides generated by OCEAN and Orekit for Stella.

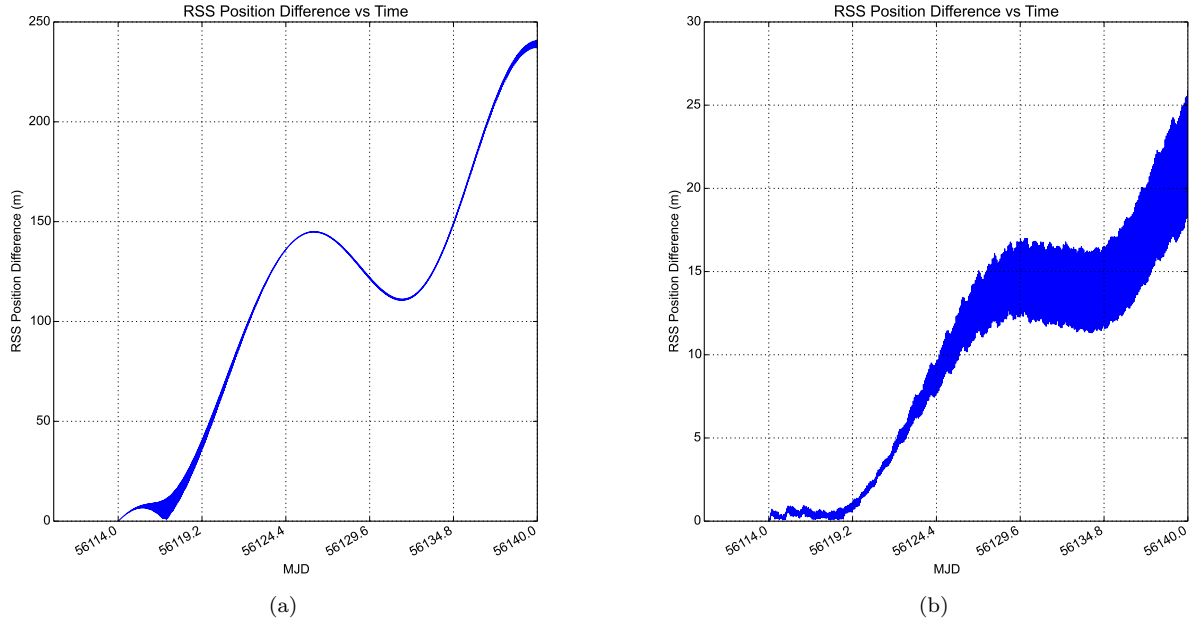


Figure 4: The effect of solid Earth tides, Figure 4a, and ocean tides, Figure 4b, on Stella's orbit.

Orekit both support several atmospheric density models they do not have any models in common. For the results presented here OCEAN is using the NRL MSIS atmospheric density model, while Orekit is using the Harris-Priester model. In related testing, it was observed that switching the atmospheric density model caused hundreds of meters of difference in the orbit solutions over a similar time span, so it is plausible that the entire difference is due to atmospheric modeling. Additionally, the Orekit orbit determination software uses the Levenberg-Marquardt algorithm to solve for orbit parameters, while OCEAN uses the Newton iteration algorithm. This may account for a portion of the difference as well.

Overall, out of the 70 days studied, OCEAN performed best for 56 days and Orekit performed best for 14 days.

IV. Conclusion

In conclusion, it is seen that the use of the open-source astrodynamics toolkit Orekit produces results on par with the heritage tool OCEAN for both orbit propagation and orbit determination applications.

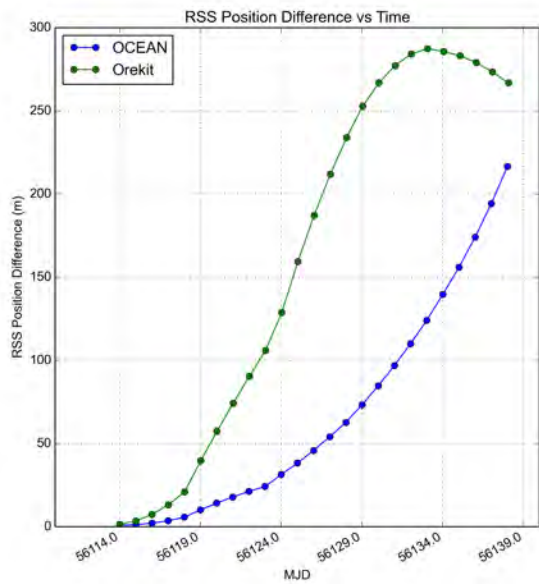
The difference between propagated orbits using each tool varied only by 7 meters over 25 days. It can be seen that the addition of solid and ocean tidal forces within Orekit has been well implemented in that the resulting orbit difference can only be attributed to at most 3% of the total tidal effects.

For orbit fitting and prediction, OCEAN performed better in two out the three cases studied, while in the last case Orekit performed better. Even in the cases where OCEAN outperforms Orekit, the Orekit orbit prediction error is on the same order of magnitude as OCEAN's orbit prediction error. However, OCEAN appears to have better accuracy in the majority of cases.

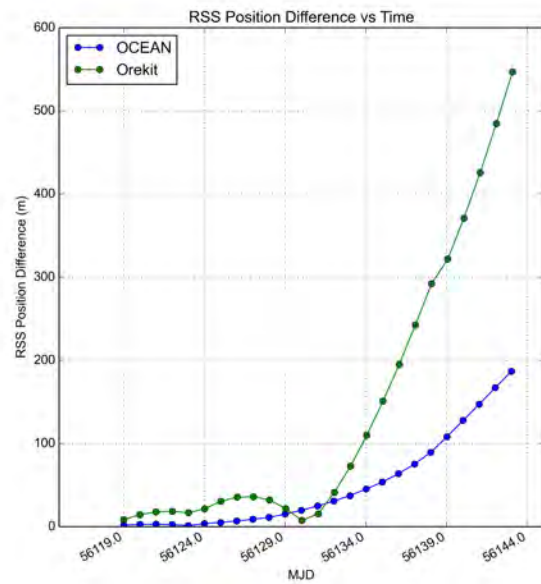
Future efforts can make several improvements over the methodology used in this paper. First a common atmospheric density model could be implemented and the remaining differences in the direct ephemeris comparison assigned to specific discrepancies.

More testing using a wider array of satellites and data types is needed to fully characterize the effectiveness of the Orekit orbit determination tool. There are many variations in orbit solution quality due to orbit regime and data type that can be explored.

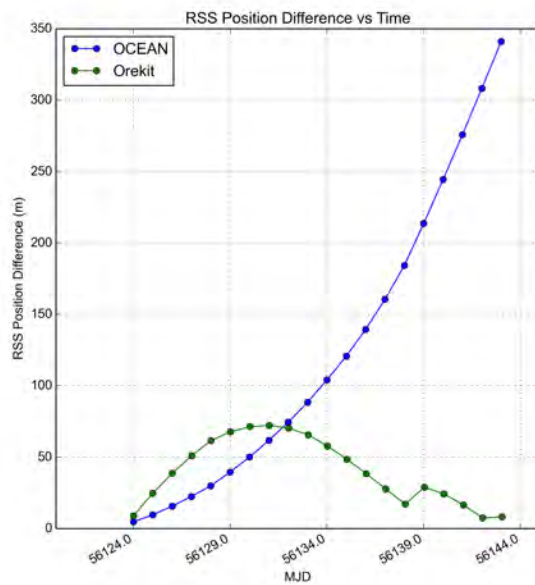
Finally, OCEAN has been tuned and refined for almost 2 decades while the Orekit orbit determination application was built in a few weeks. This rapid development demonstrates the agility of a well architected library written in a modern language. However, additional work is needed to tune the method for maximum



(a)



(b)



(c)

Figure 5: Predicted vs. fitted orbits for OCEAN and Orekit. For each figure the predicted orbit is determined from the five days of observations before the first data point.

performance.

The proliferation of accurate open source astrodynamics software has the potential to change the space community by providing easy access to functionality in package that is easily developed and maintained that formerly was only found in heritage systems. Thus, new applications and opportunities are enabled.

References

- ¹Wooster, P., Boswell, D., Stakem, P., and Cowan-Sharp, J., “Open Source Software for Small Satellites,” *21st Annual AIAA/USU Conference on Small Satellites*, 2007.
- ²San-Juan, J. F., Lara, M., López, R., López, L. M., Folcik, Z. J., Weeden, B., and Cefola, P. J., “USING THE DSST SEMI-ANALYTICAL ORBIT PROPAGATOR PACKAGE VIA THE NONDYWEBTOOLS/ASTRODYWEBTOOLS OPEN SCIENCE ENVIRONMENT,” *62nd International Astronautical Congress*, Cape Town, South Africa, 2011.
- ³Ido, H., “Space Flight Dynamics as a Service,” *Ground System Architectures Workshop*, 2012.
- ⁴Vetter, J. R., “Fifty Years of Orbit Determination: Development of Modern Astrodynamics Methods,” *Johns Hopkins APL technical digest*, Vol. 27, No. 3, 2007, pp. 239.
- ⁵Soyka, M. T., Middour, J. W., Binning, P. W., Pickard, H., and Fein, J., “The Naval Research Laboratory’s orbit/covariance estimation and analysis software- OCEAN,” *Astrodynamics 1997*, 1997, pp. 1567–1586.
- ⁶Soyka, M. T., Middour, J. W., and Fein, J., “Simultaneous orbit determination of large satellite constellations,” *Spaceflight mechanics 1998*, 1998, pp. 1275–1293.
- ⁷Binning, P. W., Soyka, M. T., and Middour, J. W., “Orbit determination using space to ground Differential GPS in NRL’s OCEAN package,” *Astrodynamics 1999*, 2000, pp. 421–434.
- ⁸Seago, J. H., Davis, M. A., Smith, W., Fein, J., Brown, B., Middour, J., Soyka, M., and Lydick, E., “More results of naval space surveillance system calibration using satellite laser ranging,” *Advances in the Astronautical Sciences*, Vol. 112, 2002, pp. 1177–1196.
- ⁹Petit, G. and Luzum (eds.), B., “IERS conventions (2010),” Tech. Rep. IERS-TR-36, International Earth Rotation and Reference System Service, 2010.
- ¹⁰Pommier-Maurussane, V., Maisonobe, L., and Parraud, P., “Extending Propagation with User-Defined Equations, Applications to Optimization and Partial Derivatives Computation,” *Journal of Aerospace Engineering Sciences and Applications*, Vol. 3, No. 3, 2011, pp. 45.
- ¹¹Cefola, P. J., Bentley, B., Maisonobe, L., Parraud, P., Di-Costanzo, R., and Folcik, Z., “Verification of the Orekit Java Implementation of the Draper Semi-Analytical Satellite Theory,” *AAS/AIAA Space Flight Mechanics Meeting*, American Astronautical Society / American Institute of Aeronautic and Astronautics, Kauai, Hawaii, February 2013.
- ¹²Maisonobe, L. and Fernandez-Martin, C., “Sharing the Knowledge: An Open-Source Vision for Flight Dynamics,” *SpaceOps 2010 Conference Delivering on the Dream Hosted by NASA Marshall Space Flight Center and Organized by AIAA*, 2010.
- ¹³Lefebvre, M., “New Satellite Missions for Solid Earth Studies-Status and Preparations,” *CSTG Bulletin*, , No. 11, 1989, pp. 25–32.
- ¹⁴Pearlman, M., Degnan, J., and Bosworth, J., “The International Laser Ranging Service,” *Advances in Space Research*, Vol. 30, No. 2, Jul 2002, pp. 135143.
- ¹⁵Hairer, E., Nørsett, S. P., and Wanner, G., *Solving Ordinary Differential Equations I: Nonstiff Problems (Springer Series in Computational Mathematics) (v. 1)*, Springer, 2nd ed., 4 2008.