PNT user-segment optimization integrating LEO components

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ABSTRACT

In the context of emerging Low Earth Orbit Position Navigation and Timing (LEO PNT) studies and solutions, this paper introduces the main problematics of the navigation using LEO satellites from user segment perspective. The discussion is divided in three parts.
The first part intends to capture the system differentiators of a positioning service in LEO compared to MEO. This first part deals with the principal signal modification due to LEO satellites.
The second part is focused on user algorithms. The best suited acquisition and tracking strategies are proposed to cope with the high dynamics of the signal. Then, the particularities of observations from LEO space vehicle (SV) are analyzed in the frame of the PNT algorithms and especially Precise Point Positioning and inertial navigation solutions.
The last part of this paper propose a strategy for the validation of the identified trends. This validation is centered on simulations and supported by an experimental phase.

I - INTRODUCTION

With the increasing demand for positioning solutions and the favourable context of New Space emergence, worldwide agencies examine Low Orbit Positioning solutions, to complement current GNSS systems. Actually, GNSS faces some challenges in signal constrained zones (e.g. low visibility and GNSS outage, multipath and NLOS, etc.) which degrade the performance of the computed navigation solution. Using LEO (Low Earth Orbit) satellites in addition to MEO (Medium Earth Orbit) GNSS satellites allow to deal with many of these challenges and hence to improve the navigation solution. This is due to the high dynamics of LEO satellites (compared to the MEO ones) and to their stronger signals with less path loss.

This paper focuses on the user segment and on the feasibility of integrating the LEO components in the navigation system at user level. It shows some benefits of considering such system on the navigation solution and presents a strategy to evaluate these benefits through simulations and experimentations.

Therefore, leveraging the differentiators of LEO with respect to GNSS MEO, a special attention is paid to the analysis of the impacts on user algorithms. Actually, some adaptations may be needed on baseband algorithms (acquisition and tracking) to process LEO satellites' signals with high dynamics. The LEO RAW measurements could be then used in addition to those of GNSS with different PNT algorithms. Several use cases where the use of LEO satellites would help to improve the navigation solution are presented. Finally, an experimentation/simulation plan (validation strategy) is proposed to validate the proposed solutions at the user level and to evaluate the performances in several use cases and configurations through a variety of KPIs (Key Performance Indicators).

II - LEO-BASED NAVIGATION SYSTEM

This section intends to discuss the system differentiators of a LEO constellation compared to the already existing MEO ones.
The first differentiator is the signal power at receiver antenna level. LEO constellations could have advantages in environments where the C/N0 of GNSS is degraded and signal could not be tracked. This is the case for indoor applications. Two characteristics of the LEO can leverage the signal power. The first one is to benefit from the lower altitude of the LEO satellite to enhance the link budget. Indeed for a LEO constellation at 600km of altitude, the free-space path loss is lower of 30dB compared to a MEO constellation at 20000km. This budget margin can be used in many ways such as downsizing of the on-board power budget or increasing the effective received power on ground or both of them. The second characteristics of the LEO with respect to the signal power, is the opportunity to redefine the carrier frequency of the signal emitted by the satellites. In such a case, the free-space path loss is also improved. Downshifting the carrier frequency from L1 to 200 MHz for instance provides an extra margin of free-space path loss of 18dB. In both cases, the increase in received signal power ease the acquisition and tracking process of the signal.
The second differentiator is the high dynamics of the LEO satellites. First, the high dynamic of the LEO SV increases the maximum Doppler shift of the received signal forcing the acquisition process to extend the frequency research window in case of cold start. However, one needs to put this inconvenience into perspective because of the infrequent use cases really performing cold starts nowadays. Secondly, the high dynamic of the LEO SV is expected to enhance the global geometric diversity of the accessible GNSS services. Depending on the sizing of the LEO constellation, long GNSS outages due to harsh environment such as deep canyons are expected to be replaced by shorter ones or completely removed thanks to the ability of the LEO SV to quickly cross the sky. On the other hand, if the masking conditions are shortened due to the dynamic of the LEO SV, availability of the LOS is shorten as well. This is why it is expected that reacquisition of LEO signals are going to be more frequent. Another differentiator of the LEO signal dynamic compared to MEO one is the volatile characteristic of the multipath [1] [2]. The fast evolving geometry shortens the time coherency of the channel. This is expected to be the most impactful for receiver conditions where the MEO multipath are seen to be static or slow varying, i.e. when the receiver antenna is moving slowly or with a trajectory parallel to the reflecting surface. Reduction of the multipath time coherency with respect to the integration duration does reduce the error made by the tracking discriminators.
The third and last differentiator of the LEO constellation compared to the MEO resides in the sizing of the number of satellites. Because of the relative low altitude, ensuring a good availability and continuity of the LOS to the user requires a sufficient number of satellite. The number and altitude of the LEO SV will need to complement the current GNSS constellations in signal constrained environment. In the case of severe masking, the visibility of one or two LEO SV may be sufficient to complement the low number of GNSS observations. This is particularly true for inertial navigation solutions requiring absolute observations during GNSS outages where the filters are in pure inertial propagation.

LEO satellites could then complement the GNSS ones in order to improve the navigation solution at the user level. Hence, a dedicated analysis for the user algorithms is needed in order to leverage the use of LEO satellites for PNT services.

III - USER ALGORITHMS

One of the main aspects to be addressed for the integration of LEO in the PNT user-segment is the impact on user algorithms. Indeed, due to the high dynamics of the LEO satellites some adaptations are needed at the baseband level (acquisition and tracking) to process these new signals. Moreover, the satellites dynamics and the characteristics of the received signals could have some advantages for PNT algorithms and for the navigation solution, in particular in GNSS signal constrained environments.

1 Acquisition And Tracking

From baseband point of view, LEO-based PNT is characterized by high dynamics signals due to a larger Doppler shift induced by the relatively high velocity of the transmitter. In this context, we can benefit from the know-how available in the frame of GNSS positioning for receivers that experience large accelerations and velocities, such as those on-board missiles, space launchers or LEO satellites. Two main challenges arise in these scenarios: increase of computation time during acquisition and tracking loss. Moreover, in severe Doppler conditions, code-frequency offset (also referred as code Doppler) can also be significant and needs to be compensated [3]. This effect has a bigger impact in high chipping rate signals such as those with high-order BOC modulations [4]. Considering that the visibility time window of a LEO satellite is also smaller, a standard acquisition approach is not expected to be robust enough in our new context. Regarding tracking, the increase of Doppler-rate under high dynamics might cause phase, frequency and code deviations that could not be followed by typical PLL, FLL and DLL architectures in standard GNSS receivers. Despite their configuration being able to be adapted to account for such variations, there is a known trade-off between increase of bandwidth (to add more capacity of response to fast changes) and noise reduction, thus resulting in a degradation of position accuracy.

1.1 *Fast acquisition*

Acquisition of spread spectrum signals essentially consists of scanning in both code and frequency domains (also referred as pseudorange and Doppler respectively) in order to locate a peak of energy that provides an initial rough estimation of their location in both domains. Conceptually, such scanning is done by cross-correlating the input baseband signal against a clean-replica of the different spreading codes modulated at different frequencies. This type of implementation is known as serial search, where the cross-correlation is done by means of accumulators. However, it is barely used due to its rather high processing time. In order to reduce acquisition time, there are basically three additional search strategies [5] depending on which domain a parallelization method is applied: parallel frequency search (PFS), parallel code search (PCS) and two-dimensional methods.

A relevant aspect in the frame of this project is that code Doppler compensation is usually neglected in standard GNSS acquisition, but it might have an important impact in a scenario with high dynamics such as LEO PNT. Therefore, the PCS method is then the best option in this context because its capability to apply such correction. In addition, it provides fast acquisition with moderate memory requirements, and any frequency assistance will make it more interesting compared to the other approaches. In addition, there are several FFT-based techniques [6] [7] that could be applied to further increase its efficiency. Finally, the transition from acquisition to tracking might be also a critical point under high dynamics because the initial frequency estimation could be already outdated at the initiation of the tracking process. Therefore, Doppler rate (and even jerk) shall be also estimated during acquisition in order to properly extrapolate the frequency estimate. This requirement can be incorporated to the PCS method by means of a FFT-based maximum-likelihood detection approach, as done in [8] [9].

As a last remark, in the case of using high-order BOC signals, an additional methodology shall be considered for addressing the ambiguity threat due to the secondary peaks in the autocorrelation function (ACF). Under these circumstances, BPSK-like techniques, also referred as sideband processing [10], might be the most appropriate option for acquisition purposes because they allow the use of higher search steps compared with the ambiguous ACF situation [11] [12]. The basic idea is to process separately the main lobes of the BOC signal as BPSK-like contributions to then do incoherent accumulation. The result is a smoothing on the ACF, thus allowing an unambiguous tracking by sacrificing the narrow peak of the original BOC signal, which also provides more robustness against uncompensated Doppler effects.

1.2 *Tracking under high dynamics*

Once a signal from a LEO-based PNT transmitter has been acquired, the receiver must keep track on it (if we assume a closed-loop architecture). Therefore, from the comprehensive survey available in [13], we focus on the robust tracking methods most suitable for high dynamics, which can be classified within three main families:

- *Frequency aided loops*: Despite being more robust than PLL discriminators, stand-alone FLL discriminators tend to increase the output noise level when obtaining frequency measurements. In order to overcome this limitation, a valid solution is to jointly adopt both discriminators. By means of such hybrid scheme, the FLL is in charge of tracking and coarsely removing the input carrier dynamics, thus allowing the PLL to operate with much less dynamic stress (narrower bandwidth). Another option, known as unambiguous frequency aided PLL (UFA-PLL) [14], is to combine phase and frequency measurements within the PLL structure, that is, the frequency error information is used to correct the nonlinearity of the PLL instead of constructing a parallel loop to aid the PLL. The frequency information is used to build a non-ambiguous phase detector. In terms of tracking performance and robustness the UFA-PLL is comparable to FLL-assisted PLL architectures, but with less computational complexity.

- *Adaptive bandwidth loops*: The fast adaptive bandwidth PLL (FAB-PLL) is a standard PLL with an additional stage, which determines the actual working conditions and adapts the loop filter bandwidth according to these conditions [15]. This is done with an estimation of the dynamic stress, using a jerk (Doppler rate) discriminator. With proper monitoring of these measurements a change on the working conditions may be detected, and establishing one or more thresholds, the bandwidth of the PLL can be correctly adjusted. A less complex alternative is to employ look-up-table (LUT) with some correspondence for the pair bandwidth - C/N0, which is known as projected loop bandwidth PLL (PLB-PLL) [16].

- *Kalman filters*: In contrast with the classic PLL approach, the KF framework is the natural way to obtain a closed-loop architecture where the filtering coefficients are automatically and optimally (under the linearity and Gaussianity assumptions) adjusted so as to minimize the mean square error between the input signal and the local replica. An additional advantage of KF-based techniques over the previous approaches is that they rely on the dynamic state-space model representation, which includes a statistical modelling of the noises affecting the system. This model may include any system perturbation such as multipath effects. The price paid, however, is an increased complexity. Despite of this, many researchers have considered KFs as a means to achieve robust carrier tracking for GNSS signals, as in the case of [17], where a particular configuration (unscented KF) is applied to a high dynamics case.

Considering the frame of the project, where the user equipment is envisaged for general civilian applications (low cost), a decision-driver has been to minimize complexity. Therefore, the selected techniques for closed-loop tracking that will be evaluated are UFA-PLL and PLB-PLL.

Finally, challenging scenarios where continuous tracking is not possible are also planned to be evaluated, such as indoor or situations with low-power restrictions. In these cases, open-loop architectures (sometimes referred as snapshot solutions) need to be considered. Moreover, an intermediate implementation might combine the advantages of both open- and closed-loop schemes to give rise to the so-called quasi-open-loop tracking approach. In fact, one of the first designs for high dynamics GPS receivers was based on this type of architecture for estimating Doppler frequency and code delay [18] and it is also used nowadays for keeping the communications under extremely harsh scenarios such as the entry, descend and landing of the Mars Exploration Rover [9]. The underlying idea is to benefit from the robustness of an open-loop scheme while reducing its complexity by downsizing the search grid space. This can be done by using a-priori information from time-delay and frequency estimates obtained from a loop filter during the previous epoch. In those cases where the snapshot period is too long due to long integration requirements (e.g. for processing weak signals), a linear filter can be added to the architecture in order to smooth and extrapolate such time-delay and frequency estimates. Then, it is not difficult to see that when reducing the search grid size, which essentially controls the trade-off between complexity and robustness of the whole system, the architecture tends to the conventional closed-loop approach.

2 PNT Algorithms

The GNSS could provide an accurate and safe navigation solution at lower cost but it faces several challenges and limitations. These limitations are due to signal constrained environments where effects such as multipath, interference, low visibility, GNSS signal outage and others are likely to happen.

To counteract the threats in signal constrained environments several sensors are usually used together with the GNSS receiver. The multi-sensor fusion is used to improve the navigation solution in terms of accuracy, availability and other performance indicators. The most know sensors usually hybridized with GNSS are the IMU (Inertial Navigation Unit) and the odometer. Perception sensors such as Lidar, Camera and Radar are widely used in addition to GNSS, IMU and odometer for critical applications like autonomous vehicle. Different grades of these sensors with different levels of performance are available. The grade used depends on the targeted application and the performance requirements

In addition, the use of multi-frequency and multi-constellation allows to reach better performance in terms of availability and accuracy of the navigation solution. However, this performance still insufficient for several applications and in many use cases. Techniques such as RTK (Real Time Kinematics) and PPP (Precise Point Positioning) may be used to compute high accuracy solution. RTK is a quite powerful technique because it enables centimetre level accuracies with immediate ambiguity resolution in optimal conditions. However, it remains local because it is based on a base station and on the fact that the end user and the base station are close enough. PPP is a promising technique due to its global coverage and its high accurate solution but it faces challenges related to the convergence time.

Considering all the above mentioned challenges and limitations, using a LEO constellation could have many advantages and allows to counteract several problems. This could be done due to the high speed of LEO satellites, the more accurate orbits estimation compared to GNSS MEO satellites and the stronger signal. Hence, using signals from LEO satellites allows for example to reduce the convergence time of the PPP, to reduce the impact of multipath or signal outage of the

GNSS. To study the benefits of using LEO satellites several use cases and applications with different performance requirements may be considered. Therefore, for safety critical applications, for example, where performance requirements are stringent, the LEO signals with PPP could be used in addition to GNSS and a tightly coupled hybridization with IMU and odometer to meet the requirements. For less demanding applications, the LEO signals may complement the GNSS and hybridized with IMU in a tightly coupled scheme. For low energy applications, a snapshot positioning technique with LEO signals may be considered.

In the following, the benefits of LEO satellites in different use cases and environments are discussed.

2.1 PPP Convergence Time

As mentioned above, one of the main challenges of the PPP technique is its convergence time. Several studies addressed this problematic and proposed solutions to reduce this time. PPP-AR (Ambiguity Resolution) technique can be used to reach better accuracy and improve slightly the convergence time. To do so, code and phase biases need to be provided in addition to orbit and clocks corrections in order to fix integer ambiguity. However, at this stage, convergence time is still an issue preventing using PPP techniques for many applications. [20] showed that the convergence time of a dual-frequency PPP-AR solution could be reduced by applying atmospheric constraints (for ionosphere and troposphere). [21] presented results in terms of accuracy and convergence time obtained with different configurations for PPP ambiguity resolution. The provision of Ionosphere and Troposphere corrections by an external source could reduce the convergence time with dual-frequency especially when considering multi-constellation. On the other hand, this study showed that using triple frequency with atmospheric corrections could lead to an instantaneous convergence. However, this study has not addressed the adaptability of this solution for real-time processing. Indeed, using tri-frequency with PPP may be sometimes a challenge for real-time applications where more resources might be required at receiver level to process three different frequencies and to estimate additional unknowns [22].

It has been proven that adding lines of sight from new satellites provides additional uncorrelated information to the user algorithm and leads to better and faster convergence. Therefore, considering a LEO PNT constellation, in addition to the GNSS constellations, could play a significant role to reduce the convergence time of the PPP technique. Actually, as stated in [23] LEO satellites move with a higher speed than the MEO satellites with respect to the ground receivers which brings great geometry changes. This should lead to a faster convergence, explained by a greater capacity to differentiate local errors, like clock and tropospheric effect, but also to mitigate un-modelled effects like multipath. [24] analysed the effects of using three types of LEO constellations with different number of satellites on the convergence time. The results obtained with dual-frequency AR-PPP for GNSS and LEO show that a TTFF (Time To First Fix) of 60 seconds is needed to reach several centimetres of accuracy with a LEO constellation of 298 satellites. These results prove the high potential of LEO constellations to improve the accuracy and the convergence time of the PPP solution.

A performance assessment is then foreseen in order to evaluate the number of needed LEO satellites and other key parameters (e.g. need for external atmospheric corrections) to improve the convergence and re-convergence time (after GNSS outage) of the PPP solution.

2.2 Urban Environment

In an open sky environment, the performance of GNSS and the proposed algorithm with PPP and hybridization with other sensors generally allow to meet the specified requirements. However, in signal constrained environments (e.g. urban, sub-urban, canopy and tunnel) several effects could occur and degrade the performance of the proposed algorithm in terms of accuracy, availability and integrity. Indeed, in such environments additional errors are likely to happen due to multi-path, NLOS (Non-Line Of Sight), signal outage, low signal-to-noise-ratio and others. As mentioned in [25], errors caused by multi-path could reach, theoretically, 150 m for L1 signals while those caused by NLOS could be up to several kilometres [26]. These effects are further amplified by the dual-frequency Ionosphere-Free combinations [25].

Techniques such as advanced signal processing techniques, error characterization of the GNSS measurements and Fault Detection and Exclusion may be used to deal with the abovementioned threats in urban environment. Nevertheless, these techniques are sometimes insufficient and do not allow, in some conditions, to reduce the resulting errors due to these threats. Measurements from LEO satellites could complement those of GNSS satellites and enable an improved navigation solution in this environment. Indeed, the LEO satellites have a mean motion of 0.06°/s compared to MEO satellites with a mean motion of 0.008°/s [27]. This short orbital period of LEO compared to MEO satellites may be beneficial in signal constrained environments [27] [28]. This may be explained by the fact that reflections are no longer static over short averaging times which may results in a greater multipath rejection of satellite signals [28]. In addition, LEO satellites are closer to the Earth, thus they have stronger signals with less path loss. This makes them more resilient to jamming or other effects in the urban environment such low signal-to-noise ratio [28].

An analysis on the benefits of using LEO satellites in urban environment will be done through simulations with multipath and NLOS effects. Several configurations in terms of user dynamics, LEO constellation orbit and characteristics of the received signal will be considered.

2.3 GNSS Signal Outage

During GNSS outage, the usage of sensors like IMU and Odometer allows to maintain a good performance during several seconds or tens of seconds. The performance mainly depends on the grade of the used sensors and on the accuracy of the navigation solution just before GNSS outage. However, for long GNSS outage (more than several tens of seconds) the solution error increases dramatically (several meters or tens of meters) and become insufficient to meet the performance requirements.

In some use cases and environments, signals from LEO satellites may still be visible and used by the receiver even if signals from GNSS MEO satellites are not visible or could not be tracked (e.g. low C/N0). In these specific conditions, the LEO satellites may have an added-value to improve the navigation solution especially in the case where a tight coupling scheme is considered. Indeed, for such coupling scheme even a low number of visible s atellites (less than four) may be used to update and compute a navigation solution.

Several studies have addressed the case when a low number of GNSS satellites are visible and analysed the obtained results in terms of positioning errors. By analogy, these studies could be useful to understand the benefits of having a LEO satellites during GNSS outage. For instance, an analysis was performed in [27] where an algorithm based on low-cost DF (Dual Frequency) GNSS/PPP and MEMS IMU was tested in difficult environments. The results showed that during a simulated GNSS-outage of 30 seconds, a horizontal accuracy of 40 cm and vertical accuracy of 1.2 m could be obtained with four satellites in visibility. However, the obtained results showed that the solution had a degraded performance after the end of the GNSS outage (compared to the solution without a simulated GNSS outage). This study shows that some GNSS line of sights (less than four) (or by analogy measurements from a LEO constellation) may not be sufficient to keep a very accurate solution (several decimetres) during GNSS outage. However, these results could be compliant with applications that have less stringent requirements.

A more detailed analysis will be done to quantify the minimal number of satellites needed to keep an acceptable performance for different types of applications. This analysis will be performed through simulations taking into account a variety of configurations.

IV - VALIDATION STRATEGY

In order to validate and to evaluate the performance of the user algorithms with LEO satellites, a set of experimentations with several scenarios and configurations are foreseen. A specific end-to-end simulation tool is being developed. The main objective of this simulator is to provide the means of evaluating the main performance drivers of a LEO PNT service. It uses representative models to simulate various configurations of constellations, propagation channel and user algorithms (acquisition, tracking and PVT computation).
While the simulated GNSS constellation shall represent as closely as possible the current orbits, the LEO constellation will be flexible by design to explore various altitudes, orbital configuration and number of satellites. The propagation channel will estimate the delay and power budget of the signal for an extended frequency range from FR1 to FR2 bands. The budget will be composed of antenna, clock, orbit accuracy and atmospheric effects from the signal emission up to the user reception. The effects of the local environment on the signal will be modelled in order to evaluate the benefice of the LEO where it expected to bring the most advantages. Local model will emulate masking and multipath conditions

to bring the quick variation of the LEO signal to light. The local model will also allow to simulate different kinds of local environment such as canopy, light or deep urban conditions. The propagation channel will also be representative of the user dynamics from pedestrian to road users applications. It is to be validated, at this stage of the simulation, the reduction in the time coherency of the multipath as well as the signal link budget for indoor LEO PNT users. This propagation phase of the simulator needs to be backed by an experimental process in order to increase the confidence level of the propagation channel. In particular the tropospheric attenuation model for FR2 bands during raining conditions as well as the indoor attenuation model seems to be a large contributor of the signal attenuation in and needs to be verified.

As soon as the time varying propagation channel is established, the raw measurements (e.g. Pseudo-Range, Doppler, Carrier-Phase) are created by two means. Either by running receiver tracking loops models implementing the major error contributors (noise, multipath) or by simulating real LEO signal samples ingested by specifically tuned tracking loops. It is to be validated, at this stage of the simulation, that the acquisition and tracking algorithms identified to be the best candidates in this paper, are indeed well suited for the processing of LEO PNT signal. Each acquisition process will be evaluated thanks to the acquisition threshold and processing duration. For what regards the tracking algorithm candidates two behaviours are to be validated. The first one is the ability to withstand the LEO dynamic by keeping track of the signal and estimating the tracking loop code and phase dynamic error. The second one is to confirm the whitening effect of the LEO multipath during the integration phase by measuring the code and phase tracking error in urban areas.

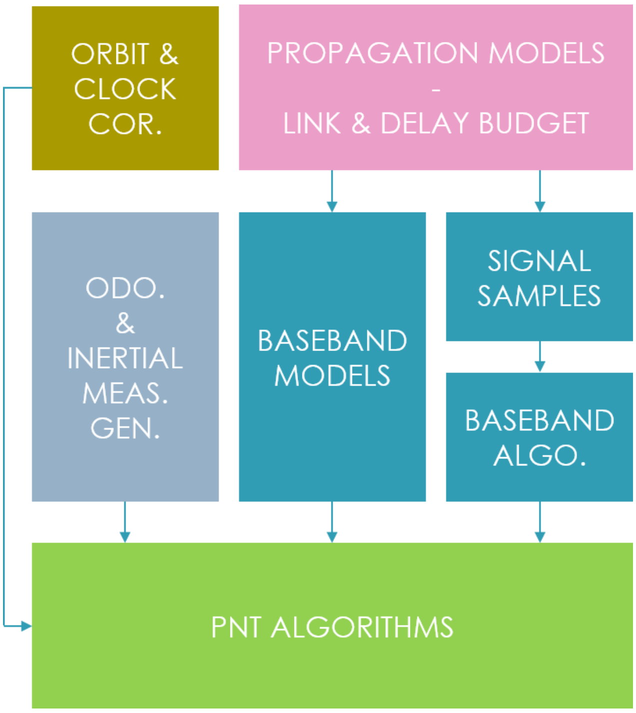

Figure 1: LEO PNT Performance Simulation Strategy

The GNSS and LEO observations will join emulated PPP corrections and inertial and odometer measurements in order to run navigation filters. The navigation filters will allow to assess the benefices of future LEO PNT in terms of solution accuracy, availability and continuity. Several use cases and applications will be considered and hence different PVT algorithms (e.g. with or without PPP corrections, with or without inertial and odometer sensors, code or carrier-phase based techniques). A performance assessment will be then done in order to evaluate the improvement of the PPP convergence time with GNSS and LEO satellites compared to GNSS-only solution. A variety of parameters will be considered in order to identify the impact of the number of LEO satellites, the considered orbits and other aspects on the convergence time. The added-value of LEO satellites in urban environment in terms of multipath rejection of satellite signals will be evaluated as well. Multipath and NLOS will be simulated and different types of users will be considered (e.g. static, pedestrian, vehicle). Moreover, GNSS signal outage will be simulated with different durations of outage. The benefits of using LEO satellites in terms of accuracy and availability of the solution will be studied and in particular when used with other sensors (IMU and odometer).

V - CONCLUSION

The main differentiators of future LEO PNT service for user algorithms has been provided. The first one being the signal power margin due to the lower altitude and the redefinition of the signal. The second being the signal dynamics impacting multipath coherence time and geometric continuity of the line of sight. And the third one being the constellation sizing driving the outages' duration impacting the provision of measurements to the inertial navigation filters.

A first assessment of the acquisition and tracking particularities for LEO PNT signals has been discussed. Parallel Code Search methods are analysed to be best suited for fast acquisition of LEO PNT signals and support of Doppler assistance. For what concerns the tracking strategy, unambiguous frequency aided PLL and projected loop bandwidth PLL are detected to be good candidates for the tracking of signal with high dynamics.

Concerning the PNT algorithms, the access to measurements from LEO satellites are expected to bring benefits for inertial navigation solutions and for the convergence time of the ambiguity resolution algorithms.

Finally, an opening is made on the validation strategy as presented in this paper. The validation strategy relies on the use of simulations backed with experimentation phase for the increase in the confidence of the models. The simulations are defined to validate the ability of the identified baseband processing to answer the particularities of signals from LEO constellations and to validate the availability, continuity and convergence trends identified on the PNT algorithms.

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