Technical Report: Orbit Propagator Model Verification
Project: VLEO slew maneuver
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This report summarizes the verification of our custom orbit propagator. The propagator's accuracy was tested against three benchmarks: an analytical Keplerian model (twobody_Benchmark_Testing.m), the industry-standard SGP4 propagator (sgp4_benchmark_testing.m), and a High-Precision Orbit Propagator (HPOP) (HPOP_benchmark.m). Results indicate the model is accurate for two-body dynamics but diverges significantly when perturbations are introduced, suggesting inaccuracies in the current force models and a likely coordinate reference frame mismatch.

1.0 Introduction

This report documents the verification and validation of the custom-built point mass orbit propagator. The objective of this test campaign was to assess the accuracy of our model against established industry-standard benchmark propagators. Accurate orbit prediction is critical for mission planning, ground station communication, payload pointing, and data downlink. The verification was performed using a series of MATLAB scripts comparing our model's output against three distinct benchmarks.

2.0 Methodology

The custom propagator is a numerical integrator that models the satellite as a point mass, subject to gravitational and atmospheric forces. To validate its performance, we conducted a three-tiered comparison:

1. **Analytical Keplerian Model (twobody_Benchmark_Testing.m):** A baseline test comparing our propagator against the analytical two-body solution. This test case assumes a perfectly spherical, uniform Earth with no atmospheric drag, isolating the core gravitational dynamics.
2. **SGP4 Model (sgp4_benchmark_testing.m):** The Simplified General Perturbations 4 (SGP4) model is the standard algorithm used by NORAD and the space surveillance community for propagating orbits from Two-Line Element (TLE) sets. It provides a semi-analytical solution that accounts for major perturbations.
3. **High-Precision Orbit Propagator (HPOP) (HPOP_benchmark.m):** HPOP is a high-fidelity numerical propagator that serves as our "truth" model. It incorporates a comprehensive suite of force models, including a 20x20 gravity field, third-body perturbations from the Sun and Moon, solar radiation pressure, and the NRLMSISE-00 atmospheric model.

3.0 Results & Analysis

The test campaign revealed a clear distinction in the performance of our model under different force conditions.

- **Keplerian Verification:** The results from twobody_Benchmark_Testing.m show that our propagator's output aligns almost perfectly with the analytical Keplerian solution. This successfully validates the implementation of the fundamental two-body gravitational equations.

- **Perturbation Model Verification:** The tests involving atmospheric drag and Earth's oblateness (HPOP_benchmark.m) showed a significant divergence. While the SGP4 and HPOP models produced results that were in close agreement, our custom model's trajectory deviated dramatically over the 24-hour propagation period. As seen in the plot_results output, the position error of our model relative to the truth model (HPOP) grew rapidly, reaching several kilometers. Furthermore, the altitude decay predicted by our model did not match the decay predicted by SGP4 and HPOP, indicating inaccuracies in our atmospheric drag or gravity model.

4.0 Conclusion & Discussion

The verification process leads to two primary conclusions:

1. The core two-body dynamics of our propagator are correctly implemented.
2. The perturbation models for atmospheric drag and Earth's oblateness are not yet sufficient for mission-level accuracy.

The strong agreement between SGP4 and HPOP provides high confidence that they represent a valid benchmark. The discrepancy in our model likely stems from one or both of the following issues:

1. **Model Fidelity:** Our perturbation models (J2-only gravity, simple exponential atmosphere) are significantly less complex than those used in SGP4 and HPOP.
2. **Reference Frame Mismatch:** There is a high probability of a coordinate reference frame mismatch between our propagator and the benchmarks. A common source of error is comparing data from different frames without proper transformation.

5.0 Recommendations & Next Steps

To address the observed discrepancies and improve the propagator's accuracy, the following steps are recommended:

1. **Investigate and Align Coordinate Reference Frames:** This should be the immediate priority, as frame mismatches can introduce large, systematic errors.
    - **Action:** Identify the output coordinate frame for each propagator. SGP4 is known to use the True Equator Mean Equinox (TEME) frame. HPOP and other high-precision tools typically use a true-of-date (TOD) or an inertial frame like Earth-Centered Inertial (ECI) J2000. Our custom model likely assumes a basic ECI frame.
    - **Action:** Implement and validate coordinate transformation routines to convert all propagator outputs to a common frame (e.g., ECI J2000) before comparison.
2. **Enhance Perturbation Models:** Once reference frames are aligned, the fidelity of the force models should be improved.
    - **Atmospheric Drag:** Replace the simple exponential atmospheric model with a more standard model, such as the NRLMSISE-00, which can be driven by space weather data (F10.7, Ap indices) for higher accuracy.
    - **Gravity Field:** Augment the J2 model with higher-order terms (J3, J4, etc.) to better capture the effects of Earth's oblateness.
    - **Integration Strategy:** Consider incorporating a proven, open-source propagator directly into our software stack for operational use, while continuing to develop the custom model

for analysis and specialized mission design tasks.

By systematically addressing the reference frame alignment and then iteratively improving the perturbation models, we can develop a custom propagator with the accuracy required for the 6U Wildfire Detection CubeSat mission.