INVESTIGATING THE APPLICATION OF THE ORBIT DOMAIN CALIBRATION METHOD IN SUN SYNCHRONOUS ORBITS

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ABSTRACT

In an era marked by an exponentially expanding satellite population and broader access to space, the capabilities of existing Space Traffic Management (STM) methods are increasingly scrutinized and questioned. The growing disparity between accuracy requirements and operational capabilities underscores the increasing demand for higher accuracy orbits. This paper investigates the application of the Orbit Domain Calibration (ODC) method, designed to increase orbit accuracy by calibrating uncooperative tracking orbits (e.g. from the United Space Surveillance Network) using precise orbits derived from cooperative tracking (via e.g. onboard GPS receivers). Building on an initial proof-of-concept tested with GRACE-FO [1], this paper employs the Sentinel-1 mission as a case study to evaluate the effectiveness and adaptability of ODC in more complex scenarios. These include challenging orbit configurations, complex satellite geometries, and the high-risk environment of Sun-Synchronous Orbit (SSO) [2]. The analysis showed mean errors in uncooperative tracking solutions, Two-Line Elements (TLE), of around 750 m by comparing TLEs to Precise Orbit Ephemeris (POE) for a year of data for Sentinel-1A and 1B. Having identified spatio-temporal patterns in TLE errors, which suggest systematic discrepancies in TLE/SGP4 likely stemming from underlying modelling assumptions, the application of the ODC method demonstrated promising results. The application of the developed correction significantly improved accuracy, reducing the mean positional error from approximately 750 m to 390 m, an almost twofold improvement. These promising results, coupled with the exploration of various methodologies, support the potential for further refining the ODC method through the development of new correction techniques.

Keywords: Orbit Domain Calibration; Two-Line Element; Sentinel-1; Sun-Synchronous Orbit.

1. INTRODUCTION

As the satellite population continues to expand, a key concern is whether the disparity between current tracking capabilities and the required accuracy is too great to sustain safe and efficient operations in the evolving space environment. As the main source of public orbit data, the Two-Line Element (TLE) [3] data format currently forms the bedrock of most STM practices. Provided by the U.S. Space Surveillance Network (SSN), the TLE and its Simplified General Perturbations 4 (SGP4) propagation model face scrutiny regarding their accuracy and precision [4]. Attempting to address these concerns, the United States Space Force have developed the SGP4-XP algorithm, an enhanced version of SGP4 [5]. While the SGP4-XP algorithm is public, no record of historic XP-TLEs is publicised making a true assessment of its accuracy difficult. Outside of the activities of the U.S. SSN, various commercial efforts have been established to increase the accuracy of orbit solutions for STM, such as LeoLabs [6]. Other methods have included: batch least-squares differential corrections [3] or support vector machine models to learn underlying prediction error patterns [7]. Many of these methods are tested and developed on spacecraft with simplistic geometries, such as geodetic spheres, with low area-to-mass ratios, that are fairly simplistic to model and perform particularly well in propagation algorithms and the underlying force models. However, these analyses do not consider the more complex geometries, with higher area-to-mass ratios that are typical of many operational satellites. As such, relying on simplified shapes provides only a lower bound on the actual error and leads to an overly optimistic assessment of system performance by neglecting the true geometric complexity and environmental interactions affecting other catalogued objects. At an attempt to overcome some of the shortcomings found in previous literature and develop a method that aims to meet a higher degree of accuracy for orbits used in STM, the Orbit Domain Calibration (ODC) Method will be introduced.

1.1. The Orbit Domain Calibration Method

In this paper, the Orbit Domain Calibration (ODC) method is tested which aims to improve the accuracy of satellite orbits. A key piece of evidence motivating the ongoing work to develop the ODC method is that systematic error patterns can be observed in the orbit solutions generated from uncooperative tracking systems, shown

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in [8]. The aim of the ODC approach is to use precise orbits, i.e., centimetre-level absolute accuracy orbit solutions routinely published by scientific satellite mission operators, from an on-orbit network of satellites operating across all operational orbital regimes, to characterise the errors in orbits generated by uncooperative tracking systems and to then use this knowledge to improve the accuracy of those orbit solutions [1]. To date, the concept has been tested using the GRACE-Follow On (GFO) mission, where a 30-fold improvement in accuracy (600 m to 20 m) and a 20-fold improvement in precision (4.5 km to 200 m) was demonstrated, by correcting the uncooperative orbits for GFO-2 using a model of the error patterns determined using precise orbits for GFO-1. The GFO test case provided ideal conditions due to the formation flying nature of the satellites, as the calibration satellite (GFO-1) was orbiting $\sim$200 km in front of the satellite (GFO-2) that was corrected. Therefore, this test provided the best case scenario for this method, as the expected systematic errors found in the TLE/SGP4 model are highly similar. Further validation of the ODC concept requires testing in more challenging scenarios, on more satellites that have increasingly different orbital parameters and configurations and are situated in different orbital regions.

1.2. The Relevance of Sun-Synchronous Orbits for ODC

Sun-Synchronous Orbits (SSOs) are a type of near-polar orbit in which the satellite's precession rate is matched to the Earth's mean orbital motion around the Sun [9]. This synchronization allows the satellite to maintain a constant local solar time over any given point on Earth, ensuring consistent illumination conditions for repeated observations [10]. The choice of a sun-synchronous orbiting mission is based on the analysis carried out by [2], which identifies the 50-statistically most concerning derelict objects in Low-Earth Orbit. The analysis highlighted two key factors that informed the selection of the orbit for this study:

1. $\sim$10 of the statistically most concerning derelict objects are situated within SSO at an altitude of around 800 km.
2. The $\sim$20 most concerning objects found through the analysis are orbiting just above the SSO region (at lower inclinations of $\sim$70°) between 800-900 km.

Due to its various applications and benefits for scientific missions, SSO is a precious orbital region [11] that is at risk due to the presence of many high-risk objects.

SSO is chosen for its scientific importance and potential impact from high-risk objects [2], emphasizing its operational significance. This selection also enables the detection of variations in TLE/SGP4 systematic errors across different orbital environments, providing a contrast to previously studied regions like that of GRACE-FO.

1.3. The Sentinel-1 Mission

The Sentinel-1 mission is composed of two spacecraft, Sentinel-1A (S1A) and 1B (S1B), that orbit with a phase shift of 180°in the same orbital plane. They are situated in a near-polar (inclination: $\sim$98.18°), sun-synchronous orbit with a 12-day ground-track repeat cycle [12]. To meet the positioning requirements of the mission both satellites are equipped with two dual-frequency GPS receivers, allowing for necessary manoeuvre operation planning. The total mass of the satellites at launch (including fuel of 130kg) was $\sim$2300 kg [13], the main body of the satellites is 2.5x4 m with 2 solar arrays 10 m long each. Sentinel-1B is soon to be replaced with Sentinel-1C due to an anomaly causing the decommissioning of the satellite in December 2021 [14].

The Sentinel-1 mission was selected for its complex orbital configuration (180°phase shift) and geometry, providing a rigorous test case for the ODC method. The significantly higher area-to-mass ratio of Sentinel-1, compared to GRACE-FO, is anticipated to generate distinct error patterns under the SGP4 modelling assumptions. This discrepancy provides a framework for an in-depth evaluation of the ODC method's capabilities and its potential for further refinement.

1.4. Research Aim & Outline of paper

This paper seeks to understand and characterize systematic errors present in TLE data by comparing it against precise orbit ephemerides, specifically within a high-risk orbital region. The effectiveness of the ODC method is evaluated by its application to Sentinel-1, a spacecraft with more complex geometry and a more intricate orbital configuration when compared to its initial proof-of-concept study on GRACE-FO. In doing so, the paper explores the potential of developing techniques to improve orbit accuracy in challenging operational environments.

The overall methodological approach is outlined in Chapter 2, where specific data sources are included along with data processing methods for orbit error characterisation and correction method application techniques. In Chapter 4 the results are presented beginning with an error analysis followed by the correction application tests. These are finally put in the broader context of existing literature in the discussion in Chapter 5.

2. METHOD

2.1. Data Collection

For this study, one year of data from December 1, 2020, to December 1, 2021 was analysed and data comparisons were conducted at 30-second intervals. Two primary data types were analysed: Precise Orbit Ephemeris (POE) and TLEs.

A total of 1576 (S1B) and 1586 (S1A) TLEs were analysed, which were sourced from Space-Track.org. The POE data was obtained from the Copernicus Precise Orbit Determination (POD) service [12] through the specified S3 path (/eodata/Sentinel-1/AUX/) [15]. The POD service produces three different types of orbital products, that vary by different levels of processing and accuracy. To carry out the following analysis the Non Time Critical (NTC) orbits known as AUX_POEORB were selected, as they have the highest accuracy requirement (5cm) [16] and are hence the closest to the "true" position of the satellite.

Additionally, a Special Data Request was made to obtain SupTLEs via Celestrak; however, the request returned the following message: "No SupGP data exists for NORAD catalogue Number 39634/41456." An attempt was also made to acquire XP-TLEs, but currently, no public catalogue exists that archives historical XP-TLEs.
Manoeuvre data was only found and obtained for Sentinel-1A from the "Sentinel-1A Manoeuvre History file" at [16]. Data for Sentinel-1B could not be sourced.

2.2. Data Pre Processing

Once the POE data was obtained, the final two hours of each file were deleted (14-hour files with 2-hour overlap) and state vectors and timestamps were extracted at 30-second intervals (initial file output interval is 10-seconds). As POE data is initially provided in an ITRF2020 [17] reference frame it was converted into a J2000 (EME2000) reference frame using the FramesFactory Module in Orekit.

The TLEs were propagated using the Simplified General Perturbations 4 (SGP4) model [18]. The initial state was propagated to the next-closest timestamp of the POE data to the epoch and from then in 30-second intervals. Each time a new TLE becomes available, this is used to propagate such that the most current TLE is always being used - thus replicating the solution produced by the 'live' TLE-SGP4 combination. Finally, the states were converted from the initial TLE reference frame TEME, into the J2000 (EME2000) reference frame.

2.3. The Orbit Domain Calibration Equations

To understand the error pattern of the TLE orbits for both satellites and compare these, the 3-Dimensional positional error $d\mathbf{r}$ is calculated between the POE and TLE at each time-step using Eq. 1.

$$d\mathbf{r}_i^j = \mathbf{r}_i^j - \hat{\mathbf{r}}_i^j \tag{1}$$

Where $\mathbf{r}$ is the position derived from the precise orbit and $\hat{\mathbf{r}}$ is the position according to the TLE orbit, at epoch i for satellite j (where 1 is S1A and 2 is S1B). The error is then projected into the Height, Cross and Along-Track (HCL) direction to understand biases and possible origins of errors in the data.

Method 1: The basic correction function is obtained using the difference between the POE and TLE positions from the state vectors as seen in Eq. 2.

$$d\mathbf{r}_{1,i}^1 = \mathbf{r}_i^1 - \hat{\mathbf{r}}_i^1 \tag{2}$$

Where the subscript 1 denotes the correction method and i specifies the epoch. The superscript 1 indicates the satellite. The correction application is then calculated as follows using Eq. 3.

$$\mathbf{r}_{1,i}^{+,2} = \hat{\mathbf{r}}_i^2 + d\mathbf{r}_{1,i}^1 \tag{3}$$

Where the superscripts $+, 2$ describes the corrected position indicated with the $+$ and the respective satellite 2. And the subscripts $1, i$ indicate the correction number and the epoch respectively.

Method 2: The time-synchronised correction function (Eq. 4) is obtained by calculating the difference between the positions from the state vectors $\sim$ 49 min later, as this is half the orbital period of Sentinel-1A and 1B. Therefore, S1B would be expected to be approximately at the position of S1A at this time, due to the $180°$ phase shift.

$$d\mathbf{r}_{2,i}^1 = \mathbf{r}_{i+49}^1 - \hat{\mathbf{r}}_{i+49}^1 \tag{4}$$

The application of the method is obtained using Eq. 5.

$$\mathbf{r}_{2,i}^{+,2} = \hat{\mathbf{r}}_i^2 + d\mathbf{r}_{2,i}^1 \tag{5}$$

The conventions are the same as for Eq. 2 and 3. The mean and root-mean-square (RMS) values are used as metrics to assess the accuracy and precision, respectively.

3. RESULTS & ANALYSIS

3.1. Error Analysis

Both S1A and S1B show fairly consistent error patterns in 3D positioning of TLE relative to POE orbits (Fig. 1). S1A has a mean error of ∼730 m with an RMS of around 840 m, while the error profile for S1B is slightly larger displaying a mean of ∼750 m and an RMS of ∼900 m.

The close agreement between the mean and RMS error values for S1A suggests a relatively uniform error distribution, implying low variability and the absence of major anomalous events. S1B on the other hand is somewhat more affected by higher deviations as reflected by the mean and RMS error values being further apart. Overall, S1A exhibits a more stable error profile, whereas S1B shows greater variability in its TLE positioning data. A significant anomaly occurs around October 2021, during

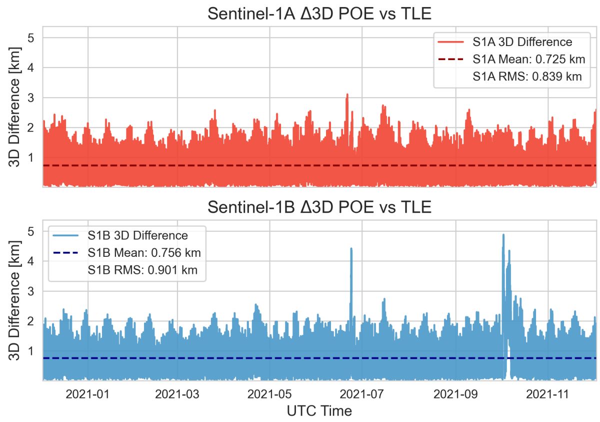

Figure 1. 3D positional difference between TLE and POE data evaluated every 30-seconds for Sentinel-1A and 1B.

which the positioning error of S1B increases to approximately 5 km, a substantial deviation from the norm. This could be indicative of a manoeuvre, an anomaly or a particularly bad or old TLE.

When projecting the error into HCL for S1A (Fig. 2), it is evident that the smallest error arises in the height, ranging from around ± 0.5 km. With the mean height error being 6 m, it is evident that there is little systematic bias in the error. The variations appear fairly uniform without significant trends. In terms of cross-track error, it ranges within ± 0.5 km with slightly higher variations and increasing errors toward the middle of 2021. The along-track component exhibits the largest variation, reaching almost 2.5 km discrepancies in TLE and POE positioning. It is also found to have a systematic positive bias of ~ 0.3 km with more pronounced periodic fluctuations.

Figure 2. HCL differences for Sentinel-1A (Note that the scales on the y-axis are not the same for all plots).

A closer examination of the data over a one-week period (Fig. 3) reveals a pronounced periodicity, suggesting the presence of a systematic error pattern. To further analyse this, the Autocorrelation Function (ACF) of the time series is plotted in Fig. 4.

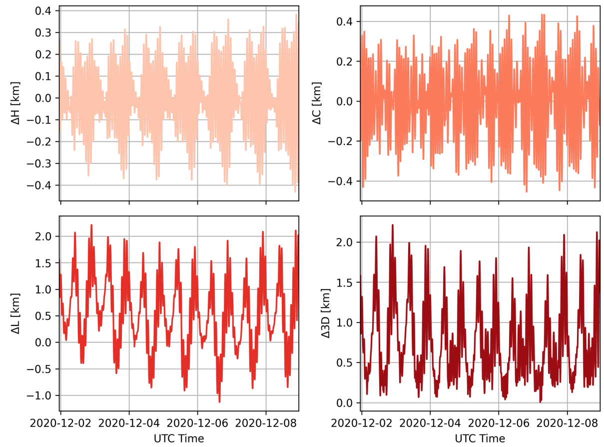

Figure 3. Height-, Cross-, Along-Track and 3-Dimensional Difference in positioning between TLE and POE for Sentinel-1A spanning 1 week.

The ACF is a valuable tool for assessing the correlation of a dataset with its lagged versions, enabling the identification of underlying error patterns and revealing potential periodicities within the data. For S1A the ACF is plotted for a 30-day time lag (Fig. 4) to understand any periodicity or patterns within a month. The data clearly shows that the strongest correlations occur within the first 24 hours and again after 48 hours, with a noticeable decline in correlation thereafter. Increasing again after $\sim$12-days and peaking at around 13 and 26-days, indicates that there is a high correlation of error at an interval of $\sim$13-days.

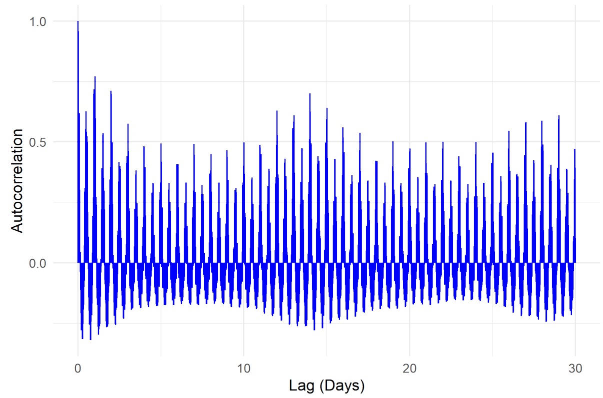

Figure 4. Autocorrelation Function plotted for Sentinel-1A for a time lag maximum of 30 days, with an output interval of 30-seconds.

3.2. Spatial Analysis

When looking at the spatial distribution of Latitude and Longitude position obtained from the POE data and colouring each position by its distance to the TLE position, it is evident that there is an earth-fixed relation to the error distribution. Both S1A (Fig. 5) and S1B (Fig.

6) display large errors in the southern hemisphere particularly around the South American and Australian region.

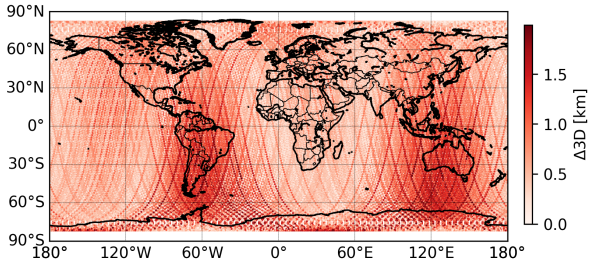

Figure 5. Geographical distribution of 3D differences between NORAD TLEs and POE of Sentinel-1A.

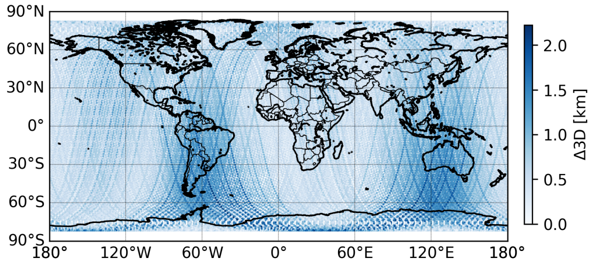

Figure 6. Geographical distribution of 3D differences between NORAD TLEs and POE for Sentinel-1B within 3 Standard deviations of the mean between NORAD TLEs and POE.

3.3. Correction Testing

Method 1: Correction Applied to Sentinel-1B

When applying the correction function (Eq. 3) to S1B (Fig. 7), a $\sim 15.5\%$ reduction in mean error and a $\sim 13\%$ reduction in RMS error is found.

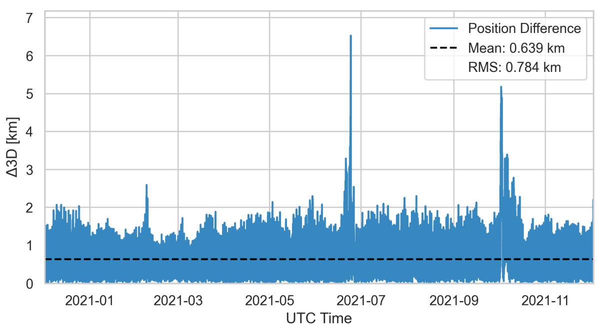

Figure 7. Correction function Application

Method 2: Time Synchronised Correction Applied to Sentinel-1B

When applying the time-synchronised correction function (Eq. 5) to Sentinel-1B (Fig. 8), a $\sim 48\%$ reduction in mean error and a $\sim 39.7\%$ reduction in RMS error is found.

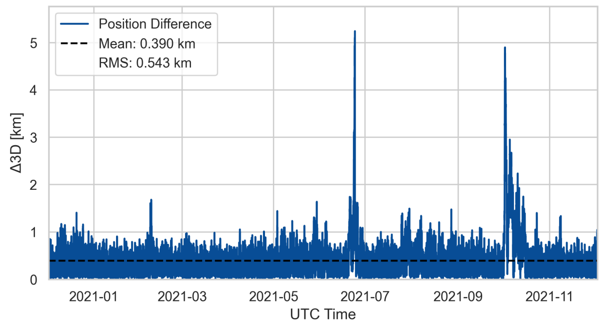

Figure 8. Correction function Application considering time synchronization

4. DISCUSSION

The comparison of POE and TLE data over a 1-year period displays typical errors on the scale of hundreds of metres. When compared to literature, these values are found to be relatively small, whilst many analyses such as [19] and [20] have found kilometre level errors in TLE data. The accuracy requirements of the community are on the scale of hundreds of metres [21], highlighting a critical shortcoming in current operational capabilities.

The systematic nature of the error uncovered in the analyses provides compelling evidence to infer and investigate the potential underlying sources of orbit error. The consistent positive bias observed in the along-track component of Sentinel-1's TLEs, is likely attributable to a mischaracterisation of the spacecraft's ballistic coefficient. Other sources of systematic mismodelling may be related to errors in the generation of initial conditions. In particular, ground based observations tend to carry higher errors in the radial direction, which then propagate into substantial along-track errors [8]. In Low-Earth Orbit (LEO) at 1200 km altitude, a radial error of 1 m in the initial conditions can lead to errors of $\sim$ 7 km after only 24-hours.

Atmospheric drag is the largest source of operational uncertainty in LEO. It's underestimation thus likely significantly contributes to the observed errors - primarily in the along-track direction [22]. The errors (bias and time-varying periodic) are likely attributable to deficiencies in the atmospheric density modelling within the SGP4 model [23]. SGP4 relies on the BSTAR parameter to scale atmospheric drag effects onto an object. The BSTAR coefficient is known to be problematic, as it absorbs all force modelling errors [24]. Moreover, all objects are treated under a simplified "cannonball" approximations of spacecraft geometry, which assumes a uniform, spherical shape [25]. This is a poor representation for a satellite like Sentinel-1, whose large, deployed solar arrays significantly increase its effective cross-sectional area and introduce complex aerodynamic interactions that are poorly modelled by SGP4, leading to systematic errors in the propagated position. This structural mismatch between the real spacecraft and the assumptions of SGP4 likely contributes to the observed bias and periodic errors in the along-track directions.

Given that Sentinel-1 follows a 12-day ground track repeat cycle [15], it is plausible that the observed 12–13 day periodicity in the orbit determination errors is driven by recurrent geometric alignments between the spacecraft and the tracking sensors, causing systematic biases that manifest consistently over each repeat cycle. This hypothesis is further supported by the presence of a spatially structured error pattern that appears to correlate with the satellite's repeat cycle, indicating geographically recurring inaccuracies that could be attributed to the same underperforming sensors. [26] highlights the critical role that sensor calibration plays in orbit determination accuracy, noting that improperly calibrated sensors can significantly degrade prediction quality. [27] demonstrates that different sensor types yield varying levels of accuracy in orbit determination, reinforcing the idea that some sensors may systematically introduce larger errors than others.

Having found systematic errors that point to deficiencies in both the modelling and measurement domain, this case study of the ODC method on the Sentinel satellites shows a promising foundation for the further development of the method. This paper has provided an long term analysis of the errors found in TLE positioning for a satellite pair in SSO which could be useful for operations conducted in this orbital region. The application of the method was able to remove some of the systematic errors found and if a broader analysis of more systems in the region were to be conducted, this could guide operators in potential collision avoidance and general operations.

5. CONCLUSION

The analysis identified systematic spatio-temporal errors in the TLE/SGP4 orbits for Sentinel-1, with mean and RMS errors of approximately 750 m and 870 m (combined for both S1A and S1B) respectively over a year. Notably, a strong periodic signal and positive bias were observed across HCL dimensions, closely correlating with the satellites' 12- to 13-day ground-track repeat period. Large errors clustered particularly around Southern America and Australia, suggesting possible sensor inaccuracies.

The application of the basic correction function obtained from S1A and applied to S1B reduced both mean and RMS errors by about 117 m. The time-synchronized correction method improved accuracy by 366 m and precision by 358 m, demonstrating a nearly 2-fold reduction in positioning error despite the more challenging test case presented by the Sentinel-1 satellites compared to the initial GRACE-FO study.

The success of the ODC method in the challenging SSO region underscores its potential to enhance tracking accuracy in this vital, high-risk orbital region. Continued refinement and application of this method could yield substantial improvements in positioning data, benefiting this and potentially other SSO operations.

5.1. Further Work

This analysis has yielded a variety of opportunities for further work that could benefit the development of the ODC method. Having found a periodic pattern in the data suggests that finding a way to quantify the periodicity and using this to inform the development of a third correction method may reduce the error further.
It also remains to be seen, how the SGP4-XP algorithm performs compared to higher accuracy orbits. As XP-TLEs are currently released on a daily basis by ComSpoc [28], gathering this data for a $\sim$3-month period would enable a broad indication of its performance relative to the basic SGP4 algorithm. It will be useful to define the capabilities of the new model in comparison to higher accuracy data and could guide the further development of the ODC method and its requirement in respect to the new algorithm. Finally, the impact of manoeuvres remains to be analysed further.

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