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

Charles Constant, Santosh Bhattarai, Marek Ziebart, **Space Geodesy and Navigation Laboratory, UCL**

Problem: Accuracy and Force Models

The impact of inaccuracies in force modelling on orbit solutions is often overlooked and poorly characterized. This is especially crucial as the number of objects in Low Earth Orbit (LEO) continues to surge with the rise of mega-constellations, amplifying the risk of collision.

Our work aims to provide a comprehensive assessment of the positional accuracy of the largest publicly available SSA system to date. We believe that improving force modelling can result in considerable advancements in positional accuracy at minimal computational cost. This can potentially lead to significant improvements in SSA and STM, contributing to safer and more efficient operations in our increasingly crowded orbital neighbourhoods.

Opportunity: Satellite Nets

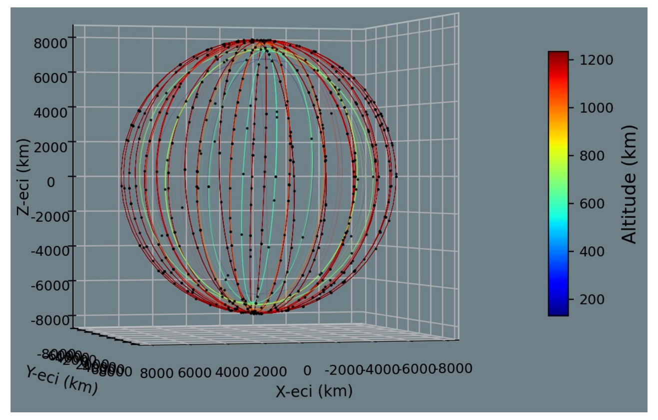

Figure 1. Visualization of the 636 OneWeb Satellites on the 30/09/2023

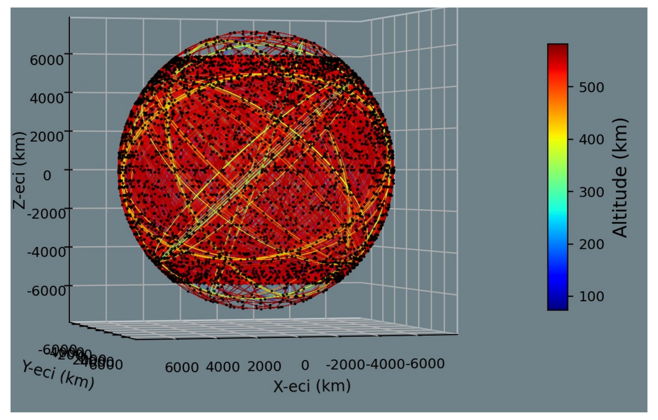

Figure 1. Visualization of the 4928 Starlink Satellites on the 30/09/2023

Methodology 1a: Data Collection, Orbit Generation and Comparative Analysis

We analysed a dataset of **165,347** Two-Line Element sets (TLEs), from both cooperative (Supplemental TLEs) and uncooperative sources (NORAD TLEs) pertaining to a subset of the OneWeb and Starlink constellations spanning the 2021-Jul-05 to 2023-Jan-06 period.

To ensure a representative study, we randomly selected 10 satellites from three separate launches.

Further, our analysis only considered those satellites within +/-20 Km of their nominal orbits and with an SMA-rate below 2Km/Day, thereby excluding any satellites consistently orbit-raising.

With our dataset in place, we proceeded to generate two continuous ephemerides for each satellite- one for each data source. This was achieved by propagating the TLEs using the SGP4 propagator and updating the spacecraft state as soon as a new TLE became available.

To characterize the differences between the solutions for each spacecraft, we employed a range of metrics: 3D Cartesian, height, cross-track, along-track discrepancies, and differences in latitude and longitude.

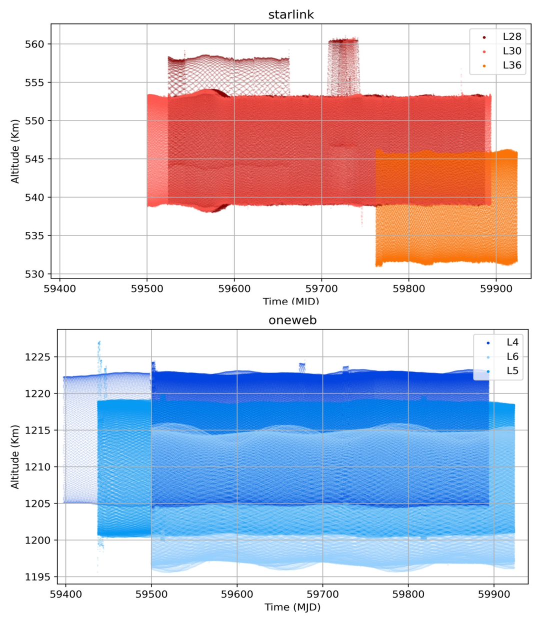

Figure 3. Altitude time series of the studied satellites. Grouped by launch number.

Constellation	Type of TLE	#of TLEs
OneWeb	NORAD	50,674
Starlink	NORAD	40,489
OneWeb	Supplemental	46,921
Starlink	Supplemental	27,263
Total	-	165,327

Table 1. Number of TLEs collected for each constellation by TLE Type/Source

Methodology 1b: Characterization of TLE Latency and Location

Intrigued by the clear signals present in the orbit solutions, we hypothesized that the TLE generation process could provide further insights into the noise source. This process could reflect various factors, including the sensor(s) used and thus the quality of the measurements.

To test this hypothesis, we recorded the latency with which each orbit was updated with a new TLE. This allowed us to track the frequency at which TLE were released and attempt to identify any correlations with the observed noise.

Inspired by the work of T. Johnson (2022), we also investigated the location within the spacecraft orbit (argument of latitude) where the TLE was generated. This could provide a clue about the data source and further illuminate the origin of the noise in the orbit solutions.

Results 1a: Height, Cross-Track, Along-Track differences and Spectral Analysis

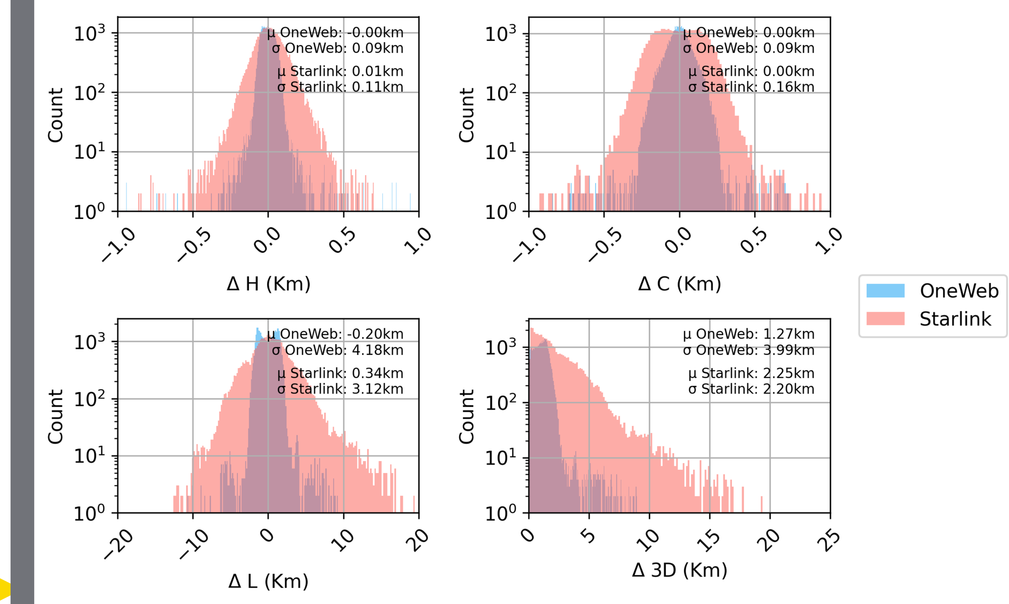

Figure 4. Histogram of the recorded discrepancies between all orbit solution pairs at each time step. Note the y-scale is logged!

Across all satellites, the distribution of errors is generally 0-centred (figure 4). However, upon closer inspection the symmetry of the bi-modal distribution can be identified in a number of these plots. A notable feature is the greater variance displayed by Starlink, presumably due to the greater relative magnitude of aerodynamic drag at lower altitudes.

Intrigued by the time series patterns, we conducted a Fourier analysis to detect any periodicity in the H,C,L data (Figure 5). Clear repeat periods of 15/day and 13/day in the data for all spacecraft in the OneWeb and Starlink constellations respectively. These frequencies corresponded to the orbital period of the satellites.

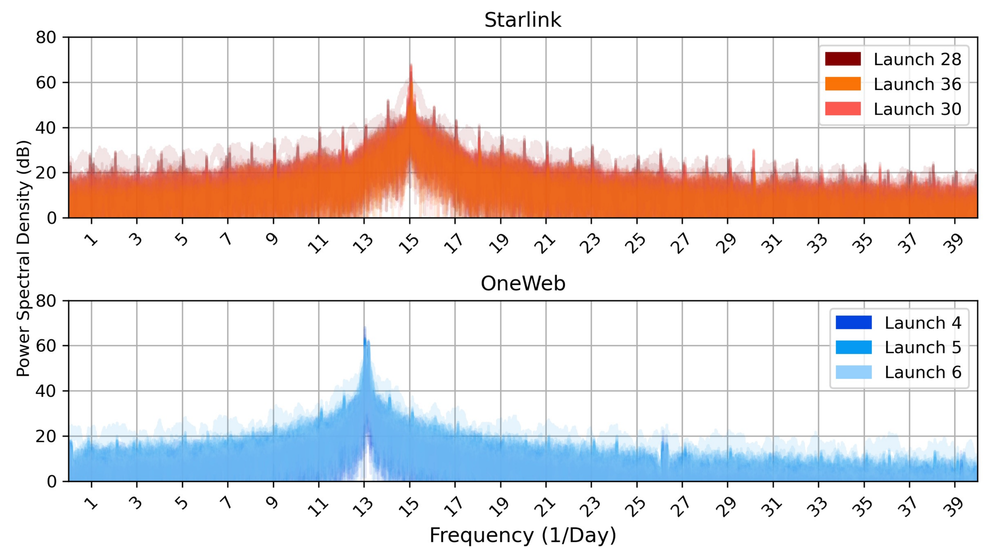

Figure 5. Cross-track time-series in the frequency domain for each constellation. Each peak corresponds to a once-per-rev for each constellation

Results 1b: Constellation-Specific TLE Production Practices

The results from the characterization above prompted hypothesizing as to the potential sources of these discrepancies. Previous literature suggested TLE age and location may be responsible.

While we found no clear correlation between these variables, the distribution of TLE latency and argument of latitude offered interesting patterns in and of themselves (Figures 6 & 7).

Contrary to reports from a decade ago that suggested an average TLE update latency of 5 days for LEO objects(REF), our findings align with recent research (Johnson, 2022) noting that TLE generation for Starlink and OneWeb constellations predominantly occurs at integer hours and ascending nodes (figures 6 & 7).

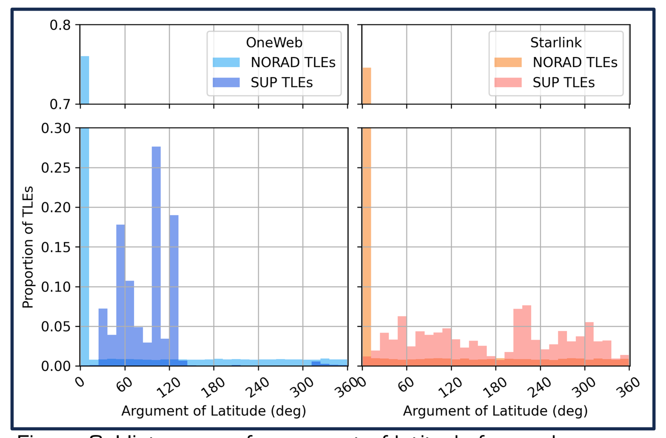

Figure 6. Histogram of argument of latitude for each TLE. Coloured by constellation and TLE source

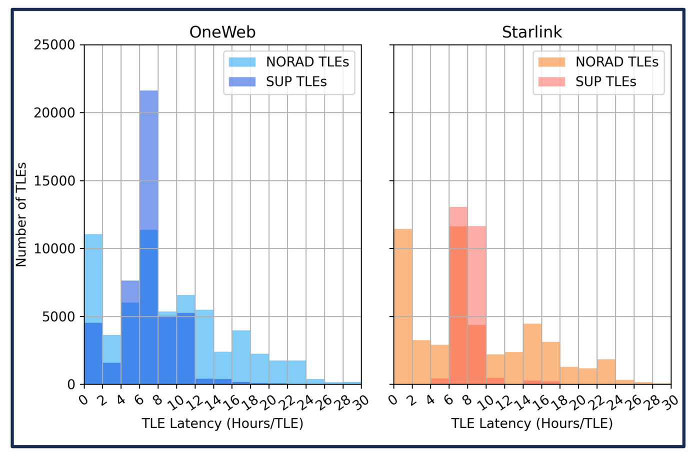

Figure 7. Histogram of argument of latency (time until a subsequent TLE was available) for each TLE. Coloured by constellation and TLE source

Approximately 75% of all NORAD TLEs for both constellations were epoched at the ascending node (0°). While OneWeb's SupTLEs were largely contained within the first half of the orbit (20°-130°), Starlink's SupTLEs displayed a more random distribution (0°-360°). In addition, Starlink's Sup TLEs seem to be almost all be generated on the circa 8-hour mark suggesting a single source. OneWeb's have more variance suggesting multiple sources

Methodology 2: Benchmarking TLEs Against Operator Ephemerides

In an attempt to achieve a more absolute understanding of the errors (as opposed to relative), we undertook a more detailed comparison of orbit solutions derived from NORAD TLEs and SupTLEs, against precision operator ephemerides. As an additional step, this involved converting the operator ephemerides from the Mean Equator Mean Equinox (MEME) to True Equator Mean Equinox (TEME) reference frames.

This tripartite comparison offered a more robust and holistic view of the orbit solutions, but was only possible for the Starlink satellites as OneWeb do not make operator ephemeris data available.

Results 1a: Earth-Centered Earth-Fixed Analysis

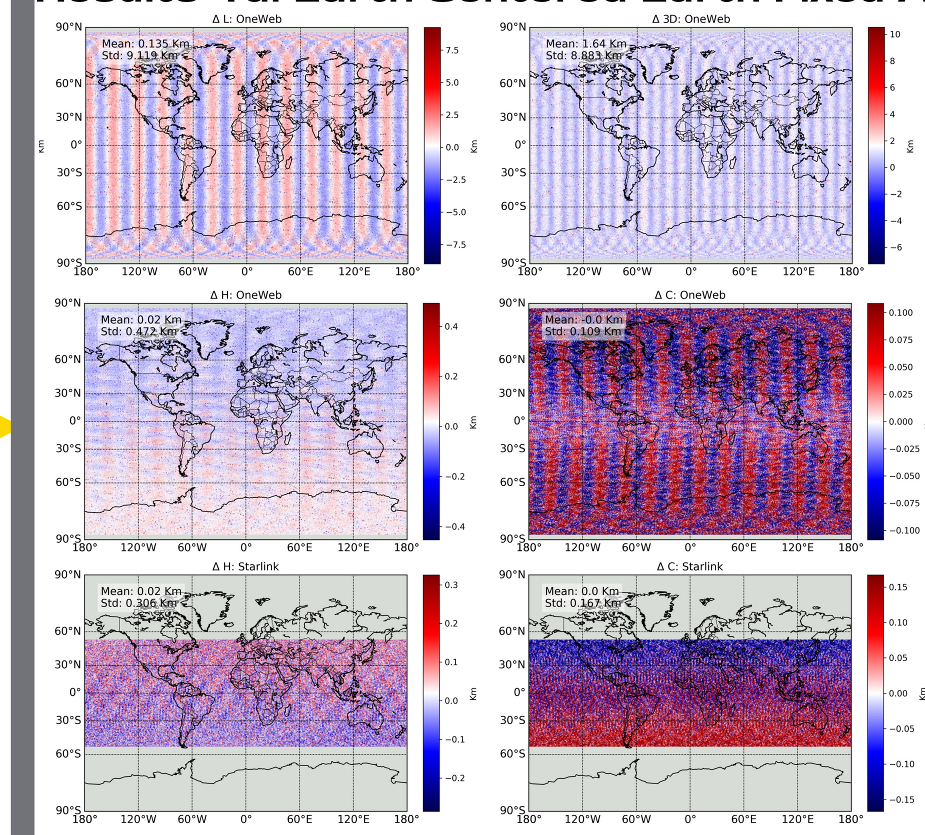

Figure 8. Select maps of the differences between cooperative and uncooperative orbit solutions for each constellation.

Prompted by the discovery of a once-per-rev periodicity within the error profiles, we examined potential links between the geographical (ECEF) location of satellites and corresponding error magnitudes (Figures 8). Notably, OneWeb demonstrated a clear, time-invariant, longitude dependent along-track error , with distinct "lanes" where this was either over or under-predicted. In contrast, Starlink showed no significant geographical correlation for along-track error, but a noisy North-South divide was discerned for height and cross-track error.

Results 2: Starlink Ephemeris Benchmarking

Here, we benchmarked both SUP TLE and NORAD TLE against operator ephemerides, using these as a "truer" reference.

We confirmed the Sup TLE's improved accuracy, being 52% more accurate on average than NORAD TLEs.

The TLE update process is clearly correlated with positional discontinuities. Interestingly, the periodicity in the error relative to the operator ephemeris persisted, implicating the SGP4 force model as a probable culprit of the periodicity within the results observed in figures 3 and 5.

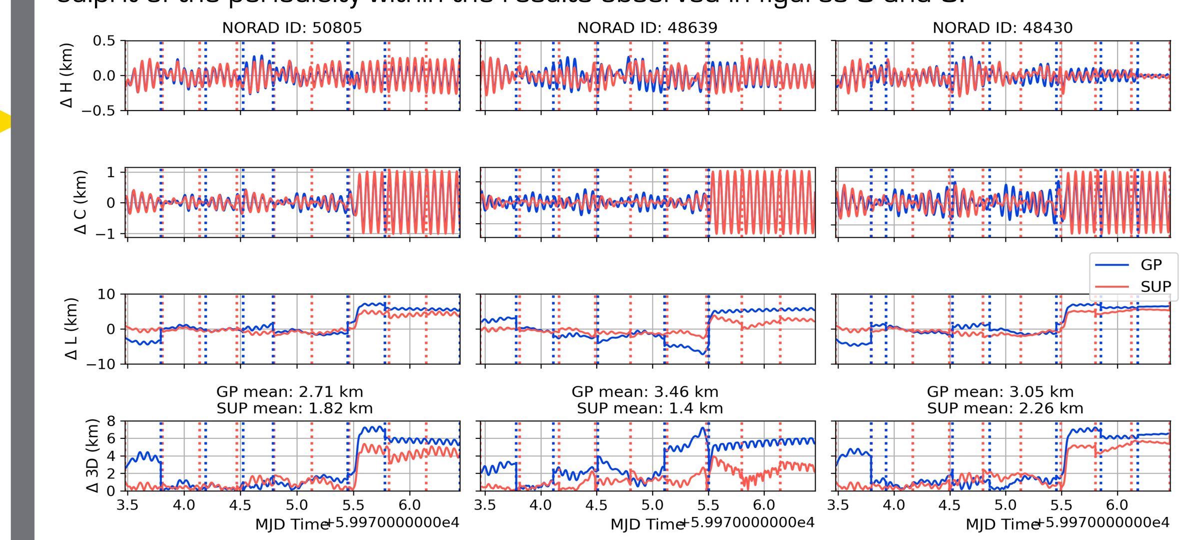

Figure 8. Height, Cross-track, Along-track and 3D error time series of the NORAD(GP) and Sup TLE solutions relative to the Starlink operator ephemerides over 72 hours

Implications for SSA/STM and Future Work

1) Cooperative TLEs are more accurate than uncooperative TLEs- but only by about 50%.
2) The difference between cooperative and uncooperative TLEs is systematic and a function ECEF location. This is an easy fix that can be applied to existing orbital products.
3) Whether these errors are spacecraft/altitude/inclination/time dependent will be key in generalizing this approach to existing SSA orbital products.
4) Come and get involved! `https://github.com/CharlesPlusC/MegaConstellationSSA`

Bonus Questions:

1) What are the limitation of using geodetic spheres in calibration ?
2) What is the impact of 1m of error in a set of initial conditions over 24 hours?