Limitations of Current Practices in Uncooperative Space Surveillance: Analysis of Mega-Constellation Data Time-Series

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ABSTRACT

In the context of Space Traffic Management (STM) and its crucial reliance on orbit prediction, this study evaluates current practices in uncooperative tracking for Low Earth Orbit (LEO) mega-constellation management. By assessing Two-Line-Element (TLE) data from cooperative and uncooperative tracking of a Starlink constellation subset, we observe a mean 52% increase in positional accuracy with cooperative tracking.

We present a 400-day time-series analysis of TLE data for the Starlink and OneWeb constellations, uncovering significant positional discrepancies and variance between cooperative and uncooperative TLE sets. A Fourier analysis reveals systematic once-per-rev signals.

Examining the TLE generation process, we discuss the influence of measurement quality, force modeling, latency, and location on these discrepancies and their implications for prediction error. We advocate for a universally accepted set of reference orbits across LEO to ensure robust SSA data source characterization amid increasing satellite launches.

The presence of inconsistencies and spatio-temporal variations in the data highlight the need for enhanced transparency and a 3- to 5-fold improvement in TLE data accuracy. This research, aims to bridge the gap between required and supplied accuracy of positional data, and to refine STM strategies and fortify mega-constellation operations safety in LEO.

The facilitating codebase is available in a GitHub repository, encouraging scrutiny and contributions towards improved space situational awareness.

1. INTRODUCTION

With the emergence of mega-constellations, the operation and safeguarding of hundreds or thousands of satellites have become new challenges in Space Situational Awareness (SSA) and Space Traffic Management (STM) [30]. As these large-scale deployments increase the number of objects in Low Earth Orbit (LEO), the probability of collision between resident space objects and operational satellites also increases. Accurate prediction and determination of orbits of uncooperatively tracked objects in LEO are crucial tasks for STM, but current SSA systems fail to meet the communities' requirements in several ways [31]. Therefore, leaders in the field have called for more comparative assessments of SSA systems to identify existing pitfalls [21]. This work aims to provide such an analysis of the positional accuracy of the largest publicly available SSA system to date.

Currently, evaluating the positional accuracy of tracking systems in LEO is challenged by the limited availability of publicly accessible reference objects that can provide a robust positional standard [32]. To ensure safe operations within the newly congested orbital regimes of mega-constellations, the community must achieve a comprehensive understanding of the overall quality (accuracy, precision, timeliness) of different sources of uncooperative tracking data.

The accuracy and precision of the data pertaining to the least-well characterized object in one's orbital neighbourhood is the greatest source of risk. This is why the following work assesses the current state-of-practice- it is the rate-limiting factor to improving operations in LEO.

The TLEs that are disseminated by the 18th Space Control Squadron are the principal SSA ecosystem that is focused on in this report. This is for three main reasons.

1. These data are the most widely accessible and as such can be analyzed. Most other SSA data sources are either difficult (e.g. Vympel) or impossible to access (e.g. EUSST), making any critical assessment impossible.
2. TLEs have been, and still are, the bedrock of many STM products (for better or for worse). Further developing an understanding of the data that goes into these products is critical to better decision making.
3. Largely as a product of the two points above, TLEs tend to be the de-facto source of orbital data for many communities worldwide: cubesat operators, military, commercial satellite constellation operators, astronomers, policy makers, and anyone else that wants to know about the Earth's orbital environment. A critical appraisal of this data source is to the benefit of all.

The following paper first presents the current state-of-research on the accuracy of uncooperatively tracked objects. To put this into context with regards to mega-constellations, we first compare high-precision operator ephemerides against TLE data for a subset of the Starlink constellation over the course of 72 hours. We find that TLE data based on uncooperative tracking data has an average positional difference of 0.89-2.06km relative to operator ephemeris data. TLE data based on cooperative data are around 52% better. This provides an indication of the absolute precision of the TLE data.

We then compare TLE time-series based on cooperative (Operator epehemeris-based) and uncooperative (observation-based) data for 30 satellites of the OneWeb and Starlink constellation over roughly 400 days. The cooperative and uncooperative data were $\sim$ 50% less consistent in absolute positional distance (3D) for Starlink than for OneWeb. The Starlink data was also more noisy, but the OneWeb data exhibited more frequent "very large" discrepancies ($\geq$ 50km). Some of these "very large" discrepancies are launch-specific, whilst others are spacecraft-specific. Across all spacecraft, the largest magnitude direction of discrepancy was the along-track ($\mu \sim -200mto300m$; $\sigma \sim 7000mto20000m$), followed by height ($\mu \sim 10mto20m$, $\sigma \sim 150mto1400m$), and finally the across-track ($\mu \sim 1mto2m$, $\sigma \sim 100to200m$). All three dimensions exhibited a strong once-per-rev signal. Moreover, constellation-specific relations were identified between the height, cross-track and along-track differences and geographical position. The latency of TLE production between constellations and sources was analysed. Ephemeris-based TLEs were found to be produced relatively consistently on the 7-8 hour mark ($\sigma \sim 1.45$hrs for Starlink and $\sigma \sim 3.27$hrs hours for OneWeb), whilst the observation-based TLEs were produced predominantly on an hourly or 8-hourly basis and with more variation ($\sigma \sim 6.93$hrs for Starlink and $\sigma \sim 7.00$hrs). No significant relation was found between TLE latency and positional discrepancy.

The results are then discussed in the context of existing research on the topic and current and future needs in SSA data. It is found that some of the claims made by SSA-data providers are incomplete and could be misleading. It is proposed that the SSA community develops a set of IGS-like reference orbits across LEO. This would provide an external verification of the accuracy of data provided by SSA data providers and encourage transparency in the field. This approach has already proven useful in improving technologies across the spaceflight domain for GPS spacecraft.

Note that the focus of this paper focuses on orbit solutions, and not on the selection or architecture of the hardware used to achieve these.

2. CURRENT PRACTICES IN UNCOOPERATIVE SPACE SURVEILLANCE

2.1 Two Line Elements

Project Space Track was initiated by the US government to develop a fast-updating space monitoring system, utilizing available computing power for large-scale space applications and simulations [16]. The creation of Two-Line Elements (TLEs) and the adoption of the Simplified General Perturbations 4 (SGP4) model facilitated efficient data processing and situational reporting for commercial and scientific spacecraft operators.

The TLE format is described in detail in [40]. In essence, a single TLE indicates -on two 69-character lines, a satellite's identity, it's orbital geometry, a term related to the ballistic coefficient (B-star or $B*$) of the object, and the epoch that this information was generated. This final term is widely understood to be somewhat problematic as the simplified force modeling and the way in which the data is processed means that this term ends up serving as a catch-all term for model errors [40]. More on this later.

Today, TLEs are generated by fitting data to the SGP4 force model from a variety of data sources (e.g. radars, ground optical sensors, in-orbit sensors). All of which fall under the United States Space Surveillance Network (USSSN).

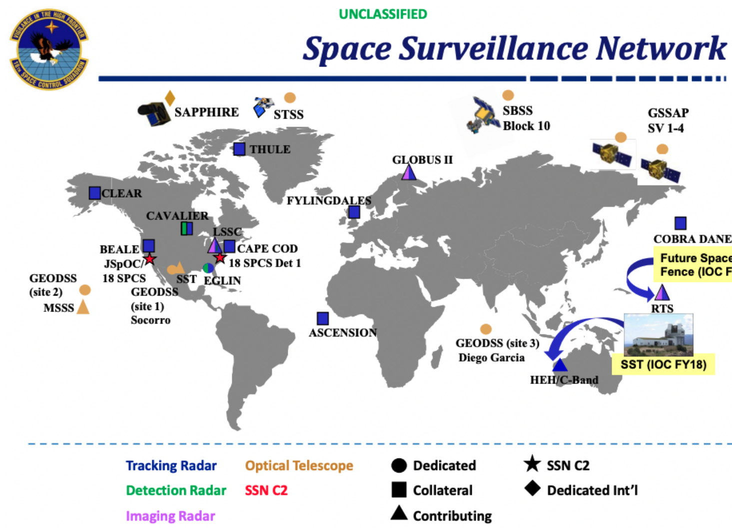

Fig. 1: Space Surveillance Network Overview as of 2018(source:18th Space Control Squadron)

Since March 1998, T.S. Kelso pioneered the dissemination of TLEs through his website Celestrak.org. TLEs are now generated by the 18th Space Control Squadron (18th SpCS) and also shared through their website (space-track.org). Spacetrack serves as the de-facto source of information for many spacecraft operators.

2.2 Operator TLEs

As of late 2021, Celestrak has also been sharing Operator TLEs for certain spacecraft. Operator TLEs (also referred to as Supplemental TLEs or SupTLEs) are TLEs that are "derived directly from owner/operator-supplied orbital data" instead of 18th SPCS measurements [20]. Celestrak uses the operator provided data to fit the SGP4 orbital model (as described in[23]) in Systems Tool Kit (STK) to generate TLEs [22].

SupTLEs are of value as the operator-supplied orbital data provided to generate them are typically derived from on-board Global Navigation Satellite System (GNSS) receivers [37], or operator ephemerides [18]- both of which are likely to be orders of magnitude more accurate than uncooperative data.

2.3 Limitations of TLE format

The usefulness of TLEs as a source of information is constrained by a number of factors:

- The fitting of parameters within the TLE to the SGP4 force model means TLEs perform badly in any other propagator [22]
- As NORAD TLEs are mean values obtained via batch-least squares [40], reconstructing variations requires classified information unavailable to the public [18].
- TLEs do not include any covariance data, meaning that characterizing the quality of a given TLE in a manner that is meaningful to spacecraft operators presents a significant challenge as covariances provide estimates of uncertainty inherent in these data.

2.4 Positioning requirements for STM

The limitations of the TLE format and the lack of transparency regarding the measurement and generation process of TLEs are crucial considerations for space traffic management. The precise positioning of uncooperative assets is essential for ensuring the safety and sustainability of the space environment. As stated by [32], SSA data must not only meet, but greatly exceed the operators' probability of collision threshold. Typically, acceptable positional error thresholds for LEO objects (assuming a probability of collision threshold of 0.01%) are on the order of 100-200 meters [6, 32].

2.4.1 Validation Using Geodetic spheres

Some SSA systems claim to be capable of producing ephemerides with covariances of a few hundred meters both for cooperatively ([2]) and uncooperatively ([30] and [8]) tracked assets. These statements should be interpreted with care. For example in [30], an orbit determination error of a few hundred meters is found when validating against International Laser Ranging Service truth ephemeris for the Stella Geodetic Reference Sphere. There are known issues with using geodetic reference spheres to validate OD solutions. Geodetic spheres, by virtue of being spheres, perform uncharacteristically well in simplistic force models (i.e. SGP4). This is because these force models assume the spacecraft to be a sphere when computing non-conservative forces (e.g. Solar Radiation Pressure (SRP), Aerodynamic Drag)- so any error that stems from mismodelling geometry and attitude are “hidden”. Moreover geodetic spheres have small area-to-mass ratios. This attenuates the errors associated with the calculation of non-conservative forces such as solar radiation pressure and aerodynamic drag. However, mismodelling of spacecraft geometry and attitude constitutes some of the largest sources of error in computing non-conservative forces [41]. Therefore, accuracy and precision achieved using these spheres as calibration tools should be treated as lower-bound/best case scenario in the validation of orbits. Spacecraft with differing geometries, attitudes and orbital geometries will likely perform worse. Nonetheless, geodetic spheres provide us with a sense of what is possible in terms of uncooperative tracking.

2.4.2 The impact of positional error

Let us consider an example to understand the impact of positional error on spacecraft orbits: A spacecraft operator assumes their spacecraft is at 1200 km altitude and calculates the gravitational acceleration (g_h) using Equation 1, with h as altitude, g_0 as standard gravitational acceleration, and R_e as Earth’s mean radius.

If the spacecraft is actually 1 meter higher, the new gravitational acceleration ($g_{1200+1m}$) is calculated using Equation 3. The difference in acceleration (Δa) is found using Equation 4. To calculate the overall distance between both states after 24 hours, Equation 5 is used, resulting in a significant distance of 6718.464 m.

This example highlights that small errors in initial conditions lead to disproportionate errors in position over time. This effect is increasingly pronounced with decreasing altitude due to the growing strength of the monopole gravity term [29].

$$g_h = g_0 (\frac{R_e}{R_e + h})^2 \tag{1}$$

$$g_{1200Km} = 9.80665(\frac{6371}{6371 + 1200})^2 = 6.9443147 m/s^2 \tag{2}$$

$$g_{1200+1m} = 9.80665(\frac{6371}{6371 + 1200.001})^2 = 6.9443129 m/s^2 \tag{3}$$

$$\Delta a = 6.9443129 - 6.9443147 = 1.8 \times 10^{-6} \tag{4}$$

$$\frac{1}{2} at^2 = \frac{1}{2} \times 1.8 \times 10^{-6} \times 86400^2 = 6718.464 m \tag{5}$$

2.5 The role of TLEs in STM

2.5.1 Applications of TLEs to space traffic management

Various STM systems exist and many of them use TLEs in the development of their orbital safety products. A few examples of SSA product/service providers are: 18th SpCS, European Space Surveillance and Tracking (EUSST), The Space Data Association, AGI Commercial Space Operations Center (ComSpOC), JSC Vimpel Data Portal, and LeoLabs.

The largest and most readily available source of SSA data to date has been the space-track catalogue maintained by 18th SpCS at Vandenberg Air Force Base. For this reason it will be the sole focus of this report.

2.5.2 Orbit Determination and Collision Assessment

The 18th SpCS of the United States Space Surveillance Network (USSSN) is responsible for the analysis of observations from across the USSSN, and the generation of Conjunction Data Messages (CDMs) to assess the risk of collision between space objects. In this section, we describe the general modus operandi of 18th SpCS in terms of orbit determination and collision assessment.

The 18th SpCS utilizes batch least-squares orbit determination to fit Two-Line Elements (TLEs) and Special Perturbations (SP) orbits to observations from across the USSSN. TLEs are freely available to all without precondition [1], whilst SP orbits require SSA sharing agreements.

The 18th SpCS scans every orbit in their catalog against every other orbit to assess the likelihood of collision. For Near-Earth Orbits (NEOs), if the following criteria are met between two objects, a CDM is issued to spacecraft operators [42]: Time of closest approach $\leq$ 3 Days, Overall miss distance $\leq$ 1 Km, Probability of collision $\geq$ 0.01

The calculation of the probability of collision is described in detail in the 18th SpCS's Spaceflight Safety Handbook for Satellite Operators [1].

As of 2021, 18th SpCS reported generating of over 200000 CDMs per day. Of these, 180000 involve Starlink [14]. Of those, a "large majority" are accounting for close approaches between Starlinks. Most of these are attributed to the fact that the state vectors (in the "High-Accuracy Catalog") used in the screening process do not contain thrusting information [14]- however Starlink satellites are thrusting on a near continuous basis.

2.5.3 Challenges in the Current Space Situational Awareness Ecosystem

Challenges faced by the TLE ecosystem include the inflexibility of TLE data in incorporating new information, limited accuracy of force models, a high number of CDMs, and prerequisites to access high-fidelity data. These issues contribute to a lack of trust in SSA products among operators [31] and create a barrier to entry for actors in the space industry. This work aims to investigate the quality of the largest and most readily available source of orbit data- TLEs, with a specific focus on the emerging threat posed by mega-constellations.

3. BACKGROUND AND MOTIVATION: MEGA-CONSTELLATION DATA ANALYSIS

3.1 TLE Quality Evaluation

TLEs are the most prevalent format for satellite orbital information dissemination at present. The underlying SGP4 force model is capable of kilometer-level accuracy after 1 day with high-quality data [15]. It often underperforms due to poor underlying data quality [33]. Characterizing TLE behavior and limitations is crucial, as they currently inform mission-critical decisions in space traffic management (STM)[14].

At the time of writing, the 18th SpCS provides on-orbit collision avoidance (CA), TLE data, and decay and reentry prediction services without pre-condition. However, general perturbations (GP) force model-based orbital products lack the required accuracy for use in STM [28]. Higher fidelity services, such as anomaly resolution or special perturbations (SP) data, require SSA data sharing agreements (SA). Operators unwilling to agree to an SA face increased risk due to inferior data. This study addresses the broader SSA community's needs by quantifying the most accessible data type's accuracy: GP data.

Previous research in the area of TLE quality focused on improving TLE generation [13] or comparing orbit propagators [33]. However, TLE quality assessment for mega-constellations is limited. [18] offers insight into TLE production for various mega-constellations but lacks positional accuracy evaluation. Few studies (*e.g.* [10]) have rigorously assessed TLE quality against robust data sources across a number of resident space objects ($\geq$10).

Table 1 summarizes key literature studies that characterize or validate TLE accuracy, or focus on mega-constellation-specific TLEs.

Given the growing significance of LEO mega-constellations and limited characterization of orbital data pertaining to these, this study aims to evaluate TLE positional accuracy for the current two largest mega-constellations and to identify potential error sources.

Author(s)	Year	Area Studied	Relevant Findings
Johnson[18]	2022	∼1.8M TLEs All orbital regimes covered Spacecraft/orbit type on TLE generation cadence Tracking station performance Operational cadence Tracking constraints In-depth analysis of OneWeb, Starlink and Planet	Generally: TLEs are generated on the hour, or time of last observation. For Starlink and OneWeb: TLEs generated at the integer hour This is strategy is attributed to constant low-thrust Suspected these are TLEs are fit to operator ephemeris
Frueh and Schildnecht[10]	2012	Geostationary and High-eccentricity orbits benchmarking against high-precision optical measurements	GEO average errors: Along-track ∼25km Cross-track 10km Height N/A HEO average errors: Along-track ∼35km Cross-track 25km Height N/A Orbit propagator selection is not significant for GEO orbits. SDP8 slightly better for HEO objects (vs SDP4)
Flohrer et al.[9]	2008	Analysis of covariances between TLE data and orbits based on pseudo-observation derived from TLEs orbits. Analysis over entire TLE catalog (11286 objects) at a reference epoch. Main focus on uncertainty	Systematic relation found between eccentricity and uncertainty. Out of plane effects are stronger in medium inclination orbits. Standard deviations up to 5km in the along-track. Studied across LEO, MEO, GEO, GTO, HEO
Racelis and Joerger [36]	2018	Benchmarking of ∼150,000 MEO and ∼6000 GEO TLEs for ∼30 satellites over 2-20 years	MEO errors are larger in the along-track than radial or cross-track. At GEO along-track and cross-track are similar. Errors are not all normally distributed (e.g. GPS radial)
Aida and Krischner [5]	2011	TLE data benchmarked against POD solutions for 3 LEO satellites : CHAMP, GRACE, TerraSAR-X (460-510km alt. range) Solutions assessed 1/4/7 days after propagation TLE error found to be correlated to high atmospheric density and high solar flux	After 1 day: Height error ∼10m Cross-track error ∼1m Along-track error ∼500m
Aida and Krischner [4]	2013	Benchmarking of GRACE-1 (450km alt.) POD data against TLE data ∼1 month period	After 1 day: Height error ∼32m Cross-track error ∼3m Along-track error ∼4984m
Riesing et al. [38]	2013	Benchmarking of TLE data against two-way ranging on a Flock1B	Median error of 4.52Km. 1-sigma propagation error growing by 10-30Km after 24hrs.
Kelso [22]	2007	Benchmarking of TLE data against GPS Precision orbits	3D error mean for 31 GPS satellites: After 1 day (TLE vs POD): 7.54 km After 1 day (SupGP vs POD): 0.87 km 3D error mean for 14 GLONASS satellites: After 1 day (TLE vs POD): 9.39 km After 1 day (SupGP vs POD): 0.2 km
Oltrogge and Ramrath [33]	2014	Parametric analysis of SGP4 accuracy	SGP4 fit is capable of >1km accuracy over many orbit altitude ranges (∼LEO to GEO). Conclude that this is not typically achieved due to the error in non-cooperative tracking systems.
Hirose et al. [15]	2010	Comparison of TLE data to high-precision operator data for LEO satellites: ALOS and ASTRO-F (692-750km alt. range) Removal of "bad" TLEs from dataset a-priori (method explained)	Average distance of 2 km between TLE and Operator Data.
Xu and Xiong [43]	2018	Comparing TLE data to GPS precision ephemerides of CHAMP from 2002-2008	TLE data are systematically biased by multiple kilometers. This is attributed to mismodelling of forces by SGP4. The sign and magnitude of these errors are correlated to longitude.

Table 1: Summary of Crucial Findings from Select TLE Quality Benchmarking Literature

3.2 Leveraging Mega-Constellation Data

Mega-constellations provide a unique opportunity to study orbital products at a high granularity by deploying a vast network of spacecraft across a broad geographical area that share similar altitudes and inclinations. This study capitalizes on this phenomenon to investigate the quality of SSA data within these valuable regions of space.

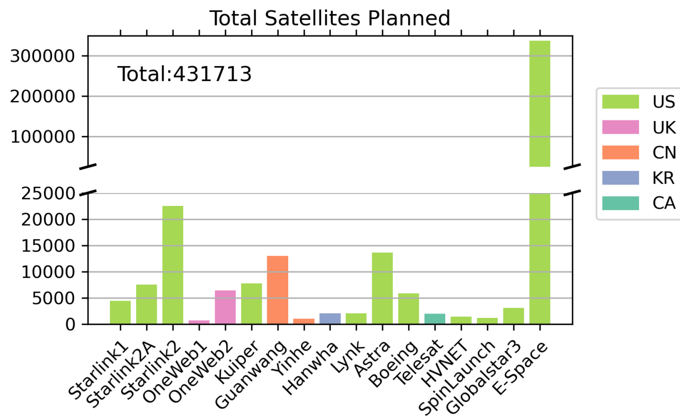

Fig. 2: Bar chart of planned mega-constellation satellites. Data from Jonathan's Space Report [27]. Bar colour represents launch country (US=United States of America, UK=United Kingdom, CN=China, KR=Korea, CA=Canada)

Mega-constellations, comprising over 1,000 satellites [27], are rapidly expanding in LEO. With 431,713 planned and 4,129 currently launched satellites (as of December 2022), the need for accurate and reliable data for space traffic management and conjunction analysis is increasingly felt [27].

Despite only Starlink and OneWeb having thus far exhibited a substantial capacity for satellite deployment, Figure 2 underscores a robust international ambition for orbital launches. This global aspiration, underscores the rapid evolution in the field of space exploration. Transformations in mission prerequisites are catalyzing a paradigm shift in spacecraft operations, necessitating enhanced understanding of asset dynamics [39].

4. METHOD

4.1 Data collection

30 Oneweb and 30 Starlink satellites were selected for this study. Table 4.1 shows the number of TLEs from each source for each constellation. A total of 165347 TLEs were analyzed.

Constellation	Type of TLE	No of TLEs
OneWeb	NORAD	50674
OneWeb	Supplemental	46921
Starlink	NORAD	40489
Starlink	Supplemental	27263

Table 2: Number of TLEs for each constellation from each source

Selection criteria:

- 3 launches per constellation to reveal launch-specific effects.
- Similar time periods for both constellations for comparable environmental conditions.
- 10 spacecraft per launch to identify outliers and launch-specific effects.
- Spacecraft within +/-20 Km of nominal orbits and an SMA-rate below 2Km/Day to ensure no spacecraft that were consistently orbit raising were selected [27, 18].

Satellites were selected randomly within these parameters.

Collected Data:

- Starlink Launch 28, 30, and 37
  - NORAD IDs:
    - 48042–48051
    - 47258,47260,47264,47266,47269,47273,47277,47279, 47280,47288
    - 48210–48219
- Oneweb Launch 4, 5, and 6:
  - NORAD IDs:
    - 48638–48647
    - 50803–50812
    - 48430–48439

Figures 3 and 4 show altitude time series and ground tracks of the selected sub-constellations, respectively. Operator

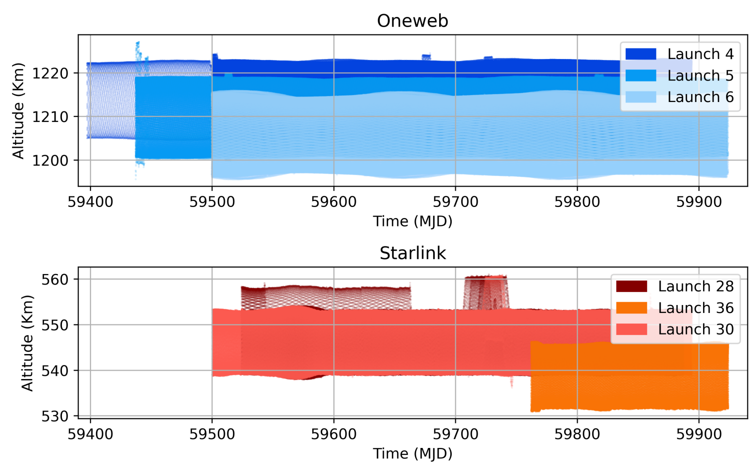

Fig. 3: Altitude time series of the selected satellites. Coloured by launch number. Individual satellites are not coloured differently within launches as this makes the plot more difficult to read.

TLEs were obtained from Celestrak's SupTLE/SupGP database [20] and corresponding TLEs from space-track's API. Note that whilst it is not uncommon for TLEs to occasionally be discarded as they are considered ”bad”, all collected TLEs were used in this study to generate a representative characterization of the data at hand.

4.2 NORAD TLEs vs. Sup TLEs

The aim of this study is to characterize the orbit solutions associated with different TLE products.

- NORAD TLEs: which are the TLEs released by 18th SpCS on space-track.org. These are based on uncooperative tracking data
- SupTLEs: Also known as supplemental TLEs, these are TLEs that are fit to cooperatively generated data. These are released on celestrak.org

Over the selected time period of around 400 days, each object is assigned two state vectors (the NORAD TLE state vector and the SupTLE state vector). The state vectors were computed and stored in ephemerides for 00, 15, 30, and 45 minutes past the integer Coordinated Universal Time (UTC) hour. State vectors were calculated using the newest available TLE at any given time-step.

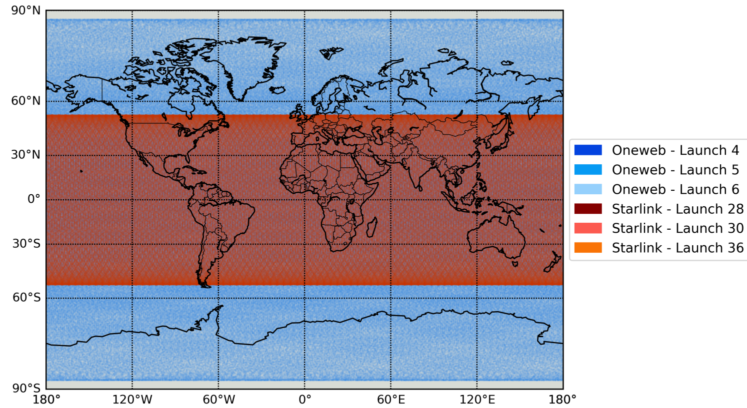

Fig. 4: Ground track plots of both constellations (Miller cylindrical projection), colour coded by launch number.

4.3 Assessment Metrics

The facilitate the characterization and comparison of orbit solutions from the two TLE sources, the following metrics were computed for each orbit:

- The three-dimensional Cartesian, height, cross-track, and along-track (HCL) discrepancies between each pair of state vectors were calculated using the methodology detailed in [7].
- Latitude and longitude at each time step.
- Power Spectral Density/Frequency was computed over the entire time series for each vector.
- The ”age” of each orbit, represented by the time since the most recent TLE update to the state vector, was determined at each time step.
- The argument of latitude at which each new TLE was originated was also calculated.

4.4 Benchmarking the TLEs: NORAD TLEs, SupTLEs, and Operator Ephemerides

As a preamble, the orbit solutions from the NORAD TLEs and SupTLEs were first compared with precision operator ephemeris, thereby facilitating a tripartite comparison. In this context, the NORAD and SupTLEs were propagated to align with the timestamps of the operator ephemeris data, as opposed to the previous 15-minute intervals. It is important to note that the operator ephemeris data is expressed in the Mean Equator Mean Equinox (MEME) inertial reference frame. This is in contrast to the SGP4 data, which is in the True Equator Mean Equinox (TEME) reference frame. A conversion is required here.

5. RESULTS

5.1 Benchmarking

The aim of this first section is to benchmark NORAD TLE and SupTLE data against higher-accuracy data. Operator ephemeris data (found at `https://www.space-track.org/#publicFiles`) is generated through an orbit determination process applied to data received from GNSS data. As such, we can at least expect accuracy on the 10-100m level [2]. In comparison, uncooperative data is typically 1-2 orders of magnitude less accurate [8]. As such it was deemed sufficient in the context of benchmarking the two sources of TLE data relative to one another. OneWeb does not currently share operator ephemeris data. As such the analysis is restricted to Starlink spacecraft.

In all spacecraft the along-track contains the most error, then the height and then the cross-track. On average, the error of the NORAD TLEs solution is around 52% larger than the SupTLE orbit solution, relative to the operator ephemeris. It is suspected that the data in the final third of the plot coincides with an maneuvering phase for all three satellites.

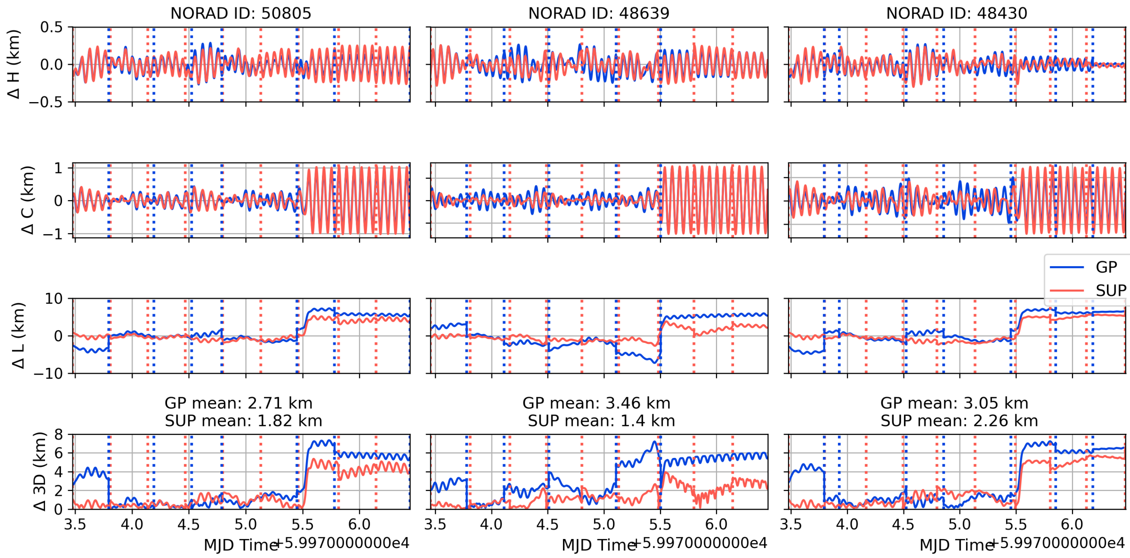

Fig. 5: Time series of height, cross-track, along-track and Cartesian (3D) differences between the operator provided positions and the NORAD TLE (Blue) and SupTLE (Red) SGP4 orbits, and operator ephemerides for one satellite from each Starlink launch studied. A vertical line represents the time at which a TLE is used to update the SGP4 orbit of the same colour. Note that the y-axis of the plots are 0-centred except for the bottom plot.

Finally, it is interesting to note that both the SupTLE and NORAD TLE data orbits share similar periodic errors- especially in the height and cross track errors. In the along-track direction, there is also some resemblance in the periodicity of the error, however NORAD TLEs suffer from stronger bias each time a new TLE is added.

5.2 Constellation specific position differences

5.2.1 Time Series

In this section, we present a comparison of longer time-series of position differences between only NORAD TLE and SupTLE for the two mega-constellations, Starlink and Oneweb. Figure 6 illustrates the 3D (Cartesian) difference between each position reading for each spacecraft in a given constellation. The data displays a small consistent background error that varies in the 0-20Km range, overlain by larger, more infrequent spikes that rise up in excess of 100Km. The periodic background error is more pronounced in the case of the Starlink satellites.

We provide key statistics for all dimensions in Figure 7. These statistics reveal that average height differences are on the scale of tens of meters, average cross-track differences are on the scale of meters, and average along-track differences are on the scale of hundreds of meters. All of these statistics exhibit a variance that is roughly 1-2 orders of magnitude above the mean.

5.2.2 Histogram

The distribution of the data is further described in Figure 8.

Although the distribution of data is similar in both cases, Starlink mean positional error is higher by $\sim 50\%$. In addition it is more noisy as highlighted by the higher variance.

- Across all plots, the Starlink data follows a wider, more noisy distribution
- The ΔL for Starlink is positively biased, whereas Oneweb is negatively biased. For Oneweb the distribution is not Gaussian. It follows a near-symmetrical bimodal distribution.
- The ΔC for Starlink also seems to follow somewhat bi-modal distribution, although less pronounced than the one seen in the ΔL for OneWeb.

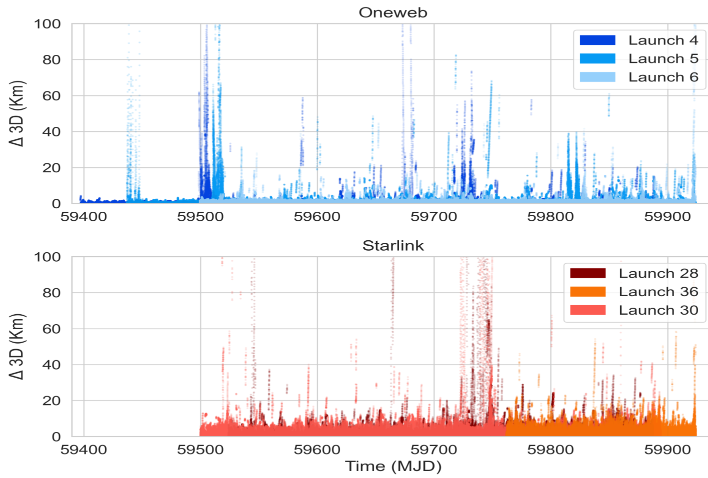

Fig. 6: Time series of 3D differences between the NORAD and SupTLE-based SGP4 orbits for all the satellites in each constellation. Each satellite is coloured by the launch number it belongs to. 30 satellites per plot.

		ΔH				ΔC				ΔL				Δ3D			
Operator	launch No	μ	σ	min	max	μ	σ	min	max	μ	σ	min	max	μ	σ	min	max
OneWeb	All	0.02	1.32	-4.65	173.50	0.00	0.12	-6.23	6.23	0.17	17.36	-1468.44	1584.91	1.65	17.34	0.00	1594.38
	4	0.02	0.52	-2.69	142.43	0.00	0.09	-1.32	1.32	-0.26	9.53	-1468.44	171.35	1.58	9.33	0.00	1475.33
	5	0.03	0.69	-4.65	173.50	0.00	0.14	-6.23	6.23	0.48	12.06	-276.52	1584.91	1.88	11.88	0.00	1594.38
	6	0.01	0.20	-4.52	33.05	0.00	0.10	-1.20	1.21	0.21	5.57	-144.88	681.91	1.44	5.23	0.00	682.64
Starlink	All	0.02	0.72	-9.25	142.51	0.00	0.19	-14.62	14.53	0.35	13.47	-1421.13	608.85	2.72	13.21	0.00	1428.26
	28	0.01	0.15	-6.30	7.63	0.00	0.18	-14.62	14.53	0.29	7.35	-374.92	352.16	2.33	6.86	0.00	374.95
	30	0.04	0.59	-9.25	142.51	0.00	0.15	-1.65	1.67	0.42	13.00	-1421.13	608.85	3.09	12.42	0.00	1428.26
	36	0.01	0.15	-3.19	3.15	0.00	0.16	-1.93	1.91	0.32	4.17	-54.25	93.18	2.69	3.21	0.01	93.19

Fig. 7: Summary of the results including the height, cross-track and along-track positional differences. All results expressed in Kilometers.RMS is not included to reduce clutter- as most of the means are near-zero the RMS is very close to the mean in all cases. Green = mean, Yellow = variance, Blue = min, Red = Max. Colour strength varies as a function of relative magnitude (more positive = darker).

5.3 Fourier Decomposition of the Time Series

Following visual inspection of the time series of each spacecraft (full set of plots available in the code repository), a Fourier analysis was undertaken to ascertain whether any periodicity was present in the data (one of these is displayed in figure 9. Others were omitted for brevity but are available in the code repository). A repeat period of 15/day and 13/day was found in the data (ΔH, ΔC, ΔL, $\Delta 3D$ time series) of all spacecraft in the OneWeb and Starlink constellations respectively. Both signals are of a similar magnitude (peak at circa 60 dB).

The 13 and 15 per-day frequencies match the orbital repeat period of the satellites in each case. Respectively, these translate to periods of 96.4 minutes for the OneWeb satellites and 109.7 minutes for the Starlink satellites. This lines up near-perfectly with the mean orbital period of the studied satellites which were are follows:

- OneWeb satellites: 109.7 minutes (σ 0.07min)
- Starlink satellites: 95.5 minutes (σ 0.07min)

5.4 Geographical Dependence of Error

The discovery of a circadian rhythm within the error profiles, as detailed in Section 5.3, prompted the exploration of potential links between geographical location of satellites and corresponding error magnitudes. This section elucidates the geographical influence on the observed errors by plotting orbit solution error values on a map (figures 11 and 10).

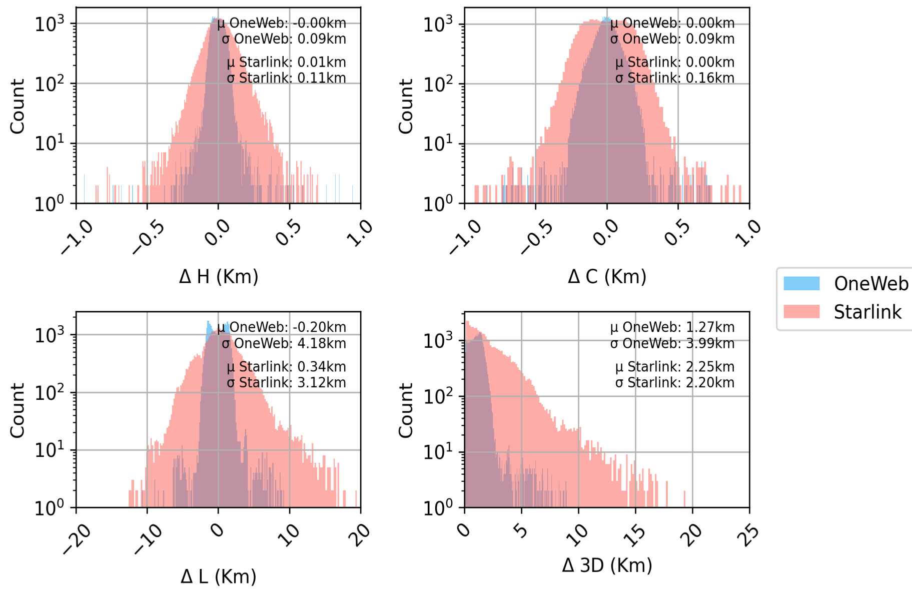

Fig. 8: Distribution of Height, Cross-track, Along-track and Cartesian (3D) position difference for all the satellites in each constellation. Note the y-axis is log-scaled to ease viewing of the bins with fewer values. Figure7 summarizes the mean and standard deviations of the plots above.

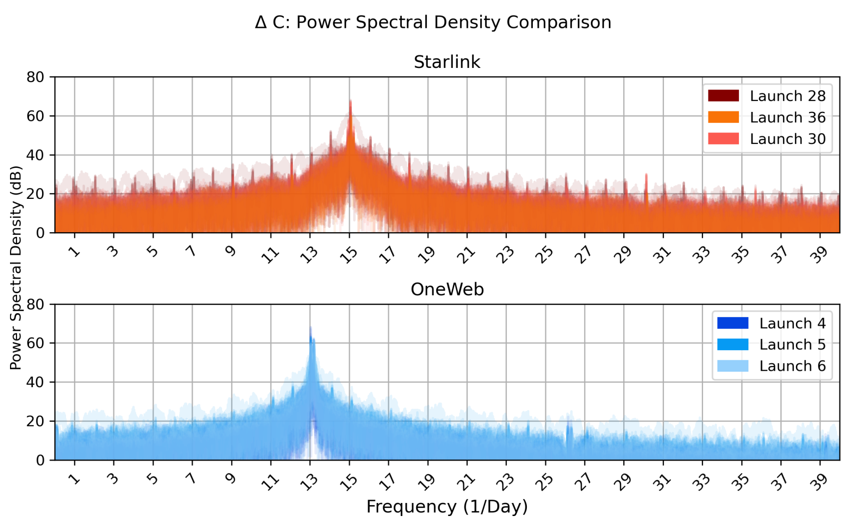

Fig. 9: Power spectral density of the cross-track difference time series for all the Starlink and Oneweb satellites. Each satellite is plotted as a translucent line. The full set of plots is available in the accompanying Github repository.

As outlined in Section 5.2.1, positional errors in the dataset mainly consisted of small periodic variations, punctuated by intermittent, substantial spikes. Observations concerning errors within one standard deviation of the mean for each position component are highlighted below:

Along-Track Error (ΔL): Analysis revealed no significant geographical correlation for the Starlink constellation. Conversely, the OneWeb constellation demonstrated a conspicuous longitude dependence, with 13 distinct "lanes" where along-track position was either over or under predicted. Interestingly, these lanes are reminiscent of the sectoral components observed in a spherical harmonic expansion of the gravity field.

Height Error (ΔH): A noisy North-South divide was discerned for all Starlink satellites. A systematic underestimation of the height in the southern hemisphere and overestimation in the northern hemisphere was noted. The OneWeb constellation exhibited a clearer structure with the presence of 13 longitudinal lanes, though these appeared overlaid by a latitude-dependent underestimation.

Cross-Track Error (ΔC): Despite representing the smallest mean error direction, this component displayed a distinct structure for both constellations. For Starlink, there was an overall overestimation in the northern hemisphere and underestimation in the southern hemisphere. For OneWeb, longitudinal "lanes" emerged, corresponding to bands of Right Ascension of the Ascending Node, wherein the error was either over or under predicted.

No discernible correlation was found when analyzing errors that exceeded two standard deviations from the mean.

5.5 TLE Production Practices

One hypothesis for the large spikes observed in figure 6 is that these are due to so-called "stale TLEs"- TLEs which have passed the date beyond which they are fit for use [8]. In addition to this, the location of the spacecraft at which the TLEs were produced was also studied in an effort to understand the factors influencing the heterogeneity of the data quality.

5.5.1 TLE latency

Our investigation into TLE latencies and locations aimed to ascertain whether the age or position of a TLE could predict degradation of the position solution. No discernible correlation was found between the either variable and the positional error associated with it. However, the distribution of TLE latency and argument of latitude presented noteworthy patterns (figures 12 and 13).

Whilst a decade ago [19] reported an average TLE update latency of 5 days for LEO objects, our findings corroborated those of [18], who noted that for the Starlink and OneWeb constellations, TLE generation predominantly took place at integer hours and ascending nodes.

5.5.2 TLE Location

Again, following on from the work of [18], the argument of latitude of each TLE was recorded and separated on a per-constellation basis.

In terms of the argument of latitude, about 75% of all NORAD TLEs were epoched at the ascending node (i.e. $0°$) for both constellations. This broadly agrees with observations recorded by [18]. In addition, we found noticeable differences in the SupTLE location across the two constellations. For OneWeb, SupTLEs were largely constrained to the first half of the orbit (between $20°$ and $130°$), whereas for Starlink, SupTLEs were more randomly distributed (from $0°$ - $360°$).

6. DISCUSSION

6.1 Operator ephemeris benchmarking

The following section discusses the findings outlined in section 5.1.

6.1.1 Comparison to values in the literature

In line with existing literature, discrepancies found between NORAD TLEs, Supplemental TLEs, and Operator ephemerides are generally consistent. The discrepancies in height, cross-track, and along-track positions share magnitudes similar to those documented by [3] and [43]. The 3D position differences between NORAD TLEs, SupTLEs, and high-precision ephemerides align with the magnitude of differences noted by [22]. However, it is worth noting that these discrepancies are less pronounced in this study compared to those of [22], who reported a mean RMS of 7.51km after 24 hours for the NORAD TLEs, and 0.87km for the SupTLEs across 31 GPS satellites. While [22] observed

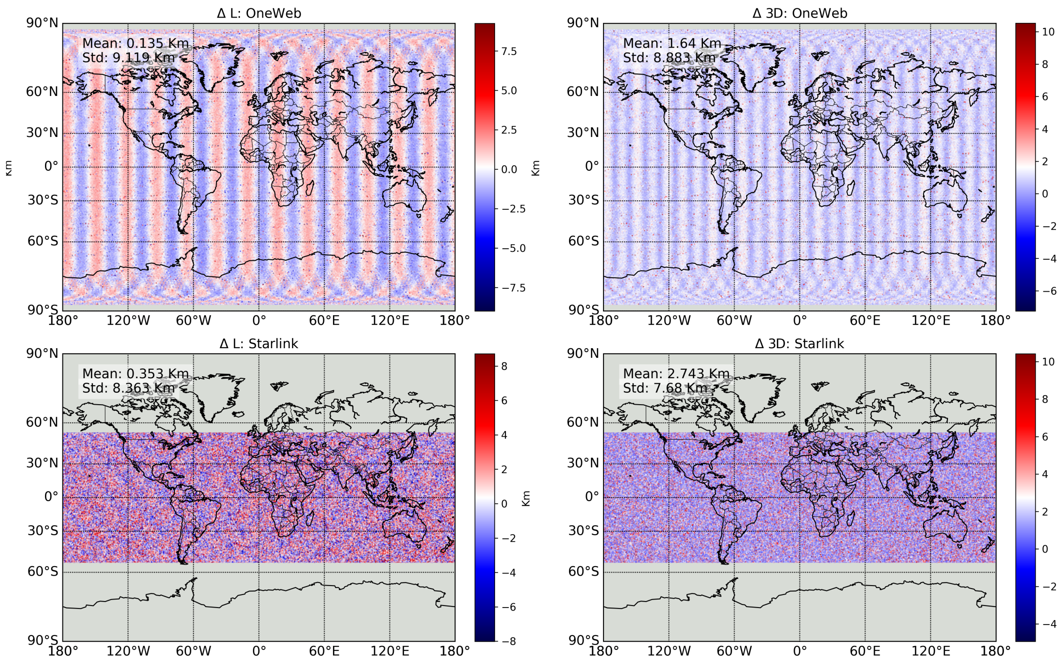

Fig. 10: Geographical distribution of the along-track and 3D differences within one standard deviation of the mean between the NORAD and SupTLEs for all Starlink and OneWeb satellites studied.

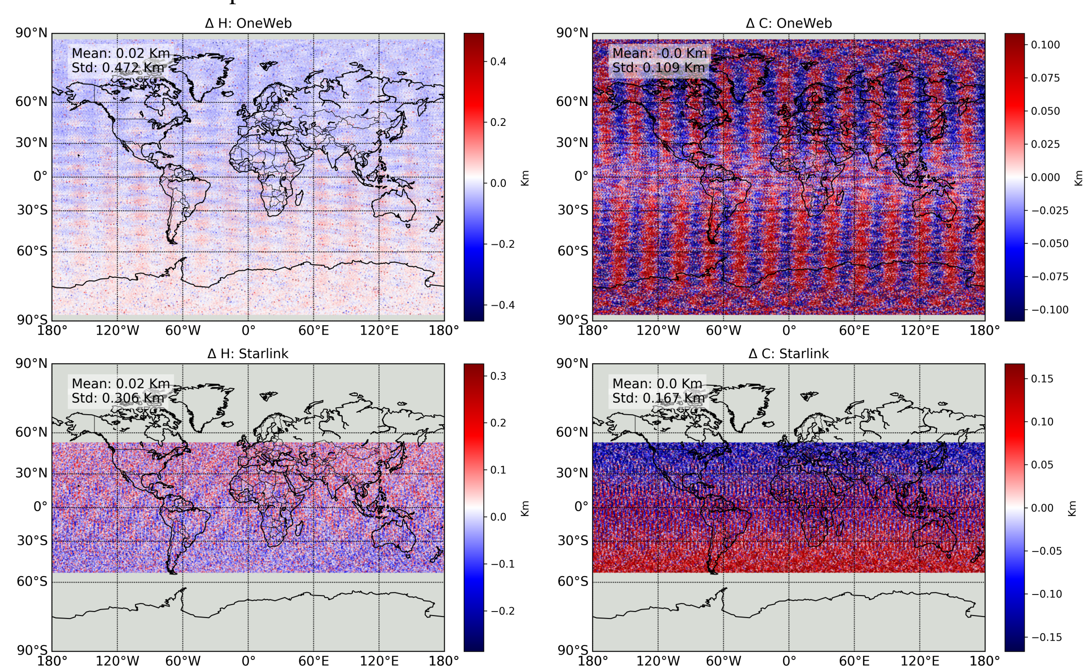

Fig. 11: Geographical distribution of the height and cross-track differences within one standard deviation of the mean between the NORAD and SupTLEs for all Starlink and OneWeb satellites studied.

almost a ten-fold difference between the two data sources, this study finds a much smaller discrepancy, around one fifth that value ($\sim 52\%$).

The role of the B-Star term as a catch-all term for errors in the modelling process has implications for the transferability of [22]'s statistics at LEO altitudes. At the altitudes encountered by GPS satellites (20000km), the impact

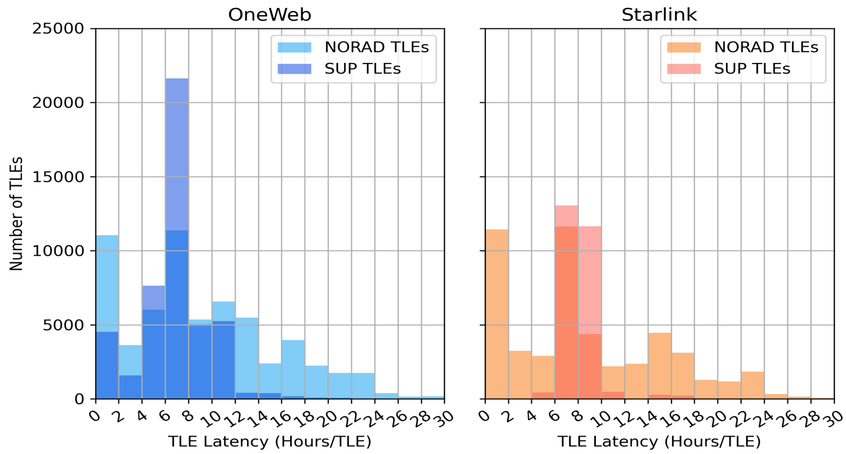

Fig. 12: Histograms of the rate at which both NORAD and Supplemental (operator) TLEs are updated for each constellation. The mean and standard deviation of each plot is displayed alongside it.

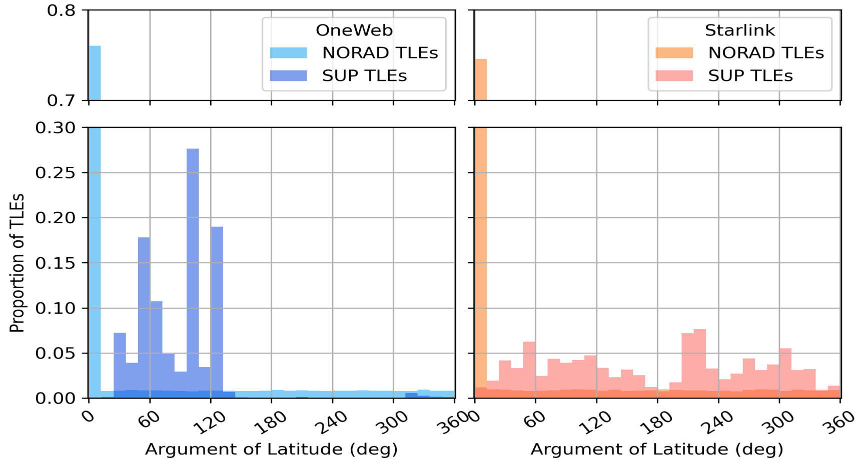

Fig. 13: Histograms of the argument of latitude at which both NORAD and SupTLEs are produced for each constellation.

of aerodynamic drag, and thus any associated modelling inaccuracies that might be reflected in the B-Star term, is significantly minimized.

At LEO, aerodynamic drag is the second strongest forcing mechanism after the monopole gravity term [29]. Given its strength and stochastic nature, inaccuracies in drag modelling are poorly absorbed by the B-Star term, consequently degrading orbit prediction quality relative to higher altitudes.

The SGP4 model, which utilizes the B-Star term, was developed during a time when LEO operations were less common. The model was primarily designed with a focus on military and communication satellites that predominantly orbit at higher altitudes where aerodynamic drag is less significant. Consequently, the SGP4 model, and by extension the B-Star term, are not ideally suited for accurately capturing the intricacies of aerodynamic forces at LEO.

6.1.2 Analysis

A detailed examination of Figure 5 presents three notable conclusions:

- The mutual periodicity observed in positional error, found in both the ΔH and ΔC directions, suggests a shared catalyst for this pattern in the data. The SGP4 propagator emerges as the probable culprit.

- The $\Delta 3D$ and ΔL subplots reveal a significant source of error in the NORAD TLE solution, particularly evident when a fresh TLE is used to update the solution. This pattern is less conspicuous with SupTLEs, which supports the hypothesis that measurement inaccuracies in initial conditions play a role in the inferior performance of NORAD TLEs compared to SupTLEs [33].
- All plots unveil a discernible alteration in the final third of the temporal series, coinciding with a suspected orbit-raising phase (ascertained via altitude data examination). The sudden degradation predominantly manifests in the along-track direction, further underscoring the inadequacy of TLEs as tracking tools for modern spacecraft that frequently engage in thrusting maneuvers multiple times per day.

The SupTLEs demonstrate a $\sim 52\%$ improvement in accuracy over the NORAD TLEs when juxtaposed with the Starlink operator ephemeris. The primary discrepancies between the two orbits appear to stem from the orbit update process where inaccurate measurements lead to erroneous adjustments in the orbit position, eventually causing the state divergence over time. This effect is particularly pronounced in the along-track directions. With these observations in mind, we put forth two primary hypotheses:

- Larger errors, defined as those exceeding 2 standard deviations from the mean, can be attributed to measurement inaccuracies. These errors prompt an abrupt divergence between the operator ephemeris and NORAD TLE state vectors.
- The preponderance of errors, which are smaller (within 1 standard deviation from the mean), are likely due to inaccuracies in force modelling.

6.2 Time Series Analysis of NORAD and Supplemental TLEs

The time series of positional differences, as detailed in section 5.2.1, highlight two distinct types of errors:

1. **Erratic Spikes:** Large spikes, tied to specific satellites, indicate positional discrepancies not ascribable to mis-modeled environmental factors, as similar geographic paths would yield similar error patterns. Factors such as erroneous initial conditions or thrusting events could be responsible, particularly considering the frequent orbit-maintaining thrusting of mega-constellation satellites, a behavior that TLEs fail to account for [14]. Figure 6 exhibits this characteristic, aligning with minor orbit-raising maneuvers (refer to Figure 3). A lack of correlation between the F10.7 flux index [24] and positional differences effectively rules out environmental variations, such as atmospheric density fluctuations, as a likely cause.
2. **Periodic Background Errors:** Analysing the HCL error time series data in the frequency domain (Figure 9) reveals a once-per-rev repeat periodicity. Examining the error in relation to Earth-centered Earth-fixed (ECEF) location uncovers geographical bias in the height and cross-track data, while along-track and Cartesian differences remain relatively noisy. This geographical bias differs between OneWeb and Starlink. Potential explanations for these constellation-specific error biases could include:

   - **Discrepancies in TLE Construction Data Quality:** NORAD TLEs, epoched on an hourly basis, may be based on ephemeris, while those epoched at 8-hour intervals could be observation-based [18]. The differing proportions of 1- and 8-hour TLEs for each constellation (Figure 12) may hint at variation in data sources and quality.

   - **Orbital Geometry Variations:** The specific subset of OneWeb studied orbits at an altitude of approximately 1200km and an inclination of around 88°, contrasting with the Starlink subset at approximately half this altitude and inclination. Given that perturbation strengths fluctuate with orbital geometry, it's plausible that the SGP4 model systematically mismodels different forces. For instance, atmospheric density is the primary non-conservative force at Starlink's altitude, while Solar Radiation Pressure is dominant for OneWeb satellites [29].

6.3 TLE Latency and Location Investigation

The identified bimodal distribution in NORAD TLE latencies suggests the existence of two primary data sources. Drawing from [18]'s proposition, these could likely be ephemeris-based and sensor-based. This notion is further supported by the predominant presence of the 8-hourly data type in the SupTLEs for both Starlink and OneWeb. Interestingly, no hourly TLEs were identified for Starlink, suggesting that the 8-hourly TLEs might, in fact, be the ephemeris-based TLEs, where [18] had suggested these could be the hourly kind.

Building on [18]'s hypothesis that TLE latency reflects the data source, we further the idea that, with some validation, the distribution of latency and location with which TLEs are produced could serve as a means of inferring the quality of a set of TLEs. The variations in TLE location further underscore the complexity and potential implications of these factors.

6.4 STM Practical Implications

This study has practical implications for STM by shedding light on potential discrepancies in data related to uncooperatively tracked objects. Precise and accurate positional data is essential for effective SSA and becomes more critical as satellite numbers rise in LEO [25].

Current tolerable positional accuracy error thresholds for operators are around 500m [31]. This is expected to narrow as space becomes more congested and contested [34]. Mega-constellation growth presents significant navigation challenges [26].

Current widely available SSA products based on TLEs are insufficient to meet these evolving requirements [28]. TLEs are inaccurate on a multi-kilometer scale [3], while operator requirements are in the hundreds of meters range [31]. As accuracy thresholds narrow, the TLE system will become increasingly obsolete. Over 20 years ago, [11] demonstrated that collision avoidance maneuvers based on data with errors beyond the kilometer level (as in NORAD TLE orbits) provided no significant reduction in collision probability.

To safely operate the planned numerous satellites in increasingly congested LEO and VLEO regions, achieving $\leq$ 100-meter accuracy for all objects will be crucial for maintaining low collision probabilities [32].

Additionally, the rise of low-cost launches and platforms, with mass and link budget limitations, may lead smaller operators to consider using NORAD TLEs for positional data. However, current discrepancy levels between data sources are unacceptable under the typical 0.01% probability of collision threshold [3]. This underscores the need for accurate and reliable positional data sources to ensure safe and efficient STM amidst increasing satellite populations and LEO congestion.

6.5 Limitations

The present study aimed to evaluate the quality of Two-Line Elements (TLEs) for a subset of the two largest mega-constellations, however, several limitations must be acknowledged.

Firstly, the data sample used in this study is not exhaustive, spanning only around 400 days and comprising of only three launches per constellation and ten satellites within each of these launches. This means variations in environmental variables beyond this time period, such as atmospheric density variations resulting from geomagnetic storms, are not captured.

Additionally, it should be noted that this study characterizes TLE data quality and operator behavior for a limited time period. SSA data quality and operator practices are evolving on a near-daily basis, therefore, the behaviors and errors observed in this study may not hold true in the future. However, it is believed that in addition to the characterization of the quality of the most widely available SSA data, this kind of analysis remains useful as a record of current practices and to promote transparency in the field of SSA. In particular, it would have been beneficial to be able to compare TLE and SupTLE data against their matching operator ephemeris data for a more extended period of time. This would have allowed to further elucidate the geographic discrepancies observed between the TLE sets. The accessibility of these is currently limited.

7. CONCLUSION

This investigation provides a comprehensive characterization of the positional discrepancies between operator ephemerides and NORAD TLEs for 60 LEO mega-constellation satellites. The findings underline a general inaccuracy of TLEs at a scale of several kilometers, with the greatest positional deviations appearing along the track, followed by the height, and finally in the cross-track directions. A high variance was particularly observed in along-track measurements, aligning with literature precedent. A comparative analysis between the SupTLE and NORAD TLEs of the Starlink constellation revealed a positional consistency approximately 52% less accurate than that of the OneWeb constellation. Two categories of errors emerged in the data: background error and significant spikes. The background error exhibited a daily periodicity coinciding with each satellite's ground-track repeat period, with a discernible dependence on the geographical location of the spacecraft. Conversely, the larger errors seemed geographically independent and lacked any constellation-specific trends. These larger errors are postulated to originate from ground segment errors, such as loss-of-tracking events, thrusting events, or isolated spacecraft hardware failure events, for instance, a malfunction in the spacecraft's guidance and control systems causing it to tumble. Additionally, the study explored TLE production rates. The NORAD TLEs demonstrated a clear bifurcation in production rates, supporting the hypothesis of their construction from a mix of network-based measurements and operator TLEs. In summary, this study underscores the limitations of the extant TLE-based system for space situational awareness, emphasizing the need for more accurate positional data to maneuver within an increasingly crowded and contested space environment. The study advises that NORAD TLEs serve as a rough guide to satellite population, rather than a precise source of positional data.

8. CONCLUDING THOUGHTS AND FUTURE DIRECTIONS

The heterogeneous quality of data provided by TLEs, both spatially and temporally, harbors a wealth of unknowns, presenting substantial challenges in the swiftly advancing field of Space Situational Awareness (SSA). While efforts to refine TLEs through techniques like covariance inversion ([17] and [9]) and filtering approaches ([12] and [35]) are ongoing, these are tied to the bureaucratic pace of USSTRATCOM, whose objectives and interests may not always align with other stakeholders. This paper advocates for the establishment of a universally accepted set of LEO benchmark orbits, akin to the International GNSS/DORIS Service for GNSS satellites. Such a resource would empower users to evaluate the quality of any SSA data independently. It would also foster transparency among SSA data providers and stimulate the development of robust solutions by researchers. Current validation methods relying on geodetic spheres or scientific mission data fail to provide a satisfactory data quality assessment. To achieve an engineering-grade understanding of SSA data, a concerted effort to develop a set of International GNSS Service (IGS)-like orbits is required. In essence, this paper calls for a paradigm shift in SSA data collection, validation, and usage to facilitate safe and efficient space operations in the future.

9. OPEN SOURCE CODE AND COLLABORATION

In alignment with our advocacy for transparency in Space Situational Awareness (SSA), we have decided to openly share our research codebase. All the code utilized in this study is available in a public GitHub repository:

`https://github.com/CharlesPlusC/MegaConstellationSSA`

We believe that the advancement of SSA is a collaborative effort that can be accelerated through open access to research tools and data. We therefore invite fellow researchers, academics, and enthusiasts to explore our code, scrutinize its contents, engage in constructive discourse, and contribute to its continual improvement.

10. ACKNOWLEDGEMENTS

We express our sincere gratitude to those who have contributed to this research. In particular, we wish to extend our thanks to T.S. Kelso for his generous insights into TLE production practices. His expertise and willingness to share his understanding have significantly informed our approach and have enriched the depth of this study. We are also indebted to Mr.Tom Johnson for his valuable time and willingness to discuss SSA sensor calibration practices. His hands-on knowledge and real-world experiences have allowed us to critically assess and contextualize our results.

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