The potential of LEO mega-constellations in aiding GNSS to enable positioning in challenging environments

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Keywords: GNSS, LEO augmentation, Positioning, POD, LEO satellite clocks.

SUMMARY

Signals from the emerging Low Earth Orbit (LEO) satellites from mega-constellations that broadcast internet, such as Starlink (Space X), OneWeb, Iridium etc., also known as "signals of opportunity" (SOP), can potentially aid positioning. These LEO satellites are approximately 20 times closer to Earth compared to the GNSS medium-earth orbit (MEO) satellites – with 300-1500km altitudes, and 90-120 minutes orbital periods. Hence, LEO satellites provide a new navigation space infrastructure with much stronger signal power than GNSS signals. This makes these LEO signals more resilient to interference and available in deep attenuation settings. In challenging environments, with limited GNSS observations that may not allow positioning, such as in urban canyons, bushland, or bottom of mining pits, integrating LEO signals with the available GNSS observations can enable positioning. Moreover, the corresponding high speed of LEO satellites enables faster satellite geometry change, and hereby significantly shortens the convergence time for precise point positioning (PPP).

In this contribution, the positioning from LEO Doppler shift time variation integrated with GNSS and two challenges in positioning using LEO will be briefly discussed. For positioning, the orbits of LEO satellites and their clock behaviour must be known. In addition, unlike GNSS satellites, LEO satellites are not equipped with atomic clocks, and typically use ultra-stable oscillators (USOs) or oven-controlled crystal oscillators (OCXOs), nor are they tightly time-synchronised with each other. The estimation and prediction of these orbits and clock errors and drift are discussed.

1. INTRODUCTION

Reliable precise positioning navigation and timing (PNT), which depends mostly on the use of Global Navigation Satellite Systems (GNSS), such as GPS, is essential to many of our essential applications in transport, defence, mining, construction, automation, space and agriculture. However, the provision of this positioning service in challenging environments such as in urban areas, when working close to buildings, and bottom of open-pit mines, has long suffered from signal blockage, causing receivers to track only a limited number of satellites, which severely limits positioning capability. In addition, due to the weak GNSS signals strength, they are vulnerable to "spoofing" and electrical interference.

Over the next decade, LEO satellites will be abundantly available. Hundreds of LEO satellites in constellations such as SpaceX, OneWeb, Iridium, OrbComm, and Globalstar provide internet access worldwide (Psiaki, 2021; Khalife and Kassas, 2020). A significant part of these constellations is currently operational and providing internet service. Their signals can be employed for positioning, and thus are known as "signals of opportunity" (SOP). A second type of LEO satellites that can be used for positioning will be equipped with navigation payloads to provide GNSS-like signals, such as code and carrier-phase observations. For example, Future Navigation (China) is building a constellation comprising more than 100 satellites for GNSS augmentation supported by laser inter-satellite communication links. Moreover, the Kepler system, which is a possible evolution of Galileo, will include LEO satellites in addition to the medium earth orbits (MEO) satellites.

These LEO navigation signals can supplement GNSS signals in challenging signal-visibility environments and offer several additional benefits. For example, their satellites are approximately 20 times closer to Earth compared with GNSS satellites – with 500-1500km altitudes, thus, providing much stronger signal power, 24 to 34 dB higher than GNSS signals. This makes them available in deep attenuation environments, such as in urban canyons, and even in some areas indoors, addressing a known gap in GNSS positioning, and more resilient to interference. Their rapid change of geometry will also lead to multipath decorrelation.

The use of LEO signals for positioning to supplement GNSS is in its early phases, with only a few groups working in this area. Most results, for example, Psiaki, 2021; Reid et al., 2018; Wang et al., 2018, are presented through simulations due to the need for developing appropriate receivers or front ends for navigation of moving objects. Early results based on actual LEO SOP signals from Starlink are presented in (Neinavaie et al., 2021).

The positioning also requires estimation of satellite clock offset from its constellation reference time and their drift, in addition to the satellite precise orbit determination (POD). These two aspects will be briefly discussed. POD for LEO satellites was addressed in our research (Allahvirdi-Zadeh et al 2021 and 2022) using a reduced-dynamic method that combines dynamic models (describing the satellite motion under gravitational forces and other perturbation terms) and GNSS measurements, and the integrity of POD was addressed in Wang et al. (2022). Additionally, Geoscience Australia (GA) is introducing POD of LEO in their GNSS analysis centre software 'Ginan'. Moreover, the main weak part of the LEO system is its timing accuracy. Most LEO satellites do not have atomic clocks, but rather employ OCXO or ultra-stable oscillators (USO) that have poorer stability than the current GNSS clocks. These clocks may also exhibit mid- and long-term systematic effects. This paper is designed as follows, positioning from LEO is briefly discussed in the next section followed by a discussion of POD and clocks of LEO, and finally, some concluding remarks are drawn.

2. POSITIONING USING LEO SOP

An advantage of LEO satellites over MEO (GNSS) with respect to the Doppler effect lies in the satellite's higher orbital speed resulting in a greater Doppler effect that is more easily detected. The carrier-Doppler shifts from the mega-constellation LEO satellite downlink signals can be estimated as the negative of the time derivative of the accumulated delta range divided by the carrier wavelength, which are generally feasible (Psiaki, 2021). The corresponding beat carrier-phase data can be obtained as the negative time integral of these Doppler shifts. The details of the broadcast SOP LEO satellites signals, including modulation, timing, and spectral characteristics are currently under investigation. Many research challenges are still under investigation including studying the LEO small footprint, the number of usable satellites for positioning as they do not have significant overlap, limited time visibility of the

LEO satellites, which is typically less than 20 minutes, their low elevation angles, type and size of the antenna, and tracking of satellites for a moving object. Moreover, while the orbits, frequencies, polarizations, and beam patterns of these systems, are given in the public record through the licensing databases of the US Federal Communications Commission, details on the signal waveforms themselves and the timing capabilities of the hardware producing them are still being researched. The high data rates and more frequent updates to the broadcast message of LEO satellites could potentially compensate for the less accurate clocks used.

Following Psiaki, 2021; and Neinavaie et al., 2021, in forming the observation equations, pseudorange rate observables are formed from the tracked Doppler frequencies by two steps (i) downsampling by an estimated factor to avoid large time-correlations in the pseudorange observables and (ii) by multiplying them by the wavelength to express the Doppler frequencies in distance per second. The pseudorange rate observable from LEO satellites can be written as a function of the vector between the receiver and the satellite spatial position, the satellite 2–D velocity vector, a constant bias due to the unknown Doppler frequency ambiguity, and the measurement noise, which can be modelled as a zero-mean, white Gaussian random variable.

The position estimation method is based on using an extended Kalman filter. The state model includes the user position and velocity, satellite clock offset and drift, receiver clock offset with respect to different constellations, and their rates, and system combined biases, which are formed using the S-system theory to address the rank deficiencies underlying the problem. The ionosphere delays can either be estimated or provided externally, e.g. from a network, such as those defined as Network RTK, which covers almost all urban areas in Europe, North America, Australia, Japan and many countries. The spatial estimation of the user location needs knowledge of the satellite orbits and clocks. This will be addressed in the next sections. The integration of these LEO satellites with GNSS can minimise the number of needed simultaneous satellites, so any observed GNSS satellites could reduce the need for LEO, and vice versa. In addition, to minimize the number of unknowns, the tropospheric delays, can be estimated from GNSS satellites and are predicted in time. The troposphere variation with time over this period can be assumed as negligible.

3. PRECISE ORBIT DETERMINATION (POD) OF LEO SATELLITES

Estimation of the satellite locations is dependent on whether the LEO satellite is equipped with GNSS receivers and whether they are sharing this information with users. If the LEO satellites do not share their position with the user, their orbits can be estimated using the two-line element almanac (TLE) data available from North American Aerospace Defence Command (NORD) and the TLE epoch time is adjusted for each satellite to account for ephemeris errors. Next, the orbits are predicted using a dynamic model that describes the satellite motion under forces such as gravitational forces and other perturbation terms. For LEO satellites with GNSS receivers onboard, the orbits can be determined in real-time or post-mission with two main methods, kinematic POD which considers only GNSS observations, and Reduced-Dynamic (RD) POD which combines both the dynamic modelling with GNSS measurements (Allahvirdi-Zadeh et al., 2022). Post-mission POD is a well-established procedure to reach accuracy within 1 cm, by considering all dynamic models and implementing the integer ambiguity resolutions using carrier-phase measurements. However, the real-time POD has different requirements and reaching similar accuracies to the post-mission mode is still in question. One of these requirements is the availability of real-time precise orbits and clocks of GNSS satellites in space that are used to determine the location of GNSS receivers onboard LEO satellites. The new generation of Australian/New Zealand Satellite-Based Augmentation System (AU/NZ-SBAS), as well as the Japanese MADOCA service, provide these corrections in space through geostationary and navigation satellites, respectively. The orbital accuracy and the clock stability of these corrections are validated in comparison with the IGS final products (Allahvirdi-Zadeh et al., 2021). The RMSE values of these products are within 15 cm for GNSS orbits and 0.2 ns for their clocks computed over a testing period between 14 and 20 August 2018, as shown in Figure 1. POD accuracy of a few centimetres is achieved using these products for LEO satellites such as GRACE-FO and Sentinel-3 satellites based on batch least-squares adjustment, which show the potential for reaching such accuracy for LEO satellites used for positioning.

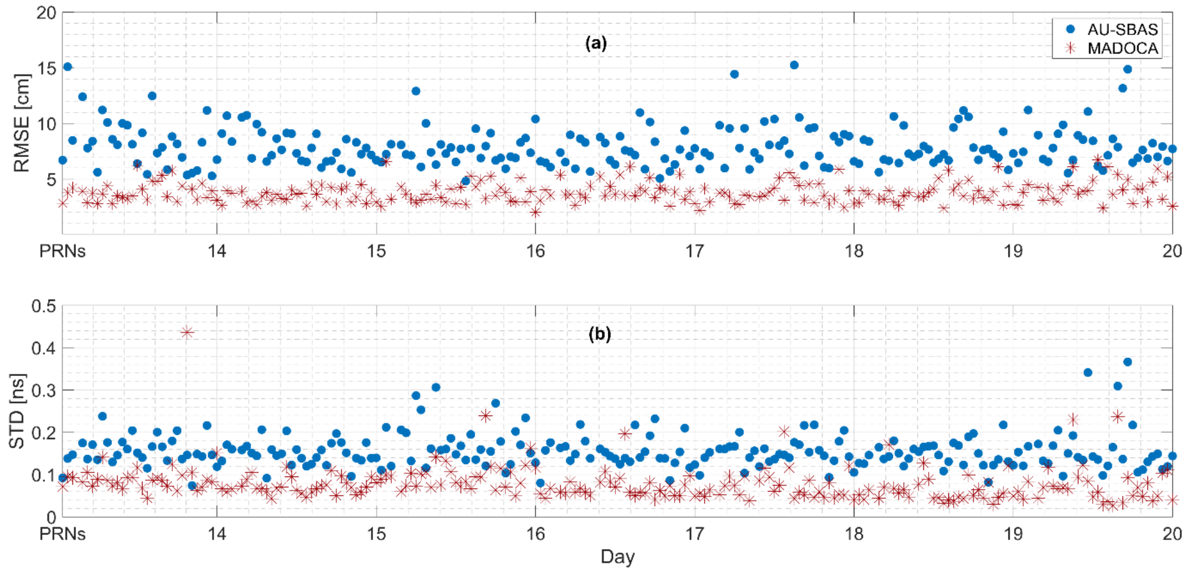

Figure 1. RMSE of the (a) orbits and (b) clocks of MADOCA and AU/NZ-SBAS with respect to IGS final products for August 14–20, 2018. The area of each day is divided into 31 sections, representing 31 GPS PRNs. Each dot/star represents the result of one GPS satellite on a corresponding day.

The GNSS observations are usually equally weighted in the POD procedure of LEO satellites. On the one hand, the identity weighting matrix is not an impartial choice for all receiving observations. On the other hand, the elevation-dependant weighting models that are used for GNSS are developed for the signals influenced by tropospheric delays and relatively large multipath effects, while such circumstance does not exist for LEO orbits. Therefore, a new weighting model based on the signal-to-noise ratio of the received signals is proposed and has been tested in the POD of 17 CubeSats, which is one form of LEO satellites. The internal validation methods confirm the orbital accuracy improvement using this method and the corresponding residual reduction (Allahvirdi-Zadeh and El-Mowafy, 2021). The overlapping differences are less than 5 cm in all directions and the posterior sigma values, plotted in Figure 2 for one month, are less than 4 mm. These values are doubled in the case of using elevation-dependent weighting models.

The available Attitude Determination and Control System (ADCS) of some LEO satellites are usually equipped with low-power GPS-only space sensors and are not capable of receiving signals from other constellations and real-time corrections in space. One solution is to equip the LEO satellites with software-defined radio (SDR). The SDR can receive a wide range of signals, including GNSS signals and corrections, perform some tasks of real-time POD in its Field Programmable Gate Arrays (FPGA), and transmit information to the other LEO satellites. The possibility of using SDR as a separate GNSS receiver is tested and the limitations are discussed in (Allahvirdi-Zadeh, 2021a).

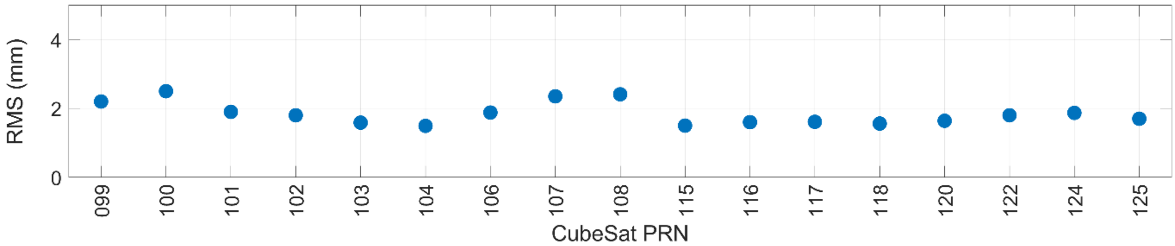

Figure 2. Root mean squared (RMS) of the posterior sigma values for all 17 CubeSats over the testing period (16 Dec 2020 – 15 Jan 2021)

The phase centre offsets and variations (PCO and PCV) of the antennas are essential in POD. The LEO satellite's GNSS antenna is calibrated by the manufacturer and the PCV values are derived using ground calibration methods such as anechoic chamber and robotic methods. However, these PCV values do not reflect the real situations of the antenna in space such as near-field multipath. Therefore, an empirical PCV pattern based on the actual observations should be computed using the iterative residual method. Such a PCV pattern of the patch antenna onboard an LEO satellite is compared with the initial pattern provided by the manufacturer in Figure 3. Applying this pattern in kinematic POD can reduce the observation residuals to 6-7 mm (Allahvirdizadeh, 2021b).

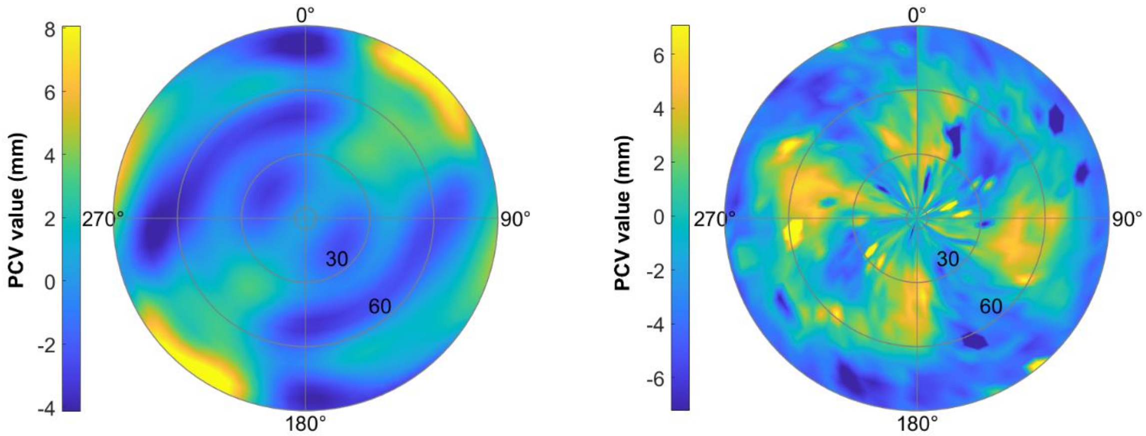

Figure 3. Initial PCV pattern provided by the manufacturer (left), the empirical PCV pattern from real observations (right)

4. LEO SATELLITE CLOCKS

Similar to the LEO satellite orbits, precise LEO satellite clocks are essential to realizing single-receiver precise positioning for users on the ground. Benefiting from the fact that LEO satellites can receive dual-frequency phase and code measurements when being equipped with a GNSS receiver and antenna onboard, the satellite clocks can be estimated together with the satellite orbits using the least-squares adjustment. The accuracy of the LEO clock estimates is related to the accuracy of the used GNSS measurements associated with satellite orbits and clocks, and the processing strategy. It is nowadays also possible to fix the integer ambiguities at the un-differenced level when having the observation-specific biases (OSBs) introduced in the estimation process (Mao et al. 2020). This, again, improves the accuracy of the LEO satellite orbits and clocks to another level, i.e., within 1 cm.

The estimable LEO satellite clock error contains not only the clock bias itself but also hardware biases that are lumped together with the clock parameter. As the true values of the estimable clocks are difficult to be obtained for a real LEO satellite flying in its orbit, the accuracy of the LEO satellite clock errors is evaluated by simulations. The observed-minus-computed (O-C) term of the phase and code measurements have considered the following errors:

i. The equal-weighted noise with a standard deviation of 0.001 m for phase observations, and 0.1 m for code observations.
ii. Real-time GPS satellite clock and orbital errors from the French National Centre for Space Studies (CNES) (Kazmierski et al. 2018) compared to the final GPS products of the center for orbit determination in Europe (CODE). The real-time clocks are re-referenced to that of the CODE final clocks. The combined orbital and clock errors are generally at a few cm.

Figure 4 shows the LEO satellite clock errors estimated in different modes using the simulated O-C terms as described above. The “KN” and “RD” denote the kinematic and reduced-dynamic estimation modes, respectively, while the abbreviation-addition "F" indicates the case that the integer ambiguities are fixed. The noise and real-time GPS satellite clock and orbital errors are projected on the clock estimates of different estimation modes. The decreased high-frequency noise due to the strengthened model when applying dynamic models (see the RD items in the legend) can be observed in the blue and green dots. With the ambiguities fixed and the model further strengthened (see the yellow and green dots), the long-term errors caused by the float ambiguities are driven from the clocks to the residuals. Still, the real-time GPS orbital and clock errors, i.e., the miss-modelled errors, degrade the RDF clocks (green dots) with a once-per-revolution (1/rev) systematic pattern of the LEO satellite. This corresponds approximately to the 1/rev geometry change between the LEO and the GNSS satellites.

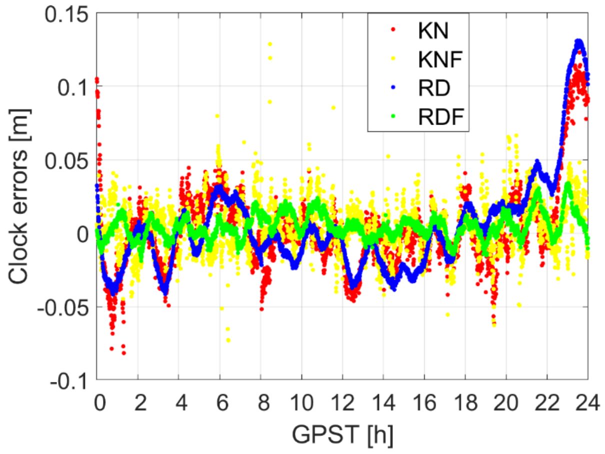

Figure 4. LEO satellite clock errors of different estimation modes considering equal-weighted noise and real-time GPS satellite clock and orbital errors. “KN” and “KNF” represent the kinematic estimation mode without and with the integer ambiguities fixed, respectively. “RD” and “RDF” represent the reduced-dynamic estimation mode without and with the integer ambiguities fixed, respectively.

With the real-time GPS satellite orbital and clock errors not considered in the O-C terms, i.e., considering only the noise, as shown in Figure 5 for one day of simulated data, the ambiguity-fixed clocks (see the green and yellow dots) become almost white noise. However, without fixing the ambiguities, as shown by the blue and red dots, long-term systematic effects over hours can be observed due to the influences of the float ambiguities.

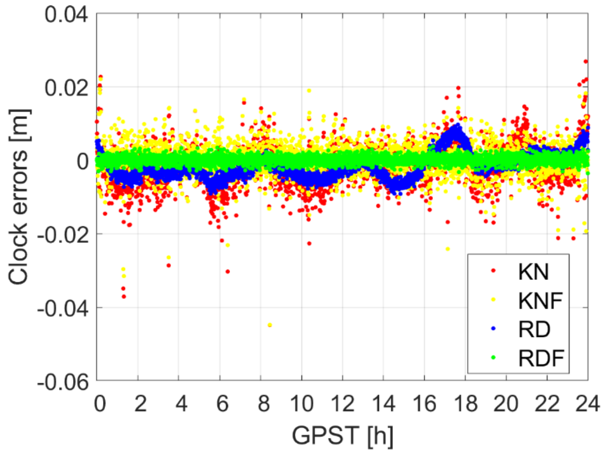

Figure 5. LEO satellite clock errors of different estimation modes considering only the equal-weighted noise. “RD” and “RDF” represent the reduced-dynamic estimation mode without and with the integer ambiguities fixed, respectively.

The short-term stability of the onboard clocks is essential and augmenting GNSS for positioning, navigation and timing applications using LEO constellations. For CubeSat clocks that confront challenges in achieving good short-term stability, there are some possible remedies for the instabilities observed in these clocks (Allahvirdizadeh et al., 2022b):

- Increasing the strength of dynamic models in POD,
- Applying a better thermal control model to decrease the hardware biases due to thermal variations;
- Applying empirical PCV patterns based on actual space situations
- Considering the higher order of gravity in the relativity model
- Equipping the LEO satellites with chip-scale atomic clocks.

The impacts of each proposed remedy on improving short-term clock stabilities are discussed in (Allahvirdizadeh et al., 2022b). In summary, several microseconds improvements in the estimated CubeSat clocks are observed after applying the proposed remedies.

For real-time users, the high-accuracy LEO satellite clock estimates, no matter in which mode, is not the end-product that can be directly used for positioning. Real-time users are using predicted clocks, and the prediction time depends on the latency of the GNSS measurements to be transmitted to the ground, the processing time, the signal transmission time, and the sampling interval of the clock transmission. Unlike the GNSS satellite clocks, the LEO satellite clock prediction faces new challenges. As mentioned in (Wang et al. 2021), the prediction of the LEO satellite clocks is related to the following issues:

i. The stability of the clock itself. Nowadays, many LEO satellites are equipped with very stable frequency oscillators. The ultra-stable oscillator (USO), as an example, exhibits very good short-term stability of $1-3\times10^{-13}$ within 10 to 1000 s (Weinbach & Schön 2012).
ii. The systematic effects induced by non-clock sources. For example, due to the much lower orbital height, the relativistic effects of LEO satellites are more influenced by the Earth's gravitational field and are more complicated than those of the GNSS satellites (Larson et al. 2007). In addition, long-term systematic effects that cannot yet be perfectly explained were also detected in the first GRACE Follow-on satellite and Sentinel-3B satellite (Wang et al. 2021).
iii. The GNSS observation errors could lead to higher short-term instability in the clock estimates than the clock itself.
iv. The LEO clock estimates contain the ionosphere-free (IF) code hardware biases of the LEO satellite. Although the LEO satellite signal transmitter (to the ground) is assumed to be synchronized by the same clock as that by the GNSS receiver, the users conventionally expect the LEO satellite clocks to contain the IF code biases of the transmitter. A bias, which could be more or less constant over time, needs to be calibrated and bridged.
v. The time reference to calculate the LEO satellite clocks is often not stable enough. This disturbs the prediction. The LEO clock estimates are to be aligned to a more stable time reference before the prediction.

5. CONCLUDING REMARKS

LEO-based positioning is a promising technique that can cover a known gap in GNSS positioning, where due to its weak signals, GNSS signals can be obstructed by structures and tree canopies, hence, positioning becomes unavailable in areas such as urban environments. LEO signals are stronger than GNSS signals and thus are available in such challenging environments. LEO mega-constellations signals, which provide internet service, can be employed for positioning, and thus are known as “signals of opportunity” (SOP). A significant part of these constellations is currently operational. The second type of LEO satellites will be equipped with navigation payloads to provide GNSS-like signals. LEO-based positioning is, however, is in its early phases and has many challenges before being commercially available.

More research is needed in many areas. Among these are, studying signal acquisition and tracking, type of receivers and antenna that can be used for positioning, satellite number, geometry and footprint and their impact on positioning, signal direction, angle of arrival, and strength, and the utilisation of Doppler shifts in the positioning model. The positioning also requires estimation of the satellite clock offset from its constellation reference time and their drift, in addition to the satellite's precise orbits.

Estimation of the LEO satellite orbits is dependent on whether the LEO satellite is equipped with GNSS receivers and whether they are sharing this information with the user. If the LEO satellites do not share such information, their orbits can be estimated using the TLE data available from NORD, adjusting the TLE epoch time, and predicting them using a dynamic model that describes the satellite motion under space forces. For LEO with GNSS receivers onboard LEO satellites, the orbits are determined in real-time or post-mission modes with two main methods, kinematic or reduced-dynamic POD. Equipping chip-scale atomic clocks would significantly increase the stability and the accuracy of the clocks and combining them with the SDR will increase the number of available signals and bring us one step to the real-time POD onboard LEO. The accuracy of the clock estimates is related to the accuracy of the introduced GNSS orbits and clocks, the processing strategy, and whether the phase ambiguities are float or fixed. Real-time users still face challenges when utilizing LEO satellite clock products. This should draw further attention to the community of LEO-augmented PNT service.

Acknowledgement

This research is funded by the Australian Research Council—discovery project (No. DP 190102444), the Institute for GeoScience Research (TIGeR) – Curtin University, the National Time Service Center, Chinese Academy of Sciences (CAS) (No. E167SC14), the National Natural Science Foundation of China (No. 12073034).

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