Improving low-Earth orbit predictions using two-line element data with bias correction

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ABSTRACT

In this paper we present results from our orbit prediction study using the publicly available Two-Line Element (TLE) sets. The method presented here is similar to that introduced by Levit and Marshall [1]; however, we also consider the non-spherical low-Earth orbit satellites Grace A and Grace B. A state vector is generated every 10 minutes in the orbit determination (OD) period using SGP4. These generated states are subsequently used as observations in an orbit determination run considering a full set of forces to determine the orbit over the 10-day time span. All information used is from the TLE data sets. Once the orbit has been determined, it is then numerically propagated to obtain a prediction of the object's position. The TLE-determined orbit is compared to highly accurate satellite laser ranging (SLR) Consolidated Prediction Format (CPF) data to assess the accuracy. We tested the technique by performing 200 independent simulations for Stella, Starlette, Grace A and Grace B and found that it resulted in better orbit predictions 98.5%, 93.4%, 97.5% and 95.5% of the time, respectively, when compared to standard SGP4 propagation. For Starlette and Stella after a 7 day prediction period the average absolute maximum along track bias was reduced by approximately 64% and 74%, respectively. For Grace A and Grace B after a 7 day prediction period the average absolute maximum along track bias was reduced by approximately 68% and 64%, respectively.

The TLE-determined orbit contains bias in the along, across track and radial directions with the along track error dominating. If these can be estimated we can obtain an improved orbit prediction. We used our TLE-determined orbit as an initial state and determined an orbit 3 days after the 10 day OD period from only two passes of SLR data from a single station (Mount Stromlo, Australia). We then estimated the bias in the along track direction by fitting a quadratic function to the along track bias data. The error between the TLE-determined orbit and the SLR-determined orbit in the along (minus the quadratic bias), across and radial tracks was then estimated using sinusoidal functions. These estimations were then used to correct the TLE-determined orbit, resulting in drastic improvements in the prediction accuracy of low-Earth objects. For a prediction period of 7 days, the absolute maximum along track error for Grace A reduced from 16.6 km (SGP4) to 4.8 km with the TLE data fitting presented in this paper. With bias estimation this error was reduced to 1.7 km. This demonstrates the ability to obtain much more accurate orbit predictions using only two passes (19 normal point SLR ranging observations) from one station.

In the operational sense, the presented method can be used in debris conjunction analyses to improve the accuracy and reliability of the conjunction predictions. This method is currently implemented in EOSSS' conjunction analysis software. Objects of interest can then be tracked with EOSSS' tracking facilities and much better orbit predictions can be obtained.

Keywords: Orbit Determination, Orbit Prediction, Bias Correction, Low-Earth Satellites

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1. INTRODUCTION

Space situational awareness (SSA) is important for maintaining a safe space environment. One aspect of space situational awareness is accurate orbit determination and prediction. The ability to accurately predict the orbits of objects is important in many problems, such as conjunction analyses, unaided debris laser ranging, and remediation techniques to curb the growing threat of space debris, such as active debris removal [2] and laser collision avoidance [3].

Computer simulation studies have shown the threat that space debris poses to the future of space operations, particularly in the low-Earth orbit environment. The propagation of collision fragments or *collisional cascading* was introduced by Kessler and Cour-Palais [4]. A sharp indicator of the consequence of this collisional cascade, shown in the modelling studies [5, 6, 7, 8], is the so-called "No Future Launches" scenario. This shows that over the next couple of centuries there will be an increase in debris objects resulting from collisions even if no new objects were launched into space. This phenomena has motivated a variety of potential remediation techniques.

One of the most prolific examples of the necessity of performing accurate predictions of satellite states is the collision between Iridium 33 and Cosmos 2251 on 2009 February 10 [9]. This collision resulted in the loss of the operational communications satellite, Iridium 33. A close approach was predicted, however, nothing was done due to the uncertainty in the prediction accuracy. The ability to accurately predict conjunctions to a high level of certainty is extremely important for the safety of space assets.

The method of using multiple TLEs to create pseudo-observations to perform an orbit determination and prediction was introduced by Levit and Marshall [1]. The method described in this paper is similar and we analysed the accuracy of the method compared to standard SGP4 propagation. We analysed orbit predictions for four low-Earth satellites and found that the method significantly outperforms standard SGP4 propagation for all. The TLE-OD/OP method presented here reduces this variability in the predictions thus increases the confidence in collision analyses. This results in consistently better conjunction assessments and is currently used in EOS Space Systems' orbital conjunction prediction software.

We also introduce a method to improve on the orbit predictions made using multiple TLEs by correcting the biases using limited SLR data. The TLE-OD/OP method results in biases that are reasonably well-behaved as apposed to standard SGP4 propagation from a single TLE. We used 2 SLR passes from EOS Space Systems' Mount Stromlo SLR station in Australia to introduce the method. The idea behind it is after initial predictions are made using the TLE-OD/OP method, if required, accurate SLR data can be collected to improve on the prediction capabilities. The process displays a method where sparse observational information may be used to improve predictions. This area of *reliable* orbit determination using sparse data from multiple sources is critical for achieving the best possible orbit predictions and is a research priority towards improving SSA for the SPACE Research Centre, RMIT University and EOS Space Systems.

2. ORBIT DETERMINATION AND PREDICTION FROM TLEs – THE TLE-OD/OP METHOD

The method begins by defining a 10 day orbit determination (OD) window. All the publicly available TLEs that fall within this OD window were downloaded from [10]. The ballistic coefficient B of the object was estimated using the average B^* term from the TLEs through the constant transformation [11]:

$$B = \frac{1}{12.741621 B^*} \frac{\mathrm{kg}}{\mathrm{m}^2}. \tag{1}$$

Pseudo-observations are generated every 10 minutes by propagating backwards using SGP4 from each TLE in the orbit determination window, past the previous TLE epoch by an arbitrary period of time. We found it sufficient to propagate past the previous TLE by a period of 0.2 days. The idea with the backwards propagating is to use the latest available information to determine each state. The first and last TLEs in the OD window are used to create pseudo-observations up to the first and last epochs of the OD window, respectively. These pseudo-observations are then used to determine an orbit for the OD time span using least squares considering a full set of forces. We considered Earth gravitational force using a 100×100 EIGEN-05C gravity model [12], atmospheric drag using the MSIS86 atmospheric model [13], third-body gravitational perturbations, solar and Earth radiation pressure, and ocean and solid-Earth tidal effects. Immediately following the OD window is the orbit prediction (OP) period. The determined initial state is then propagated until the end of the OP window which was set to 30 days. The only satellite information used was the average B^* term obtained from the TLEs.

During the OD period there is an option to select whether the atmospheric drag coefficient C_D and the solar radiation coefficient C_R are to be estimated using the observational data. Their nominal values are set to $C_D = 2.2$ and $C_R = 1.1$. In what follows, we estimated the drag coefficient for the Grace satellites only. For Starlette and Stella we estimated the solar radiation coefficient only. This is due to their differences in altitudes. It was necessary to estimate the drag coefficient for the Grace satellites for the orbit prediction accuracy.

For comparison, we propagated using SGP4 to the end of the OP period from the last available TLE in the OD window. This hereafter will be referred to standard SGP4 propagation. The along, across track and radial biases are calculated for the TLE-OD/OP method and standard SGP4 propagation by comparing with accurate SLR CPF orbit data downloaded from NASA's Crustal Dynamics Data Information System (CDDIS) [14]. To test the accuracy of the method we performed 200 TLE-OD/OP simulations starting from random epochs in 2009 for low-Earth orbit satellites Grace A and Grace B and 2011 for Starlette and Stella and analysed the number of times the TLE-OD/OP method resulted in a better 7 day prediction than standard SGP4 propagation.

3. TLE-OD/OP RESULTS

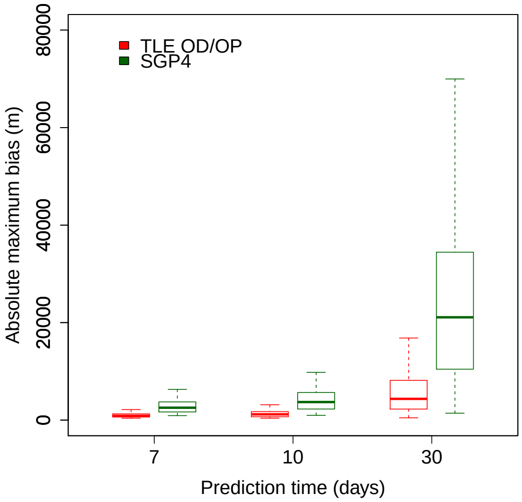
Figs. 1–4 show the results from our 200 run simulation study for Starlette, Stella, Grace A and Grace B, respectively. In each of the figures, box plots for the absolute maximum along, across track and radial biases are plotted comparing the TLE-OD/OP method with standard SGP4 propagation. Three separate prediction epochs were considered: 7, 10 and 30 days after the end of the OD window. The box plots correspond to the absolute maximum values in the biases preceding and including these epochs.

Figs. 1(a)–1(c) show a comparison of the along, across track and radial biases for Starlette. From this figure we can see that the TLE-OD/OP method significantly outperforms standard SGP4 propagation in all the biases, with lower median and smaller spread. Figs. 2(a)–2(c) show a comparison of the along, across track and radial biases for Stella. As with Starlette, the TLE-OD/OP method is consistently better than standard SGP4 propagation. This improvement in accuracy is most evident in the 30 day prediction results. Figs. 3(a)–3(c) show a comparison of the along, across track and radial biases for Grace A. The improvements made in the prediction accuracy using the TLE-OD/OP method are a little more spread when compared with Starlette and Stella after a 30 day prediction. This is due to the lower orbit of Grace A and the increased drag effects. The improvements in the radial error are excellent (Fig. 3(c)). Figs. 4(a)–4(c) show a comparison of the along, across track and radial biases for Grace B. Again. the improvements made in the prediction accuracy using the TLE-OD/OP method are a little more spread when compared with Starlette and Stella, particularly after a 30 day prediction.

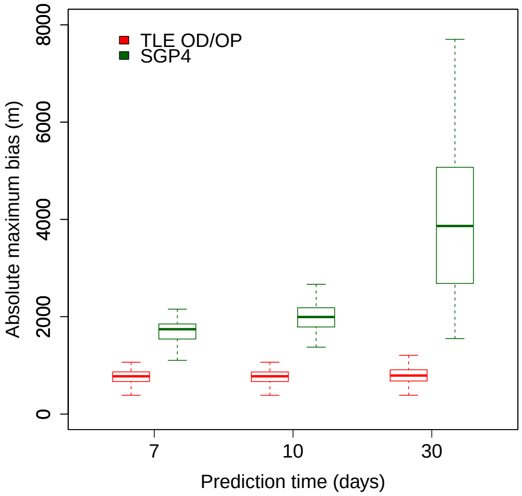
Tab. 1 shows summary results from the simulation runs for a prediction period of 7 days for Starlette, Stella, Grace A and Grace B. Win % refers to the proportion of runs where each method resulted in a lower absolute maximum along track bias. The along track bias is the dominant error when compared to across track and radial biases. From the table we can see that the TLE-OD/OP method dramatically outperforms standard SGP4 propagation. In all cases considered it results in a lower absolute maximum along track error after a 7 day prediction over 90% of the time. The reduction in the maximum absolute along track bias is 64%, 74%, 68% and 64% for Starlette, Stella, Grace A and Grace B, respectively. From Figs. 1–4 we expect similar (if not better) reductions for the across track and radial biases.

Tab. 1. Win percentages for the TLE-OD/OP method and standard SGP4 propagation for a 7 day prediction period.

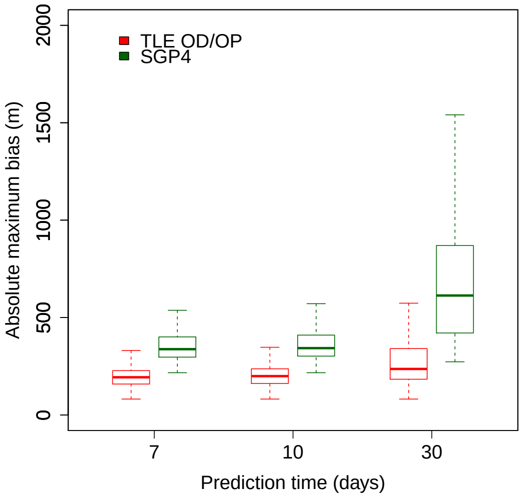
Satellite	TLE-OD/OP win %	Ave max abs along track bias (m)	SGP4 win %	Ave max abs along track bias (m)
Starlette	93.4%	1024.86	6.6%	2812.24
Stella	98.5%	1348.75	1.5%	5172.94
Grace A	97.5%	2966.78	2.5%	9373.46
Grace B	95.5%	2920.54	4.5%	8215.84



(a) Along

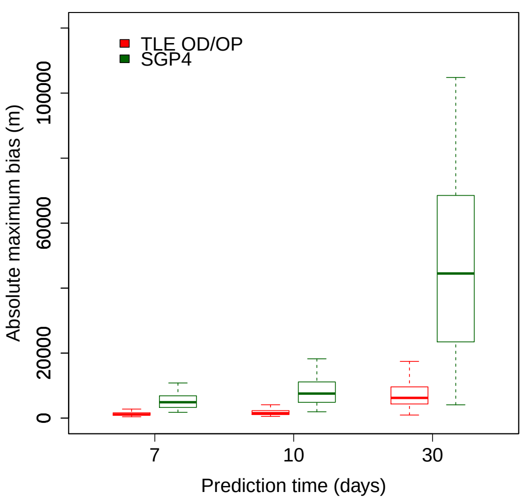


(b) Across

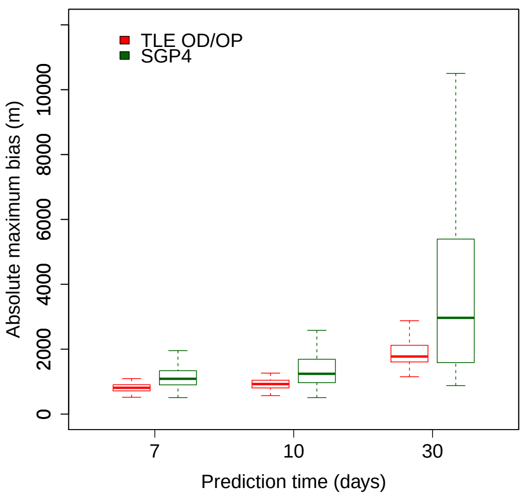


(c) Radial

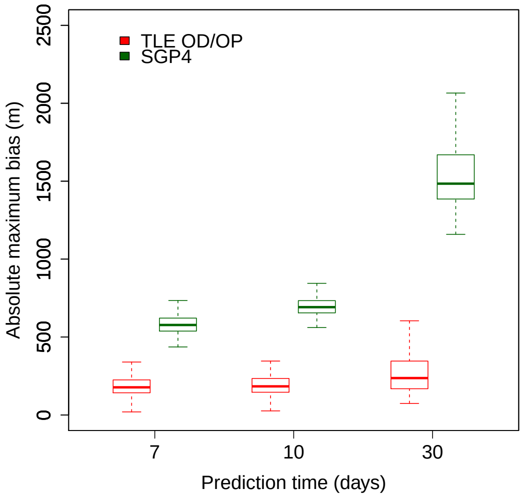
Fig. 1. Comparison between the TLE-OD/OP method and standard SGP4 propagation biases for **Starlette** for 7, 10, and 30 day predictions for the 200 simulations.



(a) Along

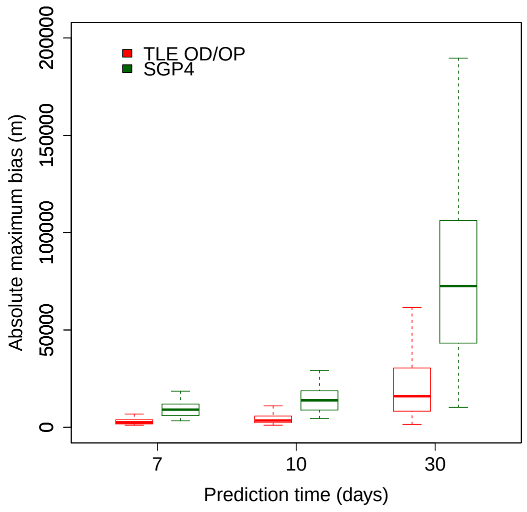


(b) Across

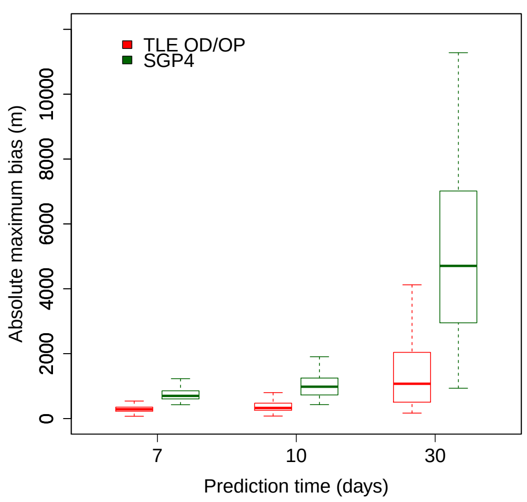


(c) Radial

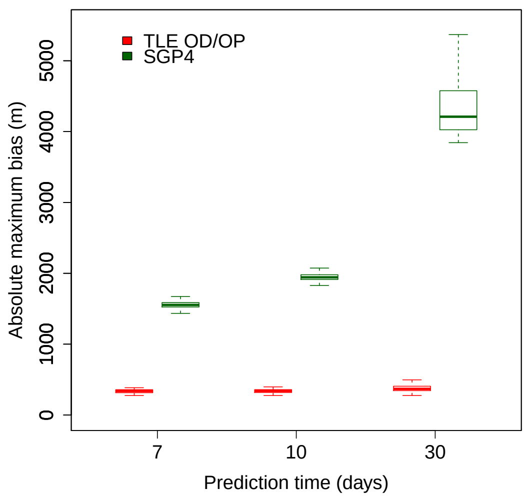
Fig. 2. Comparison between the TLE-OD/OP method and standard SGP4 propagation biases for **Stella** for 7, 10, and 30 day predictions for the 200 simulations.



(a) Along

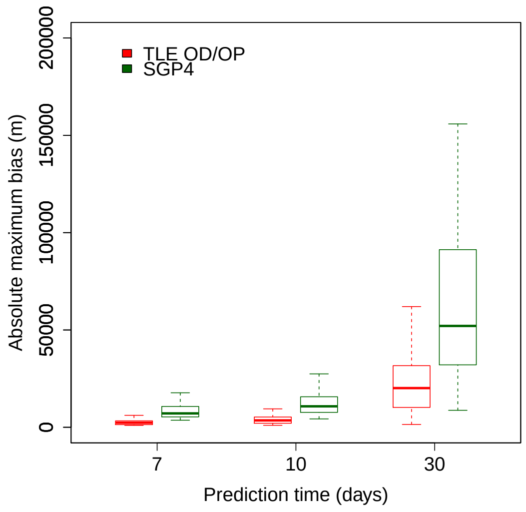


(b) Across

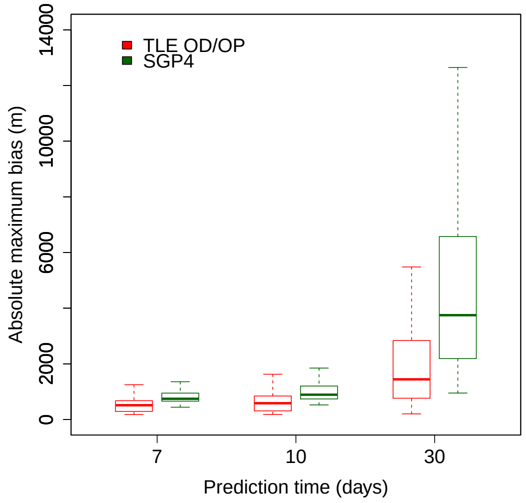


(c) Radial

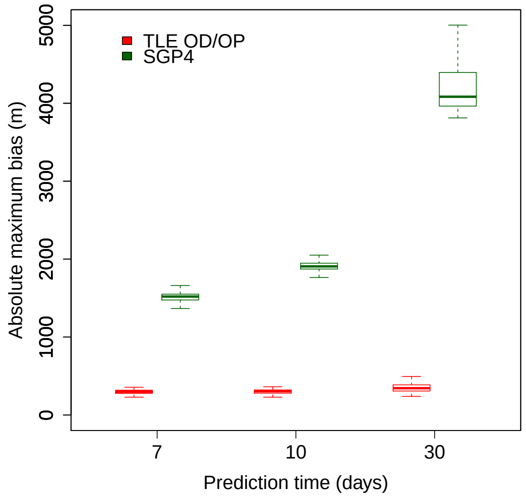
Fig. 3. Comparison between the TLE-OD/OP method and standard SGP4 propagation biases for **Grace A** for 7, 10, and 30 day predictions for the 200 simulations.



(a) Along



(b) Across



(c) Radial

Fig. 4. Comparison between the TLE-OD/OP method and standard SGP4 propagation biases for **Grace B** for 7, 10, and 30 day predictions for the 200 simulations.

4. A METHOD FOR BIAS CORRECTION USING SLR DATA

The TLE-OD/OP method yields biases that are relatively well behaved when compared to those of SGP4. This allows them to be estimated when we have access to better orbital information, for example, limited SLR observations from a single station. We used the TLE-OD/OP method to perform an OD and OP for Grace A. The OD period was set to 10 days and the OP period set to 30 days. Following the TLE-OD/OP OD window, we performed an SLR OD and OP using 2 passes of normal point observational data from Mount Stromlo. We set our SLR OD window to be 3 days (after a 3 day delay) and the SLR OP to be 30 days. This 3 day delay is so there is enough bias trend to estimate. This is particularly important in the along track since it contains systematic bias. The TLE-OD/OP prediction corresponding to the initial epoch of the SLR OD was used as an initial state for the OD. Once an orbit was determined, it was numerically propagated to the end of the SLR OP period. The SLR OD period corresponds to the period where bias estimation occurs since we determine the biases in our TLE-OD/OP prediction using the SLR-determined orbit. The timeline for the bias correction process is shown in Fig. 5.

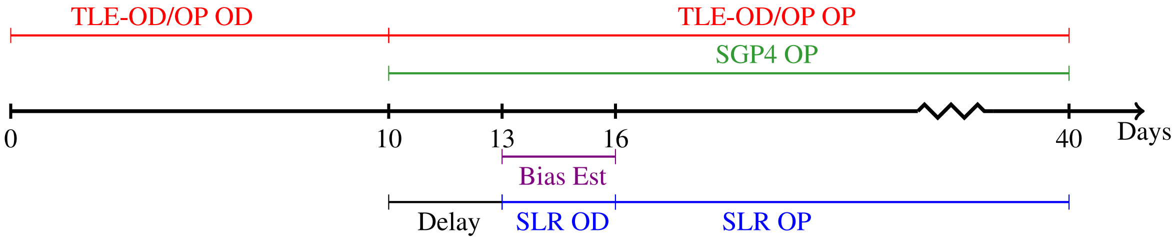


Fig. 5. Schematic of the bias correction timeline

We assumed the following functional forms to estimate the biases

$$\begin{aligned} A &= a_0 + a_1 t + a_2 t^2 + a_3 \sin(a_4 t + a_5), \\ C &= \mu_C + a_6 \sin(a_7 t + a_8), \\ R &= \mu_R + a_9 \sin(a_{10} t + a_{11}), \end{aligned} \tag{2}$$

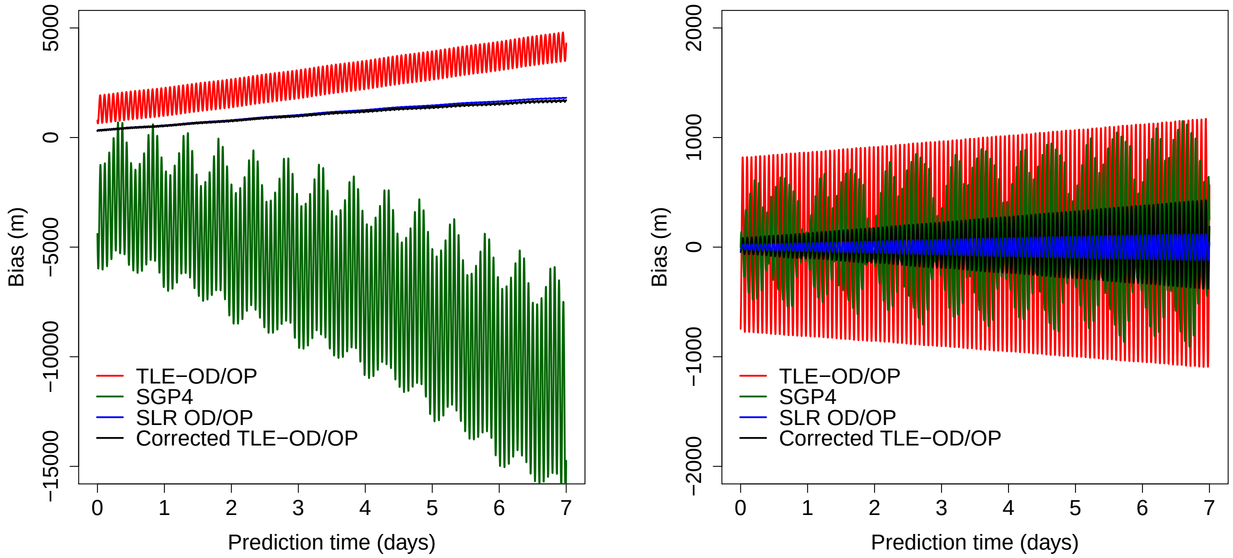
where a_i, $i = 0, \ldots, 11$ are the function parameters, μ_C and μ_R are the averages of the across and radial bias data, and A, C and R are the along, across track and radial biases, respectively.

First we calculated the quadratic bias in the along track bias by fitting $a_0 + a_1 t + a_2 t^2$ to the along track data using Least Squares. We subsequently removed the quadratic bias estimate from the along track data and then determined the sinusoidal variation using nonlinear least squares to calculate the parameters a_3–a_5. We centred the data for the across track and radial biases around their means and then estimated the sinusoidal variation using nonlinear least squares to determine a_6–a_{11}. We then calculated the position difference from the TLE-OD/OP OP required for the estimated biases in equation (2). Finally, the position is corrected and the updated biases are calculated against CPF data.

Tab. 2. Conditions for the bias estimation process.

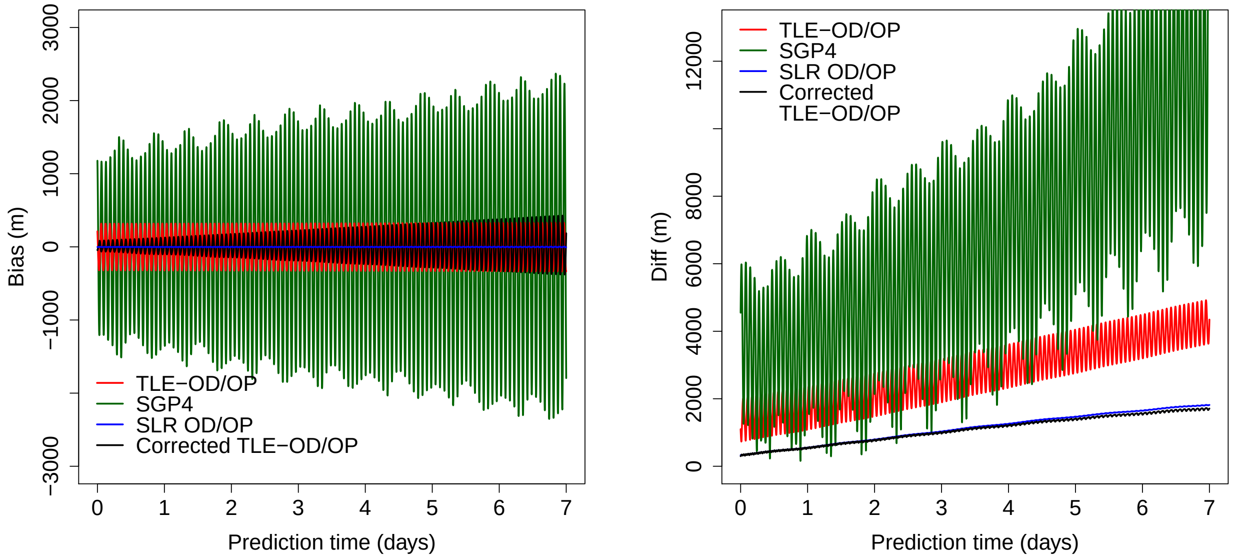
Method	Initial Epoch dd/mm/yyyy hh:mm:ss	Final Epoch dd/mm/yyyy hh:mm:ss
TLE-OD/OP OD	22/01/2009 00:00:00	01/02/2009 00:00:00
TLE-OD/OP OP	01/02/2009 00:00:00	03/03/2009 00:00:00
Delay	01/02/2009 00:00:00	04/02/2009 00:00:00
Bias Estimation	04/02/2009 00:00:00	07/02/2009 00:00:00
SLR OD	04/02/2009 00:00:00	07/02/2009 00:00:00
SLR OP	07/02/2009 00:00:00	09/03/2009 00:00:00

Fig. 6 shows the results of the bias correction for Grace A using 2 SLR passes from Mount Stromlo for a 7 day prediction. The corresponding epochs for the bias correction are shown in Tab. 2. The original biases from the TLE-OD/OP are plotted along with the corrected ones and are compared with standard SGP4 propagation and the orbit prediction made using only the SLR data. Figs. 6(a)–6(c) show the bias in the along, across and radial tracks, and Fig. 6(d) shows the position difference.



(a) Along track bias

(b) Across track bias



(c) Radial bias

(d) Position difference

Fig. 6. Comparison of predictions made using the TLE-OD/OP method with and without bias correction with standard SGP4 propagation and SLR OP for **Grace A**. The conditions for the computation are shown in Tab. 2. The along, across track and radial biases are plotted ((a)–(c)) along with the Euclidean position difference (d).

It is clear from Fig. 6 that the biases resulting from the TLE-OD/OP method are well-behaved when compared to those of standard SGP4 propagation, and thus can be estimated using simple functions. Fig. 6(a) shows the increase in prediction accuracy in the along track bias. The TLE-OD/OP method results in a much improved bias over SGP4. When the bias correction is applied we see that the along track error is reduced significantly – both in magnitude and variance. The bias correction results in a better prediction than the orbit prediction from the SLR data, albeit marginally.

The across track bias for SGP4 is better than the TLE-OD/OP method (Fig. 6(b)). However, the TLE-OD/OP bias is in a form that can be effectively estimated resulting in the improved across track error than SGP4. It is also important to note that the results of the TLE-OD/OP method for the across track error in Fig. 3(b) indicate this will not often be the case. The SLR OD/OP results in the best across track error in this simulation. Fig. 6(c) shows the biases in the radial direction are, as expected, the best from the SLR OD/OP. The TLE-OD/OP method results in a much better radial bias than standard SGP4 propagation. Fig. 6(d) shows the TLE-OD/OP results with bias correction are the best, with a lower position difference after a 7 day prediction. This shows the dominant nature of the along track error since the SLR OD/OP resulted in smaller across and radial track biases than that of the corrected TLE-OD/OP method. The absolute maximum along track error for Grace A for standard SGP4 propagation was 16.6 km. Using the TLE-OD/OP method reduced this to 4.8 km and with bias estimation this error reduced to 1.7 km.

5. DISCUSSION

Originally, in the TLE-OD/OP method, when creating the observations we propagated forwards from each TLE until the epoch of the following TLE. However, better results were (consistently) obtained by propagating backwards from each TLE past the epoch of the preceding TLE. This is possibly because the positions propagated backwards from the TLE epoch are within the OD window for generating the TLE.

The bias correction technique employed here needs a little work to become more robust. In some cases, a linear systematic bias approximation in the along track results in better bias correction results than the quadratic case. This is due to the along track bias not having much of a quadratic trend and is better approximated by a linear change. If we obtain enough SLR passes, then the SLR OP will return more accurate predictions than the bias estimation process. The method is designed to be used when this is not the case. Occasionally, there is a problem with the SLR OD converging due to the little amount of observational data available. We are working on making the technique more robust by using TLEs as supporting observations to ensure convergence. The TLEs observations are weighted so the SLR data is vastly dominant in the OD process.

We are currently working on an iterative technique for bias correction which updates the TLE-OD/OP OD results with bias correction and is subsequently used as observations for the TLE-OD/OP process to be performed again. To do this we set up a second bias estimation process and set our bias estimation window to follow immediately after an updates TLE-OD/OP OD window. In other words, we shift the TLE-OD/OP window to cover the delay period, immediately preceding the SLR OD window. This is so we can best estimate the sinusoidal variation in the biases in the TLE-OD/OP OD period. This updated TLE-OD/OP OD result is then used in the bias correction process as the pseudo-observations in the OD.

The method will be extended to debris objects. Observations collected from EOS Space Systems' Mount Stromlo Space Debris Tracking Station will be used to validate the TLE-OD/OP method as well as the bias correction method for debris objects. We will also investigate the use of optical observations to determine the biases to compare with the SLR bias correction.

Detecting erroneous TLE data is critical when attempting to provide reliable orbit determination from sparse data. We will be extending the analysis presented here to include filtering techniques to determine erroneous TLE data as well as orbit manoeuvre detection. We will develop techniques designed to use a variety of data sources which may be sparse in nature to produce reliable orbit predictions. The authors believe this to be a critical component in operational space systems contributing to SSA.

ACKNOWLEDGEMENTS

The authors would like to gratefully acknowledge the Australian government's research grant support for this project through the Australian Space Research Program (ASRP) project "Platform Technologies for Space, Atmosphere and Climate".

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