Garageware ISS Trajectory Prediction Accuracy Assessment

In an ongoing ritual, the author maintains an ISS ephemeris based on publicly accessible data and home-brewed applications informally referred to as "garageware". Orbit prediction generating an ISS ephemeris with garageware is performed by the WeavEncke processor.[1] Standard perturbation models used by WeavEncke for ISS ephemeris generation are GEM10 Earth gravity truncated beyond seventh degree and order[2], Sun/Moon point source (Newtonian) gravity from JPL's DE441 Solar System ephemeris[3], and ballistic aerodynamic drag from Jacchia-Lineberry atmospheric density[4]. Those familiar with these models may recognize the theory of orbit motion used in Mission Control-Houston (MCC-H) for Shuttle missions beginning with STS-5. This paper quantifies geocentric position accuracy of garageware ISS ephemerides immediately prior to the next update based on empirical observations. These updates extend over a period of 11 months.

Each garageware ephemeris update is triggered by a similar one typically conducted on Mondays, Wednesdays, and Fridays by the ISS Trajectory Operations Officer (TOPO) at MCC-H. The TOPO's new "anchor state vector", equivalent to initial conditions for orbit prediction in the updated ephemeris, is obtained from a TrajectorySummary.txt file posted to Space-Track.org.[5] The TrajectorySummary.txt file also includes empirically derived drag coefficient C_D and frontal area A values. It should be noted that multiple values for A may be used in the TOPO ephemeris to reflect ISS configuration changes such as differing solar array orientations. The A value supplied in the TrajectorySummary.txt file is used throughout the garageware ephemeris because a timeline of other values in the TOPO ephemeris is unavailable. Due to this data void and for the sake of simplicity, C_D in the garageware ephemeris is always 2.0. Monthly updates to 50% solar flux and geomagnetic index calibrating the Jacchia-Lineberry model are obtained from NASA-MSFC.[6]

About every month or so, a planned reboost is modeled in TOPO's ISS ephemeris. Usually, these maneuvers serve to extend ISS orbit lifetime and facilitate rendezvous by visiting vehicles. Most ISS maneuvers have a prograde change-in-velocity magnitude Δv near 1.0 m/s and span a powered flight arc about 20 minutes in duration.[7] Planned reboosts are well-documented in the

---

[1] Reference D. R. Adamo, "A Precision Orbit Predictor Optimized for Complex Trajectory Operations", AAS 03-665, Volume 116 of *Advances in the Astronautical Sciences*, Univelt, San Diego, 2003, pp. 2567–2586.

[2] Reference F. J. Lerch, S. M. Klosko, R. E. Laubscher, and C. A. Wagner, "Gravity Model Improvement Using GEOS 3 (GEM 9 and 10)", *Journal of Geophysical Research: Solid Earth*, Vol. 84, Issue B8, July 1979, pp. 3897-3916. This paper can be downloaded at https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/JB084iB08p03897 (accessed 13 March 2024).

[3] Reference R. S. Park, W. M. Folkner, J. G. Williams, and D. H. Boggs, "The JPL Planetary and Lunar Ephemerides DE440 and DE441", *The Astronomical Journal*, 161:105, 2021 March. This paper may be downloaded at https://iopscience.iop.org/article/10.3847/1538-3881/abd414/pdf (accessed 13 March 2024).

[4] Reference A. C. Mueller, "Jacchia-Lineberry Upper Atmosphere Density Model", JSC-18507, 82-FM-52, downloadable at https://ntrs.nasa.gov/api/citations/19830012203/downloads/19830012203.pdf?attachment=true (accessed 13 March 2024).

[5] A TrajectorySummary.txt file resides in the "NASAJSC_Ephemeris_23644_15Day…" .zip package downloaded from the Public Files tab at https://www.space-track.org/auth/login (accessed 3 May 2024 with a no-fee user ID).

[6] Reference 10.7 cm radio flux tabular data at https://www.nasa.gov/solar-cycle-progression-and-forecast/#solarfiles (accessed 8 April 2024).

[7] Infrequently, a retrograde "deboost" is planned. A reboost/deboost can also arise in a matter of hours when it becomes advisable to evade an orbiting collision threat.

TrajectorySummary.txt file's Trajectory Event Summary section. A garageware ephemeris models propulsive events impulsively at the associated powered flight arc's midpoint.

With each ISS ephemeris update, TOPO publishes the unsigned position change magnitude Δr of the new ephemeris with respect to the old ephemeris at the new anchor state vector's UTC. A similar computation is made for the garageware ephemeris update, but it is signed. A positive garageware Δr indicates the new anchor position is *leading* the old ephemeris position at the new anchor's UTC, while a negative Δr indicates the new anchor position is *trailing* the old ephemeris position at the new anchor's UTC. These Δr values serve as a metric for ISS prediction error in the TOPO and garageware ephemerides as accumulated during time from the previous update to the new anchor state UTC.

With these ISS update processes and metrics in mind, consider the Figure 1 data gathered from June 2023 to May 2024 and spanning about 140 ephemeris updates (this tally depends on whether TOPO or garageware updates are counted). To pair a garageware Δr with its TOPO counterpart, zoom in to the Figure 1 graphic and use the update UTC grid (light blue vertical lines) at 2-day intervals.

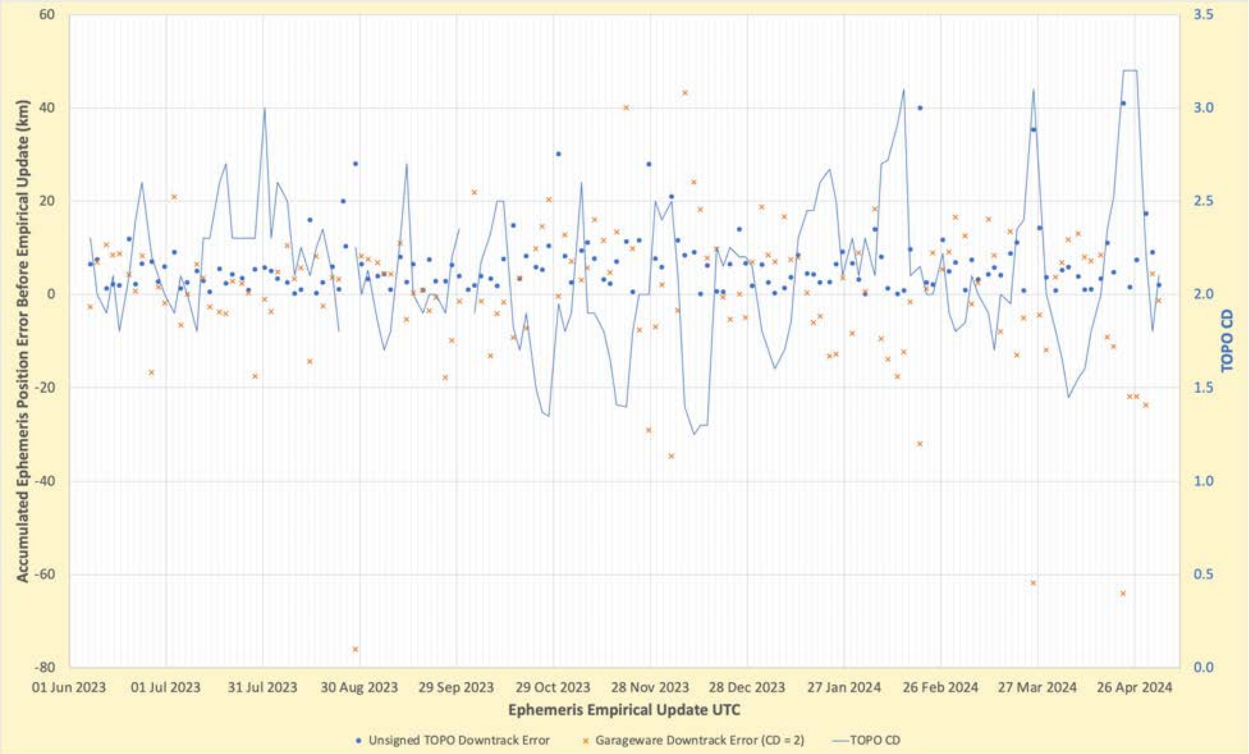

Figure 1. Discrete blue markers (•) indicate accumulated position error magnitude Δr before correction by empirical updates to the TOPO-maintained ISS ephemeris as a function of update UTC. Similarly, discrete orange markers (x) indicate Δr before correction by the same empirical updates to a garageware-maintained ISS ephemeris and are signed as explained in the narrative. Updates to the TOPO's empirically estimated C_D are plotted as a solid blue line (——). The garageware ephemeris is maintained with a fixed $C_D = 2.0$.

Breaks in Figure 1's solid blue C_D line correspond to updates where TOPO published a Δr but other pertinent data were unavailable for a corresponding garageware ephemeris update. Prior to 1 November 2023, data now obtained in a TrajectorySummary.txt file were only posted to https://spotthestation.nasa.gov/trajectory_data.cfm as part of a manual off-console TOPO task. During periods of high workload, such as preparing for an ISS collision avoidance maneuver, these postings were omitted on occasion. For example, the C_D break in late August 2023 was contemporaneous with an avoidance deboost on Thursday, 24 August at 20:00 UTC with Δv = 0.3 m/s. Failure to accurately model this deboost created a Δr = -76 km in the garageware ephemeris at the next update with accessible data on 28 August. Fortunately, TrajectorySummary.txt postings are now an automated spinoff of TOPO's on-console duties and much less likely to suffer from gaps, as the unbroken Figure 1 TOPO C_D plot after early October 2023 attests.

In Figure 1, note the correlation between TOPO C_D values far from 2.0 and corresponding garageware ephemeris Δr. A large TOPO C_D indicates the garageware ephemeris is under-modeling atmospheric drag accelerations with C_D = 2.0, and its positions tend to fall behind the real-world ISS, thus registering a negative Δr. In contrast, a small TOPO C_D indicates the garageware ephemeris is over-modeling atmospheric drag accelerations with C_D = 2.0, and its positions tend to advance ahead of the real-world ISS, thus registering a positive Δr.

Despite a fixed C_D = 2.0 in the garageware ephemeris, its Δr magnitude at an update is less than that of the simultaneous TOPO ephemeris in over one-third of the updates covered by Figure 1. These instances are likely attributable to the many unmodeled trajectory perturbations ISS encounters, primarily solar activity-driven ionospheric winds.

Because solar activity cannot be reliably predicted more than a few days in advance, it is the primary driver behind empirically estimated $C_D \neq 2$ in a TOPO ephemeris. At the onset of elevated solar activity, the TOPO ephemeris tends to track the change with $C_D > 2$ values, whereas the garageware ephemeris is literally left behind. But the end of elevated solar activity is also unpredictable such that the garageware ephemeris may more accurately model ISS position as TOPO C_D is reduced to values near 2. A good example of this prediction error cycle arises in late April at the end of Figure 1, where C_D = 3.2 for several TOPO updates.

Among all TOPO updates appearing in Figure 1, Δr has a geometric mean of 3.9 km with a standard deviation of 7.1 km, indicative of this parameter's large variations. Similarly, Figure 1's garageware Δr magnitudes have a geometric mean of 5.9 km with a standard deviation of 11.5 km.

This paper's integrity greatly benefitted from review by colleagues familiar with TOPO ephemeris maintenance. The author greatly appreciates this input, together with the ever more timely ISS trajectory data TOPOs make available for public access.