Precise Orbit Determination: A Quick Survey

Daniel Topa
daniel.topa@hii.com

Huntington Ingalls Industries
Mission Technologies

December 5, 2024

Abstract

What are the current limitations in the precision of computing and measuring satellite locations? A survey of recent literature reveals that orbit determination techniques have achieved sub-meter accuracy, with centimeter-level precision attainable under certain conditions. This report serves as a gateway to the existing body of research, providing concise summaries of key studies in satellite orbit determination. Additionally, it includes an overview of open-source orbit propagators, offering practical tools for researchers and practitioners. By presenting both state-of-the-art advancements and accessible computational resources, this report aims to bridge the gap between theoretical developments and their practical applications.

Contents

1 Introduction

Advances in satellite orbit determination have achieved unprecedented precision, enabling centimeter-level accuracy crucial for modern scientific and operational missions. Since the launch of Sputnik in 1957, advances in tracking systems, computational models, and orbital mechanics have dramatically improved satellite positioning, achieving centimeter-level accuracy.

Table 1 highlights representative studies showcasing the state of the art in Precision Orbit Determination (POD) as of 2019. These examples illustrate the range of methodologies and the precision achieved, serving as a gateway to deeper exploration of the field.

The availability of open-source tools and the integration of sophisticated perturbation models have democratized the field, enabling researchers and practitioners to address increasingly complex orbital challenges. As the capabilities of POD continue to grow, the inclusion of relativistic effects and advanced perturbation models ensures that the highest levels of accuracy can be achieved. These topics, along with emerging trends and applications, are explored in subsequent sections.

Satellite	Radial Precision (cm)	Along-Track Precision (cm)	Cross-Track Precision (cm)	Residual RMS (mm/s)
TOPEX/POSEIDON	1.2	2.3	2.8	0.406
Jason-1	1.5	3.1	3.4	0.320
Jason-2	1.3	2.7	3.0	0.360
CryoSat-2	0.65	1.02	1.3	0.295
Sentinel-3A	0.9	1.5	1.7	0.320

Table 1: Precision Orbit Determination Metrics for Various Satellites, taken from table 1 [1].

2 Literature Survey

In this section, we summarize recent studies on precise orbit determination.

Below is a summary of key insights from selected references quantifying the precision of orbit determination.

1. **High-Precision GPS Orbit Determination by Integrating the Measurements from Regional Ground Stations and LEO Onboard Receivers** [4]

   > *The orbit and clock accuracies of GPS and LEO satellites are evaluated by comparison with precise products. The average Root Mean Square (RMS) of GPS orbit errors in the radial (R), along-track (T), and cross-track (N) directions are 2.27 cm, 3.45 cm, and 3.08 cm.*

2. **Choices for Temporal Gravity Field Modeling for Precision Orbit Determination of CryoSat-2** [10]

   > *The precision orbit determination (POD) of CryoSat-2 achieves 3 cm for the along-track component and 13 cm for the cross-track component. The laser residuals converge at approximately 1.02 cm, and Doppler residuals are at the 0.406 mm/s level. Additionally, the radial orbit difference relative to the CNES POE-F orbits narrows to 6.5 mm, demonstrating high accuracy in orbit determination.*

3. **Impact of Pseudo-Stochastic Pulse and Phase Center Variation on Precision Orbit Determination of Haiyang-2A from Experimental HY2 Receiver GPS Data** [15]

   > *Validation using external precise science orbit (PSO) and satellite laser ranging (SLR) methods confirmed millimeter-level orbit precision.*

4. **A Novel Method for Improving LEO Kinematic Real-Time Precise Orbit Determination with Neural Networks** [16]

Benefiting from this method, a promising accuracy of 3.2 cm can be achieved in LEO KRTPOD.

5. **LEO Real-Time Ambiguity-Fixed Precise Orbit Determination with Onboard GPS/Galileo Observations** [5]

   Using onboard GPS and Galileo observations, the 3D orbit accuracy of the ambiguity-fixed solution is significantly improved from 5.17 to 3.61 cm, by 30%, compared to the ambiguity-float solution. Furthermore, the application of IAR also achieves a faster convergence to the centimeter-level orbit.

6. **Real-Time Precise Orbit Determination of Low Earth Orbit Satellites Based on GPS and BDS-3 PPP B2b Service** [12]

   The RMS of the RT orbital errors in the radial, along, and cross directions is 0.10, 0.13, and 0.09 m, respectively, using BDS-3 and GPS PPP-B2b corrections.

7. **High-Precision Orbit Determination of the Small TJU-1 Satellite Using GPS, GLONASS, and BDS** [2]

   According to the orbit differences between different solutions, the orbit accuracy of single-GNSS solutions is inferred to be at the level of about 4.7–6.2 cm. With the multi-GNSS fusion, the precision and inferred accuracy of orbits could be improved significantly to 1.7–2.1 cm and about 1.7–3.7 cm, respectively.

8. **Precise Orbit Determination for Low Earth Orbit Satellites Using GNSS: Observations, Models, and Methods** [6]

   Using a state-of-the-art combination of GNSS observations and satellite dynamics, the absolute orbit determination for a single satellite reached a precision of 1 cm.

9. **Precise Orbit Determination of the ZY3-03 Satellite Using the Yaw-Attitude Modeling for Drift Angle Compensation** [3]

   The orbit determination experiments revealed that the zero-yaw assumption in the zero-attitude model would result in periodic orbit errors of up to ± 86 *mm in the normal direction, while the proposed model describes yaw angle variations accurately with errors of less than* $\pm 0.01°$.

10. **Long-Term Orbit Dynamics of Decommissioned Geostationary Satellites** [8]

    Orbit propagations are performed using two algorithms based on different equations of motion and numerical integration methods. The numerical results exhibit excellent agreement over integration times of decades.

11. **Reduced Dynamic and Kinematic Precise Orbit Determination for the Swarm Mission from 4 Years of GPS Tracking** [7]

    30% improvement in the precision of the reduced dynamic orbits with resulting errors at the 0.5–1 cm level (1D RMS).

12. **Precise Relative Positioning Using Real Tracking Data from COMPASS GEO and IGSO Satellites** [11]

The precision of COMPASS-only solutions is better than 2 cm for the North component and 4 cm for the vertical.

13. **Dynamic and Reduced-Dynamic Precise Orbit Determination of Satellites in Low Earth Orbits** [13]

    Orbital arcs over a whole day can be generated with an accuracy of up to 4.5 cm RMS.

14. **Aiming at a 1-cm Orbit for Low Earth Orbiters: Reduced-Dynamic and Kinematic Precise Orbit Determination** [14]

    Both techniques have reached a high level of maturity and have been successfully applied to missions in the past, such as TOPEX/POSEIDON (T/P), leading to (sub-) decimeter orbit accuracy.

3 Open-Source Orbit Propagators

The development and adoption of open-source orbit propagators have transformed the field of astrodynamics, providing accessible, high-quality tools for a diverse range of applications. These propagators are pivotal for satellite trajectory prediction, mission analysis, and integrating advanced modeling techniques.

3.1 Key Features and Comparisons

Open-source orbit propagators vary in precision, supported orbital regimes, programming languages, and usability. Table 2 summarizes the key features of popular tools:

- **GMAT**: Excels in high-fidelity trajectory optimization for interplanetary and geostationary missions.
- **KASIOP**: Kinematic Analysis and Simulation of Orbits and Positions (KASIOP) serves as the demonstration platform for post-Newtonian perturbation modeling.
- **Orekit**: A versatile library supporting GNSS, LEO, and interplanetary orbits with extensive customizability.
- **Skyfield**: A Python-based library focused on precise computations for orbital and astronomical ephemerides.
- **NEOPROP**: Provides robust algorithms for near-Earth object tracking, incorporating advanced perturbation modeling.
- **Polyastro**: A Python-based library for rapid prototyping of astrodynamic applications, focusing on ease of use.
- **STK (Free Tier)**: Offers visualization and basic mission analysis capabilities, and prebuilt models suitable for educational and small-scale satellite projects.
- **Orbit Predictor**: Simplifies TLE-based propagation for Earth-orbiting objects, including CubeSats and the ISS.

Tool	Precision	Special Features	Programming Language
GMAT	High	Mission analysis, trajectory optimization	C++
KASIOP	High	Demonstration of PN corrections	Proprietary
Orekit	High	Customizable, GNSS, interplanetary support	Java
Skyfield	Moderate	Astronomical body tracking	Python
NEOPROP	Moderate	Perturbation modeling for NEOs	Proprietary
Polyastro	Moderate	Rapid prototyping, visualization	Python
STK (Free Tier)	Moderate	Visualization, GUI-based scenario analysis	Proprietary
Orbit Predictor	Basic	Simplified TLE propagation	Python

Table 2: Comparison of Open-Source and Free Orbit Propagators (Sorted by Precision)

3.2 Why Open Source Matters

Open-source tools democratize access to advanced orbital mechanics, fostering collaboration, transparency, and innovation. They empower researchers, small satellite developers, and students to experiment without prohibitive costs.

3.3 Emerging Trends

The field of orbit propagation continues to evolve, with trends such as:

- Integration of AI and machine learning to improve accuracy.
- Real-time data assimilation from GNSS and other sensors.
- Modular designs for extensibility and ease of use.

3.4 Applications of Post-Newtonian Dynamics

Post-Newtonian corrections are increasingly integrated into modern propagators, enhancing their capability to model relativistic effects essential for high-precision missions. Figure 1 illustrates these corrections and their relative impact.

The dominant post-Newtonian corrections are

- Φ_1 Schwarzschild perturbation: The largest contribution, caused by the spherically symmetric part of the Earth's geopotential.
- Φ_2 Lense–Thirring effect: A result of the Earth's constant rotation, also known as frame-dragging.
- Φ_3 Quadrupole relativistic effect: Due to the Earth's quadrupole moment, commonly associated with the J_2 term.
- Φ_4 Nonlinear coupling of the Earth's monopole and solar gravitoelectric tidal field.
- Φ_5 Gravitomagnetic tidal perturbation: Related to the Earth's rotational effects.
- Φ_6 Gravitoelectric tidal perturbation: Due to external bodies in the solar system.
- Φ_7 Geodesic precession (de Sitter precession): A slow precession of the geocentric spatial frame relative to the barycentric frame.

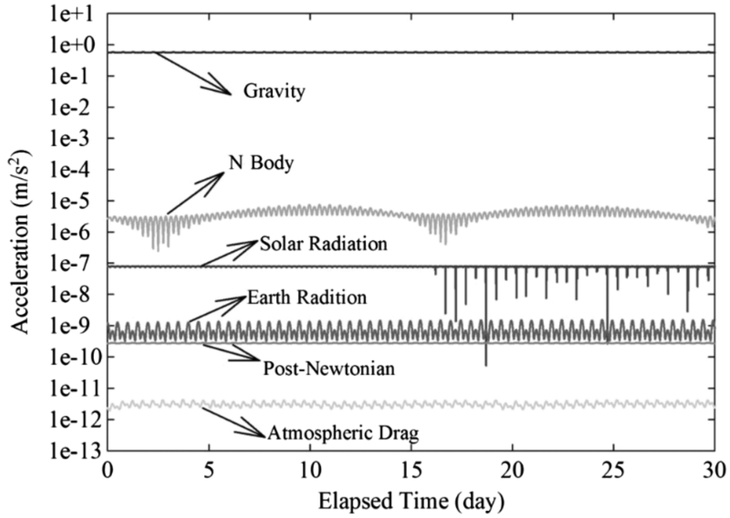

Fig. 1 Accelerations of GPS PRN01.

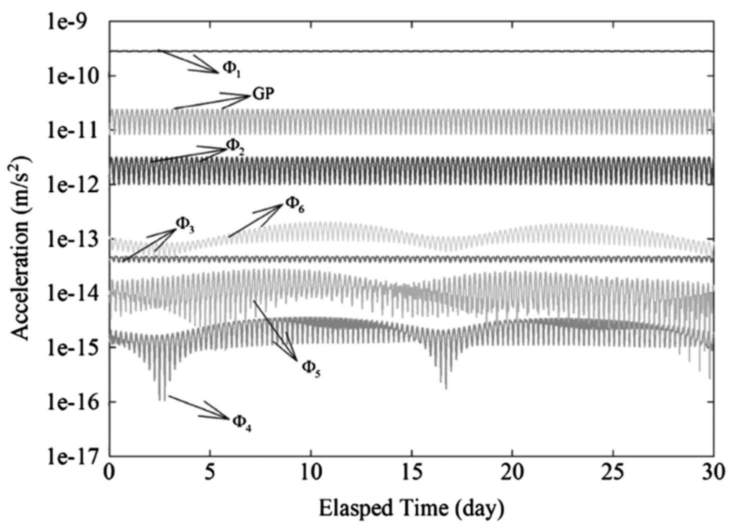

Fig. 2 Accelerations of the PN corrections for GPS PRN01.

Figure 1: Accelerations of post-Newtonian corrections for GPS PRN01, highlighting the relative impact of various perturbations from [9]. This work leverages KASIOP as a demonstration platform to evaluate the impact of post-Newtonian corrections on satellite dynamics.

References

1 Deepak Gaur and Mani Shankar Prasad. "Precision Orbit Determination for Errored Dynamic Models". In: *2019 3rd International Conference on Recent Developments in Control, Automation & Power Engineering (RDCAPE)*. IEEE. 2019, pp. 38–44.

2 Xuewen Gong et al. "High-Precision Orbit Determination of the Small TJU-1 Satellite Using GPS, GLONASS, and BDS". In: *IEEE Sensors Journal* 23.12 (2023), pp. 13340–13350. DOI: 10.1109/JSEN.2023.3272923.

3 Xuewen Gong et al. "Precise Orbit Determination of the ZY3-03 Satellite Using the Yaw-attitude Modeling for Drift Angle Compensation". In: *IEEE Sensors Journal* (2024).

4 Kai Li et al. "High-precision GPS orbit determination by integrating the measurements from regional ground stations and LEO onboard receivers". In: *Satellite Navigation* 5.1 (2024), p. 27.

5 Xingxing Li et al. "LEO real-time ambiguity-fixed precise orbit determination with onboard GPS/Galileo observations". In: *GPS Solutions* 28.4 (2024), p. 188.

6 Xinyuan Mao, Wenbing Wang, and Yang Gao. "Precise orbit determination for low Earth orbit satellites using GNSS: Observations, models, and methods". In: *Astrodynamics* (2024), pp. 1–26.

7 Oliver Montenbruck et al. "Reduced dynamic and kinematic precise orbit determination for the Swarm mission from 4 years of GPS tracking". In: *GPS solutions* 22.3 (2018), p. 79.

8 Simone Proietti et al. "Long-term orbit dynamics of decommissioned geostationary satellites". In: *Acta Astronautica* 182 (2021), pp. 559–573. ISSN: 0094-5765. DOI: https://doi.org/10.1016/j.actaastro.2020.12.017. URL: https://www.sciencedirect.com/science/article/pii/S0094576520307517.

9 Kyoung-Min Roh. "Numerical evaluation of post-Newtonian perturbations on the Global Navigation Satellite System". In: *Journal of Spacecraft and Rockets* 55.4 (2018), pp. 1028–1033.

10 EJO Schrama and PNAM Visser. "Choices for temporal gravity field modeling for precision orbit determination of CryoSat-2". In: *Advances in Space Research* 73.1 (2024), pp. 31–41.

11 Chuang Shi et al. "Precise relative positioning using real tracking data from COMPASS GEO and IGSO satellites". In: *GPS solutions* 17 (2013), pp. 103–119.

12 Yali Shi et al. "Real-time precise orbit determination of low earth orbit satellites based on gps and bds-3 ppp b2b service". In: *Remote Sensing* 16.5 (2024), p. 833.

13 Paul Swatschina. *Dynamic and reduced-dynamic precise orbit determination of satellites in low earth orbits*. Vol. 89. Dep. of Geodesy and Geoinformation of the Vienna Univ. of Technology, 2012.

14 PNAM Visser and J Van Den Ijssel. "Aiming at a 1-cm orbit for low earth orbiters: reduced-dynamic and kinematic precise orbit determination". In: *Space science reviews* 108 (2003), pp. 27–36.

15 Youyuan Wang et al. “Impact of Pseudo-Stochastic Pulse and Phase Center Variation on Precision Orbit Determination of Haiyang-2A from Experimental HY2 Receiver GPS Data”. In: *Remote Sensing* 16.8 (2024), p. 1336.

16 Wei Zhang et al. “A novel method for improving LEO kinematic real-time precise orbit determination with neural networks”. In: *IEEE Transactions on Instrumentation and Measurement* (2024).