A Review on Precise Orbit Determination of Various LEO Satellites

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Abstract

The need for precise orbit determination (POD) has grown significantly due to the increased amount of space-based activities appearing at an accelerating pace. POD has a positive contribution in achieving the requirements of Low-Earth Orbit (LEO) satellite mission which includes improved reliability and continuity. In this paper, we will review the POD approaches of various LEO satellites and discuss the accuracy levels obtained as well as the methods and algorithms used to achieve the POD of LEO satellites. With recent advancements in miniature space technology, a greater number of smaller low-cost satellites are launched into the LEO for various purposes. Furthermore, development in the Global Navigation Satellite Systems (GNSS) and chipsets played a vital role in revolutionizing the GNSS receiver technology. Lower-cost, smaller size but yet high performing GNSS receivers need to be implemented also in CubeSats in addition to the various terrestrial applications. POD using onboard GNSS receiver data will benefit the development of several upcoming space applications in the field of navigation systems, telecommunication, remote sensing, and earth observation. In the future, it is anticipated that LEO-based satellites enabled by POD can also offer positioning capabilities that will enhance GNSS and create vast opportunities for users with new features and possibilities to the navigation field.

Keywords

Precise Orbit Determination, Low-Earth Orbit, Global Navigation Satellite Systems, CubeSats, Remote Sensing, Earth Observation

1. Introduction

From the first man-made satellite, orbit determination has been done using radio transmission with major improvements seen through the years. GNSS was first applied in precisely determining the position of fixed ground antennas to aid the study of the dynamics of Earth's surface. This led to the first orbit determination of satellites using GPS [1] and later on, the widespread application of precise orbit determination to other low-earth-orbit (LEO) satellites. GNSS receivers have been designed to meet the need for precise orbit determination (POD) and used in many satellites that required accurate knowledge of their orbits depending on the objectives of the mission. The performance of the POD process depends on the measurement environment, the technique used for processing, and the mission application. The need to reduce the time latency in achieving a precise solution has been of growing interest besides accuracy. This is beneficial to many end-users as they are able to get fast access to orbit solutions [2].

The precise tracking of the orbit of the satellite using onboard GNSS receiver data will benefit the development of several new space applications in the field of navigation systems, telecommunication, remote sensing, and earth observation. Furthermore, in the future, it is anticipated that LEO-based satellites enabled by POD can also offer positioning capabilities that will enhance the Global Navigation Satellite Systems (GNSS) and therefore create tremendous opportunities for various users with new features and possibilities to the navigation field. Therefore, in this paper, we are going to take a look at

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the POD approaches of various LEO satellites and discuss the accuracy levels obtained as well as the methods, techniques, and algorithms implemented.

The rest of the paper is structured as follows, section 2 presents the materials and approaches applied in this paper and lists out the research questions used to achieve the goals of this paper. In section 3 the research questions are addressed to achieve the goal of analyzing the POD used by various LEO satellites and their methods, techniques, and/or algorithms implemented in estimating POD as well as the accuracy levels, latencies, and validation techniques. Section 4 discusses and analyzes our findings and the conclusion is presented in section 5.

2. Materials and Approach

It is essential to review from the existing literature and studies on the different methods and approaches used for precise orbit determination of various LEO satellites. This review was carried out by a systematic search for literatures on precise orbit determination of various LEO satellites from some major digital libraries. The electronic database used for the collection of papers were IEEE Xplore, ScienceDirect, Google Scholar, and Web of Science. The duration of the search criteria was from 2000 to 2021. The search term used to identify the primary studies is "*Precise orbit determination AND LEO OR Precise orbit AND positioning method OR Precise orbit AND positioning algorithm OR Precise orbit AND GNSS OR Precise orbit AND PNT OR precise orbit AND GPS OR Precision AND real-time orbit*". In addition to the aforementioned electronic databases, a relevant repository dealing with GNSS was used to collect the recent papers relevant for our review. This was the extensive archive of The Institute of Navigation (https://www.ion.org/). From the search results, papers that were deemed relevant and requiring further screening for detailed information on the POD and their methods or algorithms used in determining the orbit were selected. A total number of 60 primary papers were then selected based on research questions (RQ) outlined below to meet the review objectives.

RQ1- What is the type of GNSS receiver used in the LEO satellites (single, dual or triple frequency)? What are the accuracy levels obtained in determining the satellite orbit based on such receiver-type?

RQ2 - What is the data type used for the determination of the satellite orbit, is it real-time onboard GNSS data, simulated GNSS data or non-GNSS data?

RQ3 - What are the techniques and algorithms utilized for POD? Are they implemented for LEO orbit satellites?

RQ4 - How is the estimated POD solution validated?

3. Precise Orbit Determination of various LEO Satellites

This paper will not review the research work focused on the attitude determination of the satellites from the existing studies but focus on precise orbit determination. The following section provides a review of the POD of LEO satellites based on the following three categories: GNSS techniques, non-GNSS techniques and hybrid techniques.

3.1. GNSS Techniques

This section takes a look at various studies and implementation of LEO POD based on single-frequency (SF) and/or dual-frequency (DF), single-GNSS or multi-GNSS tracking data. Using SF requires the use of algorithms to mitigate the ionospheric delays that remain in the measurement, unlike when DF is used which has the capability to self-mitigate first-order ionospheric delays. Orbit determination at precise levels can be obtained using dual-frequency receiver with ionospheric free carrier phase observations but they are expensive and energy-consuming. Therefore, smaller satellite missions can use low-cost single-frequency receivers for orbit determination which requires only the relative position of the satellite.

3.1.1. Based on Single Frequency GPS

In [3], [4], [5], [6], [7] and [8], the studies use SF tracking data from onboard GPS to compute the LEO satellites' POD. Various ways for processing SF GPS observations using reduced-dynamic or kinematic orbit determination method for LEO satellites are applied. In [3], the validation and assessment of the quality of the pre-processed SF data are done by comparing it against the corresponding pre-processed DF data. The focus of this study was on the impact of orbital height and GPS data sampling rate on the quality of the pre-processed GPS data which affects the quality of the resulting orbit. While in [4], the estimated orbit is validated with SLR as the satellite is equipped with a laser retroreflector array (LRA). A 3D RMS of about 0.3 m accuracy levels is obtained for POD using SLR. Using a real-time onboard navigation filter, 1.1 m accuracy in 3D RMS was achieved while post-processing on the ground with flight data offered 0.7 m accuracy in 3D RMS. In [5], POD solution based on Schmidt-Kalman filter performed better in terms of accuracy than the standard Kalman filter using single-frequency GPS receiver data. POD accuracy is improved by about 6 cm compared to the standard Kalman filter.

The study in [6] utilizes epoch-differenced carrier phase measurements to smooth GRAPHIC-derived (GRoup And Phase Ionospheric Correction) positions eliminating ambiguities and ionospheric effects. The displacement information obtained is highly accurate in that it will constrain the kinematic positions estimated. Using kinematic POD, position errors and random estimation errors are largely reduced. The 3D RMS position errors are 0.72 m and 0.79 m for the IGS ultra-rapid products and broadcast ephemerides respectively (https://www.igs.org/). While [7] estimated the POD for the SJ-9A satellite with a sequential Kalman filter (SKF) using SF GPS data and ultra-rapid ephemerides products along with GRAPHIC and broadcasts ephemeris. The assessments indicate the position and velocity in 3D accuracies of 0.5 m and 0.55 mm/s respectively. In [8], an integrated POD method is used based on simulated GNSS observations. Reduced-dynamic as well as kinematic POD techniques using pseudorange and carrier phase GPS data are considered in this study. An impressive accuracy improvement of over 70% for POD of all GNSS satellites was possible using the entire LEO constellation compared with ground-based POD. However, this results in a computational challenge due to the usage of entire LEO constellation. This can be resolved by introducing only a part of the LEO constellation to achieve both orbit accuracy and computational efficiency.

3.1.2. Based on Dual-Frequency GPS

GPS-based POD for very low earth-orbiting gravity missions is of high importance. Since the altitude is very low (250 km) high precision orbit determination is challenged due to a rapid accumulation of gravity-field-induced orbit error and uncertainties in describing the effect of atmospheric drags and solar radiation. These effects can be reduced to a few centimeters' orbit error by tuning the precise orbit. Dual-frequency is able to self-mitigate ionospheric effects. [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], made use of either one or two of the following approaches namely dynamic POD, reduced-dynamic and kinematic POD. In [28], [29] the zero-difference kinematic orbit determination was discussed. [30] proposed extended Kalman filtering-based POD determination using a GPS receiver. In a later study, [31] proposed a KPOD algorithm for LEO satellites using zero-differenced (ZD) ambiguity resolution for POD. For this study, DF GPS data from SWARM-C and Sentinel-3A satellites were utilized. The paper discusses mainly the ways to improve the KPOD by fixing the ambiguities of onboard GNSS phase observations. The real-time kinematic POD was carried out for both the satellites with ambiguity fixing and floating solutions. [32] implemented an efficient orbit integrator/filter which will dramatically reduce the computational workload for orbit determination onboard the satellite. A precise orbit with an accuracy level in centimeter to decimeter level is achievable with the proposed numerical method for the integral equation of satellite orbit.

For [33], a term called pseudo-ambiguity is defined, which eliminates the range errors originated from the orbit and clock offset errors of the GPS broadcast ephemeris, providing higher accuracies for orbit determination. The results show that onboard real-time orbit determination for LEO space missions with the accuracy of 0.2-0.4 m for the position and 0.2-0.4 mm/s for velocity with standalone dual-frequency GPS receiver and GPS broadcast ephemeris can be obtained. In [34], the approach in POD is based on the fundamental rule that all observations will be used directly which implies that single or double difference linear combinations of observations are not employed to avoid the drawback of linear combinations where the measurement noise is increased. The advantage of this technique is the ability to directly apply the observed data from the receiver, thereby, preserving the original measurement accuracy and giving the possibility for full exploitation of the contained information from each individual observation type. In [35], a consider Kalman filter (CKF)-based reduced-dynamic orbit determination (RDOD) CKF-RDOD approach was used. The results showed a satisfactory POD with approximately 1.5m level of 3-Dimensional RMS error with the CKF-RDOD approach using GPS data and broadcast messages in real-time scenarios.

The study in [36] and [37], both proposed a POD algorithm to determine the orbit of the LEO augmentation satellite at centimeter-level using a dual-frequency GPS receiver. These algorithms were based on Precise Point Positioning (PPP) preprocessing algorithm utilized to determine the precise single-point position. In [37], the proposed PPP navigation solutions showed an improvement of about 0.5m over the onboard GPS NAV technique of ALOS2 suppressing the error spikes of the onboard GPS NAV data. For the study in [38], a simulation-based real-time POD solution using GPS pseudorange observations from HY2A and RINEX/DORIS 3.0 phase observation data is evaluated. For the POD solution, RTODLEO (Real-Time Orbit Determination Software for Low Earth Orbit Satellite) was used. The results showed that 3D positional accuracy calculated using GPS pseudorange observations is 6.803 m. [39] used the Kalman filter algorithm for real-time POD providing seven different solutions using the onboard and simulated data. From the results, dual-frequency Galileo and BeiDou-3 measurements lead to a significant reduction of 3D RMS orbit errors compared to GPS-only and achieve a positioning accuracy of about 10.4 cm in 3D RMS.

3.1.3. Based on Single & Dual-Frequency GPS

A reduced-dynamic orbit determination method was applied by [40] to study the POD of the GRACE satellite. A Kalman filter-based approach and least-squares estimator approach were carried out for the GRACE satellite equipped with a SF and DF GPS data. The DF orbit determination solution in terms of typical RMS errors with respect to JPL reference solution of about 4 cm was achieved. While SF data achieved better than 10 cm in 3D RMS. Both Kalman filter and least-squares approaches provided similar and accurate results which match an external reference solution. [41] proposed a new onboard POD algorithm designed with unscented Kalman filter (UKF) and extended Kalman filter (EKF) method for spaceborne GPS receivers. The real GPS data of CHAMP and KOMPSAT-2 satellites were used for verifying the onboard orbit determination. Overall, the POD results with UKF were slightly more accurate than using the EKF method.

3.1.4. Based on Single-Frequency GPS/BDS

Based on the real-time single-frequency GPS/BDS data, [42] explored the optimal force models, the effect of different measurements, and the effect of GPS and BDS data fusion. SATPODS (Space-borne GNSS AuTonomous Precise Orbit Determination Software) is used to implement the onboard real-time orbit determination (RTOD) algorithm and perform all the onboard operational scenarios. PANDA (Positioning and Navigation Data Analyst) software generates post precise orbits which was used to assess the accuracy of the orbit estimated using the onboard RTOD algorithm. For FengYun-3C, a real-time orbit accuracy of 0.4–0.7 m for position and 0.4–0.7 mm/s for velocity is achieved.

3.1.5. Based on Dual-Frequency GPS/BDS

The weak geometry of ground stations was a major concern in determining the precise orbits of the BDS satellites in geostationary orbit (GEO). The geometry of the BDS satellites can be improved using a LEO satellite with an onboard GNSS receiver apart from the ground data. In [43], the procedure used is the reduced-dynamic and a kinematic orbit solution. The combined GPS/BDS data gave good results.

From this study, the procedure is suitable for GOCE and it can meet the accuracy requirements of 2 cm (1-dimensional). Similarly, in [44], [45], [46], [47], [48], [49], [50], [51], [52], [53] combined use of GPS and BDS data are used. The contribution of BDS to the POD of LEO satellites was also discussed. [47] claims that SLR is one of the main means of external validation for the orbital solution with an accuracy better than 1 cm. These results indicate that the orbit accuracy obtained can reach centimeter-level when GPS/BDS combination is implemented. In addition, due to the fact that large GPS tracking losses happen and few channels are assigned for BDS signals, increasing the number of DF observations can further improve the POD performance.

3.2. Non-GNSS Techniques

This section discusses the various studies and implementation of the LEO POD based on non-GNSS data. Non-GNSS data utilized in estimating POD of LEO satellites include Satellite Laser Ranging (SLR) and Doppler Orbitography by Radio positioning Integrated by Satellite (DORIS).

3.2.1. Satellite Laser Ranging (SLR)

[54] & [55] utilized the SLR technique in estimating the POD solution. [54] computed the precise orbits for over six months using the tracking data from the Haiyang-2 satellite. There are no significant systematic biases compared to the DORIS data. A 3-dimensional orbit accuracy of about 12.5 cm was achieved. While [55] used SLR to determine the precise orbits of multi-GNSS satellites in geostationary orbits (GEO), medium earth orbits (MEO). Though multi-GNSS satellites are equipped with various GNSS receivers, SLR-based estimation of POD solution was analyzed by [55]. There is an increase in the accuracy levels of multi-GNSS orbit determination using SLR with increases in the number of SLR observations and the number of stations tracking the satellite. There are not many studies on LEO satellite orbit determination solely using SLR based on the search term used in this review analysis.

3.2.2. DORIS

[56] utilized DORIS alone to estimate the POD of HY-2A which delivers phase and pseudorange measurements. Centre National d'Etudes Spatiales (CNES) provide the raw phase and pseudorange measurements, preprocessed DORIS 2.2 Doppler range-rate product. VMSI software used in estimating HY2A DORIS orbits process only doppler range-rate product. A suitable method is implemented in constructing the phase increment data and estimating POD based on the phase incremented data and doppler range-rate data. The orbits estimated are evaluated by comparing with the CNES precise orbits and SLR residuals. HY2A DORIS POD is estimated using the VMSI software and the comparison of POD results with the CNES orbits and SLR range measurements shows that the two orbits have near-identical accuracy, radially approaching 1-cm.

3.2.3. DORIS & SLR

[57] on the other hand, estimated POD for Haiyang-2A satellite using DORIS, SLR, and a combination of both DORIS + SLR. The three different orbit solutions estimated from this study were compared with the CNES orbits. A centimeter-level accuracy of the POD solution was obtained. From the analysis, SLR data directly contribute to the overall estimation of precise orbits of the satellite while DORIS + SLR data requires further investigation in terms of biases from observations, tropospheric effect, and DORIS network time.

3.3. Hybrid Techniques

Hybrid techniques are the combination of the GNSS and non-GNSS techniques which utilize the onboard GNSS receiver data and one or more non-GNSS data such as accelerometer data, DORIS data, star tracker's attitude data.

3.3.1. GNSS & Accelerometer Data

Hybrid techniques using onboard dual-frequency GPS receiver data and accelerometer data were proposed by [58] & [59] for POD. [58] discussed the usage of accelerometer (ACC) data on the GRACE satellite during high solar activity to study its effect on the POD of the GRACE satellite. The orbit accuracy estimated is assessed by making use of a number of varying tests from SLR residuals, K-Band Ranging (KBR), and external orbit comparison. The residuals using accelerometer data were always better. Also, from the external orbit comparison, the results showed better orbit comparison when using GPS and ACC combinations than using only GPS data. There is no need to model the non-gravitational forces using accelerometer data for GRACE POD resulting in more accurate orbits. [59] stated that accelerometer data from the GRACE satellite offered by Information System and Data Center (ISDC) contains measurement errors. It is removed by using a certain smoothing technique such as the Vondrak method utilized in this paper and in addition, ACC data of 1-second interval is converted to a 10-second interval for POD. The ACC data provided by the GRACE satellite offers new ways to solve the effects of force model errors. The previous studies experimented using only GRACE data for reducing the effects of the force models on the POD. The results obtained from the previous study are compared with the same GRACE data processed along with ACC data to understand the performance of ACC data in POD accuracy. For this study, the zero-difference (ZD) and single-difference (SD) POD method was utilized in estimating the orbit of the satellite. The obtained POD solutions from ZD and SD POD methods are compared with the precise science orbits (PSO) provided by GeoForschungesZentrum (GFZ). The comparison shows that there are no significant offsets in all three orbital components with root-mean-square (RMS) in centimeter-levels.

3.3.2. GNSS & DORIS

The onboard GPS data and DORIS data are combined to form a hybrid technique in estimating the precise orbits for LEO. [60] focused on POD using DF GPS data and DORIS as well as validation with SLR. With dynamic and reduced-dynamic methods, three orbit solution strategies are applied such as (1) DORIS dynamic (DORIS Dyn); (2) GPS reduced dynamic (GPS RD); (3) DORIS and GPS reduced dynamic (DORIS+GPS RD). The radial orbit differences among the three solutions and DORIS (CNES) solution are calculated. Though there exist certain abnormal values, DORIS (CNES) and GPS solutions estimated RMS error is 1.66 cm while the worse comparison results among the four solutions are only 3.16 cm RMS. Validated HY-2A POD solution with SLR data from several global stations. The validation results show that SLR residuals for DORIS (CNES) and GPS solution are better than DORIS and GPS/DORIS solutions with SLR residual RMS for GPS solution of 2.75cm. From the SLR residuals results and independent solution orbit comparison analyses, a centimeter-level POD accuracy has been obtained for all solutions of the HY-2A satellite.

3.3.3. GNSS, Accelerometer & Attitude Data

[61] discussed POD for GRACE satellite using a hybrid of GPS, accelerometer data, and attitude data from the star trackers. The study was performed using the CSR Multi-Satellite Orbit Determination Program (MSODP), which is based on a dynamic orbit determination method utilizing the batch processing approach. Orbit accuracy depends heavily on the force models which are currently not modeled precisely enough. Using accelerometer data from GRACE, it is possible to reduce the effects of force model errors on POD. POD solution is estimated for GRACE GPS data with and without accelerometer data. For GPS alone case, RMS and residuals decrease as the sub-arc length decreases.

The orbit accuracy cannot be substantially improved by the tuned gravity model when compared with TEG4. From the hybrid data, GRACE cross-track component using GPS data is better than using combination of all the three data due to the accelerometer biases where cross-track bias is more difficult to estimate accurately. GRACE orbit accuracy better than 5 cm in each direction is achieved.

4. Discussion

The conducted review has indicated significant success in applying the onboard GPS technique for precise orbit determination of the satellite. The review analysis shows that a lot of work has been carried out in estimating POD solutions based on dual-frequency GPS receivers due to their advantages over the single-frequency receiver. There are very few existing studies that focused on using non-GNSS techniques-based determination of the precise orbit of the LEO satellites. There is still a need for more efficient alternative solutions for non-GNSS-based estimation of the precise orbits of LEO satellites apart from the GNSS receivers, SLR, DORIS, accelerometer, and star tracker attitude data. In addition, research work based on hybrid techniques utilized onboard GPS along with SLR and/or accelerometer data and/or DORIS and/or attitude data to estimate orbit solutions with high accuracy. From Figure 1., we can see the different methods for POD and the frequency of use based on the reviewed papers.

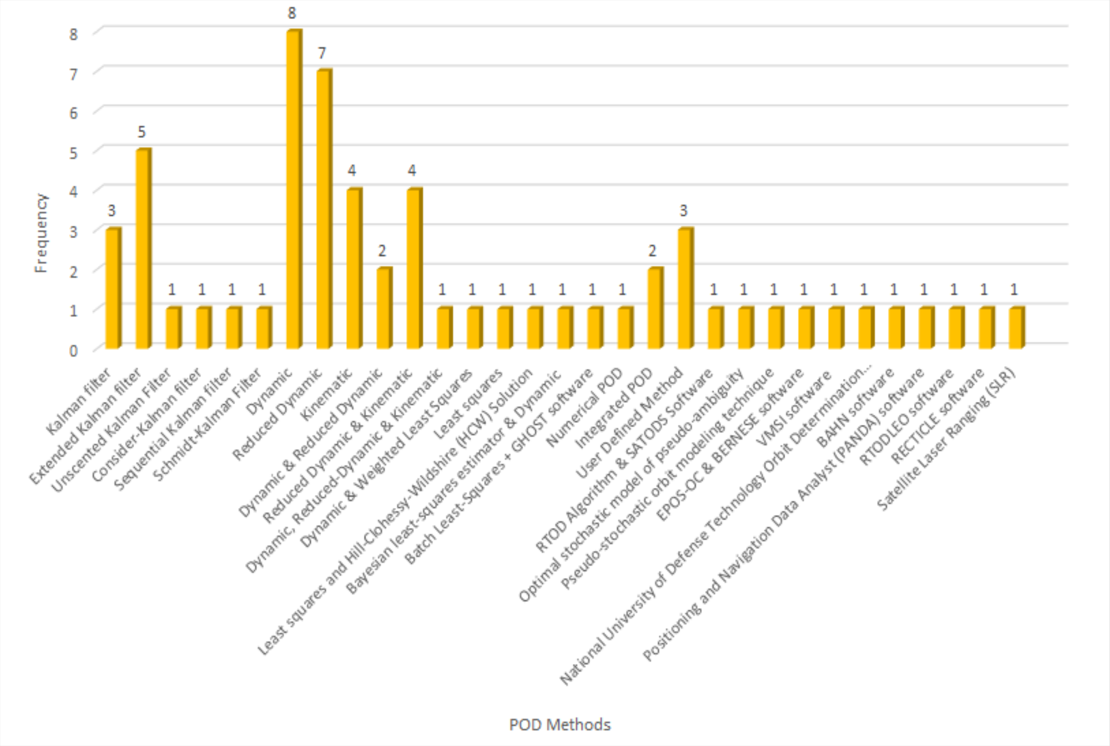

Figure 1. Different POD methods & its frequency based on the reviewed papers.

With the advancement in technology, CubeSat with low-cost high performing multi-constellation GNSS receivers are yet to be launched into space apart from the recently launched Bobcat-1 satellite mission [62]. Most of the research work on precise orbit determination was carried out on GEO and MEO satellites with GNSS payloads of higher mass, volume, and power. LEO being the future of space technology applications with CubeSats of smaller size and power, high computing, and advanced GNSS receivers require research work to be done in developing new algorithms and methods to improve the accuracy levels and reduce the latencies in the determination of real-time precise orbits of the LEO satellites. Accuracies of LEO satellite orbit determination can be improved with highly sophisticated orbital models, integrated algorithms, and filtering techniques. It involves intensive computation for the onboard orbit determination processing due to the estimation of several parameters. Also, such high computational power is a limiting factor in small satellites. Therefore, the need for models that balance between accuracy and computation efficiency making use of simple but efficient models, integrated algorithms and filtering techniques.

5. Conclusion

This paper discussed several techniques, methods, and models that have been used in various research for the precise orbit determination of LEO satellites. The various techniques presented include GNSS (single-frequency, dual-frequency), Non-GNSS and Hybrid. Onboard GNSS data have now become a major means of precise orbit determination for satellites on low earth orbit. Several of the research made use of GNSS-based POD while using Non-GNSS methods (SLR) for Validation.

The precise tracking of the orbit of the satellite using onboard GNSS receiver data will benefit the development of several new space applications in the field of navigation systems, telecommunication, remote sensing, and earth observation. Furthermore, in the future, it is anticipated that LEO-based satellites enabled by POD can also offer positioning capabilities that will enhance the Global Navigation Satellite Systems (GNSS) and therefore create a tremendous opportunity for various users with new features and possibilities to the navigation field. Future satellites with altimeter and radio-occultation payloads may require real-time POD to enable onboard processing of science data for forecasting or nowcasting of meteorology data, open-loop instrument operations of radar payloads, or quick-look onboard science data generation. Also, precise real-time orbit information may be utilized for constellation maintenance of satellite formations.

An interesting area of study for future research is in the CubeSat as not all LEO satellites equipped with GNSS receivers at present are CubeSats. Therefore, research need to be done on LEO CubeSats of smaller size and power, high computing, and advanced GNSS receivers to develop new algorithms and methods to achieve high accuracy levels and with minimum latencies in the determination of the precise orbits of the CubeSat.

Conflict of interest

The authors declare no conflict of interest.

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