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Receiver architectures for positioning with low earth orbit satellite signals: a survey

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Abstract

Positioning, Navigation and Timing (PNT) are services generally provided by Global Navigation Satellite Systems (GNSS). GNSS reside in medium to high orbital altitudes from the Earth's surface, resulting in weak signal reception. However, user applications are increasingly in need of higher power signal strength or alternative PNT solutions. An influx of satellites in Low Earth Orbit (LEO) are driving such innovation in PNT technology. Improved signal strength compared to GNSS can be obtained from LEO satellites merely due to their proximity to Earth. Therefore, even communication satellite transmissions are becoming appealing to navigation, as so-called Signals of OPportunity (SOP). In order to benefit user applications, the receiver architectures for LEO-SOP, as well as potential LEO-PNT signals are explored.

Keywords: Positioning receiver, LEO positioning, LEO satellite, GNSS signal

1 Introduction

Low Earth Orbit (LEO) satellites are promising candidates for aiding PNT robustness. So-called CubeSats populate LEO in the thousands due to cheaper manufacturing cost compared to current Global Satellite Navigation System (GNSS) satellites that need to be radiation hardened for the Medium Earth Orbit (MEO) environment. A paradigm shift has taken place where LEO constellations have outgrown any previous constellations in numbers and are launched by companies rather than nation states.

Two types of services are being built. First, companies are offering for profit Internet services [1], better known as Internet of Things (IoT). Second, PNT robustness and improvement services are being tackled. They are aimed at precision, needed in automation for example, with plans toward signal encryption improving performance against malicious attacks such as spoofing [2].

The proximity of LEO satellites to users is the driving factor behind these developments. A received signal gain is achieved due to lower path loss along the shorter distance to the user [3]. Furthermore, a user will see a LEO satellite traverse the observer's sky faster than a MEO satellite. Resulting rapid changes in satellite to observer geometry are studied as beneficial to Precise Point Positioning (PPP) convergence time [4]. However, the signal gain comes at the cost of the satellite footprint. A LEO satellite footprint is in the order of tens of kilometers whereas one MEO satellite is generally visible from half of the globe. This disadvantage has only been outweighed by manufacturing many more satellites at cheaper prices per unit. Thereby increasing the availability of LEO satellite signals.

LEO can be used for PNT in two distinct ways. The first kind is an augmentation to existing infrastructure and second are dedicated, sometimes stand-alone systems. LEO satellites can be used in combination with, or instead of MEO GNSS. Commonly LEO signals are used as so-called Signal of OPportunity (SOP). A satellite SOP is commonly measured as the Doppler shift of the signal's carrier frequency. Due to the large number of satellites per constellation, the communication and IoT constellations are the main source of satellite SOP for PNT. IoT services broadcast broadband signals, in contrast to narrowband signals for communication. LEO-SOPs have been studied as easy access but low precision PNT solutions ([5]), and as back-up ([6]) or augmentation ([7, 8]) to MEO GNSS. Designs of dedicated LEO-PNT however, target high precision applications, robustness against attacks or low signal environments [2]. Positioning strategies might resemble current MEO GNSS and the signal correlation process in case of a dedicated PNT signal. A case for a simplified GNSS signal is also made in favor of accessibility [3]. Furthermore, the concept of adapting IoT signals for positioning gain is also studied [9]. The significance of LEO satellites to PNT is showcased in increasing investment into this type of system, see for example [10].

Research into LEO-PNT use cases are diverse and increasingly numerous. From signal in space optimization [11] and geometric constellation performance [12] to LEO contributions in positioning. The latter comprises studies on LEO-PNT standalone systems [2] [13], precise positioning [14], urban positioning [15], as well as interoperability and complementing GNSS [16]. They may be summarized as "Protect, Toughen, Augment, Backup and Complement (PTABC)" to navigation and communication systems [17]. The user segment completes a LEO-PNT system. It faces challenges in hardware and software. Hardware is related to the non-availability of complete commercial receiver set-ups. The software needs to deal with the fast changing Doppler via suitable algorithm [18], while also providing precise positioning solutions. The impact of precise timing components for example is studied by Cassel et al. [19].

The need of user equipment is expected to grow with the continued interest in more LEO-PNT systems or applications. At the heart of the user segment is the receiver and its signal processing. Customized to a given system's signal, the receiver performs signal interception, error correction and PNT computation. A review of the state-of-the-art in LEO-PNT receiver solutions is thus useful to a growing number of users in diverse applications.

This paper presents an overview of receiver set-ups in LEO-PNT, and their positioning performance. The current state-of-the art LEO receiver architecture is a customized Software Defined Radio (SDR). The hardware may be composed out of COTS components [20]. We compare variations of this architecture type in terms of user positioning accuracy and availability of a positioning solution. The article is outlined in two sections, followed by the conclusion. The next section elaborates on Positioning with Low Earth Orbit Satellite Signals, and section three is titled Navigation Receivers for LEO signals.

2 Positioning with low earth orbit satellite signals

A basic method of determining a position is known as trilateration. This concept is shown in Fig. 1 using satellites. PNT satellites transmit precise timing information, that the user may calculate their own distance. When the distance to these satellites is known, the point of their intersection informs the user of their own position. An additional satellite is needed for correction of the user-receiver clock that biases the distance calculation. Therefore, the measurement range is termed pseudorange, as it includes errors that differ from the true range. The GNSS signal consists of three layers, the carrier wave, code, and navigation data. The carrier is modulated by the code and data signals to be replicated by a GNSS receiver. Once the received signal matches the replicate, acquisition is complete. Acquisition is followed by data processing to calculate the position. The interested reader is referred to [3] for further details in GNSS and PNT development.

LEO on the other hand is not home to a GNSS constellation yet. However, studies on dedicated LEO-PNT signals are emerging and will be discussed at the end of this section. Currently, LEO satellite signals are utilized in positioning as Signals of OPportunity (SOP). SOP in PNT refer to signals not being designed for positioning, that nonetheless provide a positioning opportunity. The state-of-the-art LEO SOP is presented in the following subsection. Then, we present augmentation methods of LEO positioning to MEO GNSS.

2.1 Signals of opportunity

LEO constellations that are currently broadcasting signals with a sufficiently large number of satellites are listed in Table 1. They are communication constellations completed in the 1990 s and are suitable sources of SOP. Moreover, LEO constellations providing internet in various planning and completion stages serve as theoretical SOP and are listed in Table 2. Earth observation satellites in LEO are another possibility to be

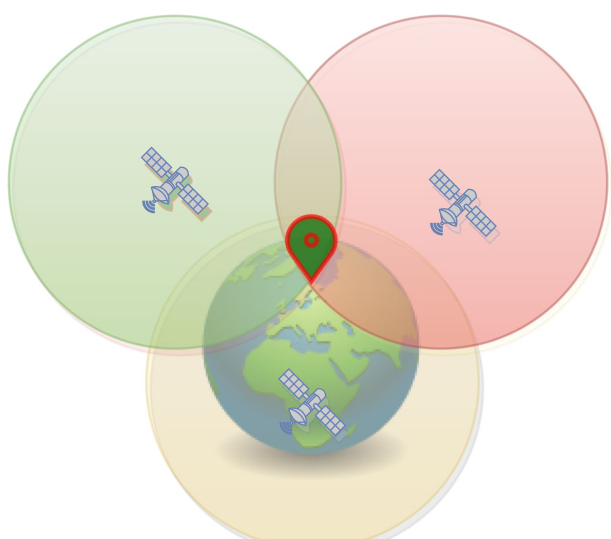

Fig. 1 The distances to a varying number of satellites is presented as spheres with the radius equal to the distance, leading to a user position determination on Earth as the intersection of three satellite ranges, known as Trilateration

Table 1 Parameter summary of currently operational LEO constellations, that are of interest to PNT exploitation

Constellation	Center Frequency	Altitude[Km]	Inclination[°]	#Sats
OrbComm	137, 138MHZ	815,785–875,740	45, 70, 108	47
Iridium	16161626MHz	625, 720	86.4	66
Globalstar	1.6, 2.5GHz	1400	52	48

Based on references [3, 3, 21–23]

Table 2 Summary of planned constellation parameters upon completion based on current proposal application status

Constellation	User Frequency	Altitude [Km]	Inclination [°]	#Sats
Starlink	10.712.7GHz	540,550,560,570	53.2, 53, 97.6, 70	>10000
Kuiper	17.720.2GHz	590, 610, 630	33, 42, 51.9	3236
OneWeb	10.712.7GHz	1200	87.9, 55, 40	6372
Telesat	17.820.2GHz	1015, 1325	98.98, 50.88	1671
Pulsar	?	600-1200	53, 90	>300

Generally the constellations are planned to be larger, but the process of approval is ongoing. Based on references [1, 24–28]

Table 3 User positioning accuracy comparison of opportunistic signal Doppler measurements

User	Aid	Lowest RMSE [m]	Note	Ref.
Static	TLE, EKF	11.38	Experiment 25 SV, 4 minutes vs. simulation	[30]
Dynamic	IMU, altimeter, EKF	10.5	TLE and GNSS initialization	[22]
Static	altimeter, TLE	7.7 (2D)	Utilizing Starlink signals	[31]
Static	TLE, EKF	132 (2D)	Experiment multi-constellation	[5]
Static	TLE, altimeter	168 (2D)	Low signal environment tracking loop improvement	[32]
Dynamic	INS, TLE, EKF	200 to 1000	Aircraft trajectory calculation	[6]
Dynamic, Static	AoA, KF	100 (near base)	Feasibility study with base station and dynamic receiver	[33]

explored for such SOP, but at the time of writing there have not been significant efforts in this direction.

The most studied SOP method is based on the Doppler effect. A relevant challenge of these techniques is the lack of a navigation message. Although possible, the position determination without accessing a navigation message is still a topic of continuous research [29]. Various methods have been formulated and compete for accuracy and availability. They are compared here, as summarized in Table 3. Common to most methods is the dependency on further sources to obtain all unknowns of the ranging equations. Two-Line Element (TLE), that are files published by the North American Aerospace Defense Command (NORAD), are often used to fill this gap. They contain almanac, that is data on the satellites' orbital state that are valid for 24 h but not very accurate. Another common component is a variant of a Kalman filter, such as an Extended Kalman Filter (EKF). As a mathematical model to produce a positioning solution based on iterations of initial input values, it belongs to the receiver structure and is discussed further in the next section.

The framework constructed by Khalife et al is exemplary for LEO Doppler positioning. It is composed out of an EKF, a stationary receiver, TLE files, an altimeter as the only source of altitude, plus enough knowledge of the signal to extract the Doppler shift and clock drift [30]. The signal is modulated with the QPSK method. Noise within the signal is modeled as a zero-mean white Gaussian distribution with known variance. The change in the timing reference is assumed to be constant, meaning a constant clock drift of the satellites and receiver. The errors of satellite velocity introduced by the TLE files are of the highest magnitude in relation to other error sources. Delays introduced by variations in ionosphere and troposphere are negligible in comparison with the short time period of the Doppler measurements. Thus, the measurement to the respective LEO satellite l of the pseudorange rate z per time step k is modeled as

$$z_{leo,l}(k) \approx \frac{\dot{r}_{leo,l}^{T}(k)[r_r - r_{leo,l}(k)]}{||r_r - r_{leo,l}(k)||} + c\Delta\dot{\delta}t_l + \nu_{leo,l}(k), \tag{1}$$

with r referring to the receiver's spatial position as its three components, c the speed of light, ν the noise model, and $\dot{\delta}t_l$ the clock drift [30]. The pseudorange rate may also be represented in relation to the Doppler shifted frequency $\hat{f}_D$ and the transmitted carrier frequency of the LEO satellite l $f_{c,l}$ [30]

$$z_{leo,l}(k) \equiv c\frac{\hat{f}_{D_l}(k)}{f_{c,l}}. \tag{2}$$

Using the TLE files, $r_{leo,l}$ is known. Considering the Doppler shifted frequency measured, noise modeled, then the position of the receiver r_r and clock drifts can be solved with the help of a few LEO satellite measurements fed into the EKF. The model of the signal as seen by the receiver is dependent on the modulation type. In this model the parameters are received signal strength, symbol duration, intermediate frequency and carrier phase shift [30]. The number of satellites used to calculate the receiver position affects the accuracy. A Root Mean Square Error (RMSE) of 11.38 m is the best result obtained with the help of 25 satellites [30]. The validation performed with two Orbcomm satellites achieves 358 m accuracy in the 2D plane within one minute. A source of discrepancy in the performance is accredited to large TLE errors of the satellite's state. Smaller error contributions are the model assumptions on constant clock drift and neglected atmospheric errors. The simulation has access to a tenfold increase in satellite measurements over four minutes. Moreover, it is assumed, that the accuracy of the LEO satellite trajectory can be more precise, improving the simulated performance further. A noteworthy comment by the authors of this study, is the fact that the EKF could also be adjusted for a non-static receiver of known dynamics.

Related methods differ slightly from this described framework. Simultaneous Tracking and Navigation (STAN) [22] is one of them. STAN utilizes GNSS data as well as a TLE file for initialization. An Inertial Measurement Unit (IMU) is added to their dynamic test equipment, an Unmanned Aerial Vehicle (UAV). After initialization, the EKF takes over the process to determine the satellite position and velocity. The recorded accuracy

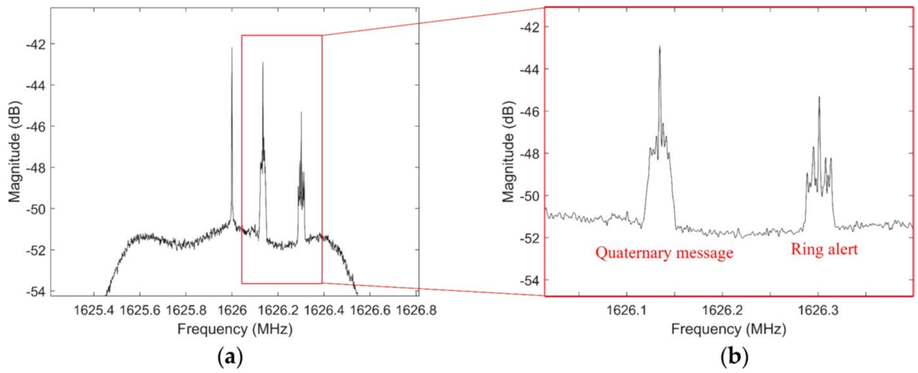

Fig. 2 The Iridium Next signal is depicted [5]. (**a**) the signal within the frequency range 1625.41626.6MHz is plotted and (**b**) is a close-up of the separate peaks quaternary message and ring alert within Iridium's signal

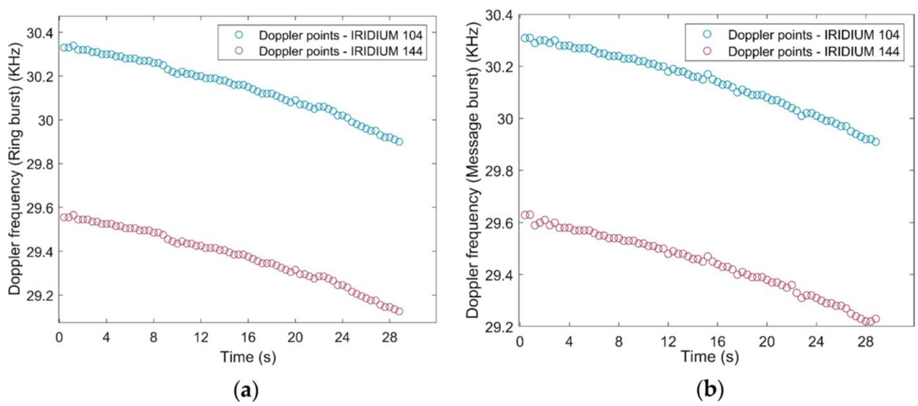

Fig. 3 The Doppler tracks created by [5] based on two Iridium Next satellite signal measurements is shown. (**a**) shows the Doppler track based on the ring burst and (**b**) is based on the Iridium message bursts

is 10.5m using Globalstar, Iridium and Orbcomm constellations. Utilizing the Starlink satellites and a known altitude, a 2D positioning error of 7.7m could be achieved [31]. The positioning error increases to 25.9m and 33.5m in 2D and 3D, respectively, without external altitude information. The measurement lasted 800s for a total of six satellites. The main challenge lies in the higher center frequency transmitted by the Starlink constellation. This is further discussed in the following as a receiver challenge. Another addition to the positioning framework is the simultaneous use of multiple constellations to obtain the user position [5]. An EKF is used for switching between the various frequency channels. The Iridium Next signal bears some special considerations too, due to its burst structure, unlike Orbcomm's continuous signal. The result are discrete Doppler shift measurements making up the tracking signal from the Iridium satellites, shown in Fig. 3, extracted from the measured Iridium signal. Figure 2 visualizes the Iridium signal structure spread around 1626MHz with their additional two signature bursts. The measured signal was received up to 30kHz shifted from the transmitted Iridium signal, that is the Doppler shift. This Doppler shift varies with the changing distance as the satellite traverses the observer's sky. Thus resulting in the measurement shown in Fig. 3 with a Doppler shift variation magnitude of about 0.4kHz over a measurement period of 28s. Orbcomm's lower frequency signal results in a Doppler shift of about about 2kHz [5].

The altitude RMSE is computed to be 118m, despite merely three satellites being used with 30s recording time and the absence of an aiding tool for the altitude. Including external altitude measurements could likely meet the needs of dynamic user receivers [5].

Further noteworthy mentions of Doppler positioning are the works of Tan et al., Thompson et al., and Benzerrouk et al. Their approaches differ to the previous framework in one aspect, respectively. First, weak signal environments are targeted via adjustments in the tracking loop, termed Quadratic Square Accumulation-Instantaneous Doppler Estimation (QSA-IDE) [32]. A 2D positioning RMSE of 163m within 30min of data collection in a forest is presented. Second, the navigation signal's Angle of Arrival (AOA) is tested alongside Doppler positioning [33]. Finally, the third study applies Doppler positioning to a dynamic receiver on an aircraft in combination with an integrated INS. The reported accuracy lies between 200m and 1km for the dynamic target without a heavy computational burden [6].

2.2 Signal augmentation and back-up

LEO satellite signals may also serve as an alternative positioning method or an aid to GNSS signal acquisition. At the time of writing one operating LEO positioning service exists. It is offered by the company Satelles and called Satellite Timing and Location (STL). It is a geographically limited service, piggybacking on the Iridium satellites since 2016. STL added a continuous wave marker to the beginning of the transmission for easy signal recognition and rough measurement. The remainder of the signal is composed out of pseudorandom sequences. In the same manner as a GNSS receiver, the receiver generates replica and performs correlation to the incoming signal [3]. Weak signal environments are targeted this way. Signal loss due to GNSS spoofing is decreased via specific overlapping beam patterns formed from multiple satellite signals, that are difficult to emulate. Reference [3] states a positioning accuracy of 20m indoors with 1μ s in timing. STL generally provides lower accuracy solutions compared to GNSS, making its purpose clear to be an aid or back-up in GNSS denied areas and spoofing occasions [3]. LEO enhanced GNSS or "LeGNSS" [4] demonstrates another way for LEO satellites to aid in positioning. LeGNSS is a feasibility study of LEO satellites re-broadcasting navigation data to optimize Precise Point Positioning (PPP) performance toward real time service without dense ground networks. An improvement of PPP convergence time down to 6.5min is simulated [34]. Guo et al. simulate this concept to improve the receiver's simulated acquisition and tracking "sensitivity", reported as 8dB and 4dB, respectively. However, orbital corrections need to be applied to the GNSS navigation data to account for the LEO satellite movement. Furthermore, PPP requires increasingly precise orbital predictions in the space segment.

2.3 Low earth orbit dedicated positioning signals

Currently there are no dedicated LEO-PNT satellite constellations, thus also no dedicated LEO positioning signals. However, plans to establish such a system exist. As it is not public information yet how the signal will be designed, an analysis of influencing factors is presented here. These are twofold. First, constraints are set by the characteristics of the LEO. Second, sufficient information needs to be transmitted by the signal. Among the most significant orbital characteristics in close Earth proximity is the observed speed. Satellites in LEO complete one Earth revolution in a couple of hours. An Iridium satellite, for example, completes an orbit in 100 min. Thus, an Earth observer sees the LEO satellite pass overhead within minutes, opposed to hours in the case of a MEO satellite [3]. The acceleration, and thus also the Doppler shift, varies along the Line Of Sight (LOS) between satellite and observer with the satellite's elevation angle. These are characteristic of all dedicated and opportunistic LEO signals.

Noteworthy is the 2018 test satellite Luojia-1A. It was designed to broadcast navigation augmentation signals from an orbit at 645km altitude and characterize LEO navigation signal reception challenges [35]. The large acceleration profile of the LEO orbit results in an increased uncertainty in predicting the Doppler shift. Subsequently, the coherent integration time needs to be shortened, resulting in increased noise and decreased sensitivity. This lowered Signal-to-Noise Ratio (SNR) due to the high dynamics leads to equally lowered precision of the pseudorange prediction compared to GNSS.

The three-layer characteristic of GNSS signals are unlikely to be abandoned. Then, carrier wave, code and data will make up the signal. This is due to factors of GNSS inter-operability, frequency allocations and the efficiency of transmitting the signal. Interoperability is important in terms of not interfering with existing signals, but also with respect to existing equipment.

Choosing the center frequency and modulation scheme are the main aspects of this signal design. While multiple modulation schemes exist, most attention is given to binary or quadrature phase shift keying. In order to pick a center frequency, one needs to consider the benefits and disadvantages of high versus low frequency spectrum and their respective application allocations. Satellite navigation, that is current GNSS, is mostly allocated in the vicinity of the L-band between 12GHz. Studies on suitability of C- and S-band have been carried out for the design of the European GNSS Galileo, see [36, 37], concluding the S-band as a possible candidate for future GNSS. Furthermore, high frequencies do not penetrate the ionosphere or building materials as well as lower frequencies. However, larger bandwidth could be allocated, thus, contain more information to improve positioning precision. The use of two carrier frequencies might be continued as well for the purpose of reducing the ionospheric errors. This is achieved via the difference in their received signal characteristics because the signal absorption by the ionosphere is a function of frequency. More information on the relationship between ionosphere modeling and LEO can be found in the study of Li et al. [38].

Moreover, the details on how the satellite is identified via code need to be unique. Thus, the code part of the signal will inevitably be distinguishable from current GNSS. The data will be composed out of a navigation message with orbital parameters. These can be still going to be orbital Kepler parameters with corrections, or orbital coordinates with velocities and accelerations, such as GPS or GLONASS, respectively. Pseudoranging is still likely for precision positioning applications.

The navigation parameters also need to be adjusted to account for the LEO environments, such as higher drag imposed on the satellite that might require more frequent correction updates. An interesting study on characterizing LEO in ephemerides data was carried out by Meng et al. [39]. Further differences to current GNSS signals may be encryption and authentication [2]. Such additions improve signal robustness and allow safety-critical applications to rely on the PNT service. Another approach is termed "simple GNSS" signal [3]. Signal power is the focus with simple referring to fewer separate signal components, and reduced modulation rates, such as the chipping rate. The simple GNSS thus achieves almost 5dB higher signal power in a user receiver. This leads to better signal penetration, with acceptable levels for phones as users under 10GHz, applying to L, S, C and X bands. The interested reader is referred to [3] for details.

3 Navigation receivers for low earth orbit signals

A general GNSS receiver is composed of antennas, a radio frontend, an Analog to Digital Converter (ADC), the Baseband, a navigation data block and an interface to the user. The radio frontend is composed of the components handling the analog radio signal, down-converting it to an Intermediate Frequency (IF), that is to be digitized. The satellite signal is first intercepted by an antenna, making its gain a significant characteristic. A GNSS's Signal to Noise Ratio (SNR) is generally of the order of magnitude -30dB, that is below the noise floor [3]. The low power signal is amplified by a Low Noise Amplifier (LNA) while imposing the least amount of noise onto it. The designated signal bandwidth is obtained via a band pass filter. Next, the signal passes the mixer component. It performs the signal down-conversion using a reference oscillator and frequency synthesizer. Furthermore, pre-correlation selection, sampling, and separating the signal into In- and Quadrature-phase (I/Q) components is done. The reference oscillator is the basis of the receiver's time keeping. Its accuracy and stability determine the receiver's degree of sensitivity via the coherent integration time. Finally, the conversion into a digital, discrete signal is performed by an ADC. The digital signal processing performs sampling and coarse acquisition. The baseband signal $x_b(t)$ that is passed on to tracking loops, generally Delay Locked Loop (DLL) and Phase Locked Loop (PLL), can be represented as

$$x_b(t) = \mathrm{ADC(t + \tau) \exp j(\omega_D t + \Phi_0) + \eta(t)}, \tag{3}$$

with the carrier's angular Doppler frequency ω_D, initial phase Φ_0, the code phase τ, and all other present noise $\eta(t)$. The signal's amplitude A, data D, and code C are all functions of time. Due to the low signal power, correlation between such a received signal and a replica needs to be performed to obtain the positioning parameters. The replica is produced with a local frequency source, such as a Numerically Controlled Oscillator (NCO). The correlation process takes place as the multiplication and integration of the two signals while they are aligned. This process is referred to as "coherent integration" time. In the coherent integration, the signal modulations are "wiped off" as non-coherent noise that averages out while the desired signal's power accumulates and obtains a measurable level. This coherent integration time hereby directly influences the SNR.

The loops DLL and PLL employ the correlation measures in slightly different ways and are focused on code and carrier parameters, respectively. A DLL is usually composed out of three correlators (early, prompt, and late) to estimate the code phase, understood as the delay from the start of the code period with respect to the time of signal reception. The purpose of the PLL is to estimate and track the carrier phase, or in some implementations the carrier frequency via a frequency locked loop. Its basic components are a phase comparator or detector, a loop filter, and a carrier reference generator, usually an NCO. The final step in the processing chain of a navigation receiver produces the desired PNT solution. All channels in the previous baseband signal processing pass on their obtained observables to the navigation data processor. This processor then derives the user receiver's position, clock drift, as well as bias in velocity, clock bias, and clock drift. The implementation of this navigation data processor varies depending on the application and signal modulation. However, the common tasks are decoding the navigation message as obtained from the previous stage, ephemeris, and other system data relating to the satellite. Information to be retrieved from the data is the signal time of transmission from the satellite, including correction from satellite time to user system time. Combined with the Time of Arrival (ToA), the pseudodelay is obtained and corrections for ionosphere and troposphere signal propagation are applied. This value may also be "smoothed" with carrier measurements. The corrected parameters allow the navigation data processor to calculate the PNT, using pseudorange equations, in the manner of Eq. 1 [3]. The most common navigation processor implementations are Kalman filters or iterative least-squares algorithm. The latter algorithm is most suitable when the correction term is small, requiring fewer iteration. Both are methods for parameter estimations. Kalman filters are model-based systems with a signal composed out of state space and measurement models. The state space is influenced by the system and measurement noise. It is composed out of the carrier phase error and state vector [3]. Kalman filters may be used with direct or error values and are generally used in feedback loops [3].

3.1 Receivers for signals of opportunity

A receiver set-up for SOP may be made up out of a Software Defined Radio (SDR) and an altimeter. The receiver in this model is stationary. The essential components, such as the tracking loops, and navigation processor are shown in Fig. 4. Due to the flexibility of a SDR, the navigation processing can be executed by a customized EKF or Weighted Nonlinear Least-Squares Estimator (WNLS). The incoming signal containing all LEO satellite signals to be tracked is divided into individual channels by mixing them with the corresponding IF. The following low pass filter is set to have a bandwidth greater than two divided by the symbol period, and large enough to contain the Doppler shifted signal. In the case of Khalife et al. it is the symbol duration of the QPSK modulation scheme, and the Orbcomm signal Doppler shift is stated as between plus and minus 3kHz [30]. The symbol duration is also linearly related to the sampling period T via a large integer M with the measurements assumed to be constant over the symbol period.

Figure 4 visualizes the signal processing as a flowchart. The incoming signal is mixed with the corresponding Intermediate Frequency (IF) per given satellite signal in each channel. Following filtering, the acquired signal is passed onto a tracking loop, producing Doppler shift to be passed onto the EKF. The EKF computes the positioning solution, or state vector to be precise in this case. The individual PLL tracking loops are shown in the bottom half of Fig. 4, as the customization of this loop is of interest. In order to initialize the loops, an FFT on the input signal is performed, that transforms the time domain to frequency domain, resulting in a crude Doppler estimate. Once initialized, the signal Doppler shift is obtained per channel from the output of the PLL as the signal phase is divided by 2π. The mathematical expression for the phase is obtained in a few steps. First, the coherent mixing, or summation, of the

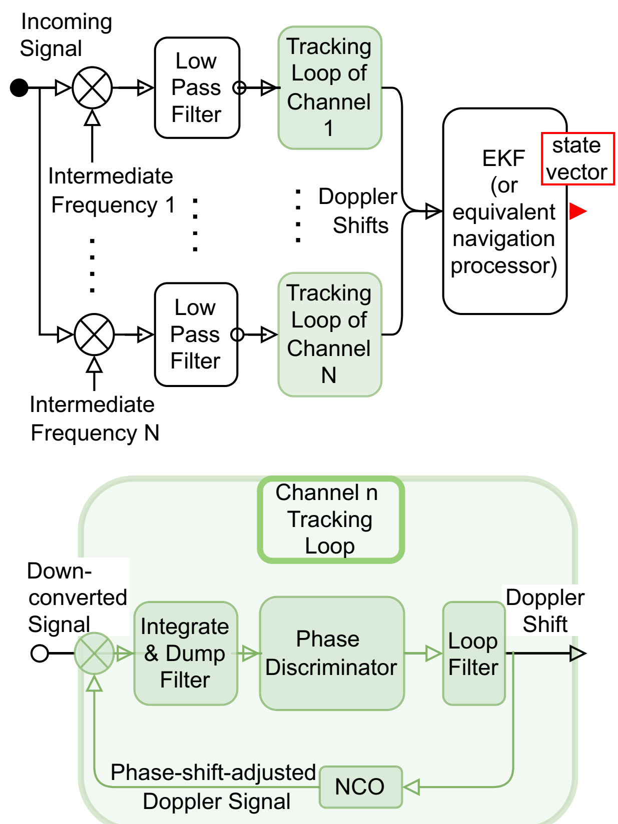

Fig. 4 Khalife et al.'s LEO receiver signal processing loops toward state vector one channel's carrier phase tracking loop passing on a Doppler shift measurement to the navigation filter

estimated carrier with incoming signal over the symbol period results in an expression *s* containing phase error, received signal strength *c*, estimated Doppler shift and noise parameters. Applying a maximum-likelihood discriminator, the phase error is obtained as a function of the resulting signal's real and imaginary parts I and Q, as well as c, and tanh. Considering lastly the filter's time transfer function, the PLL output is completed. The phase estimate is calculated into the signal Doppler, that is passed on to the EKF. Then the Doppler positioning is performed. The experimental set-up testing the described framework includes a Very High Frequency (VHF) dipole antenna and an "RTL-SDR dongle" to connect the proposed SDR.

An extended version of the above SDR is proposed for the STAN framework [22]. The additional elements are an INS and a GNSS receiver to facilitate positioning for dynamic users, here an UAV. The GNSS receiver is used for module initialization and performance comparison, see Fig. 5. The altitude information is measured with a pressure altimeter. The SDR in this LEO receiver set-up is called "Multichannel Adaptive Transceiver Information eXtractor (MATRIX)" and is customized to decode Orbcomm ephemeris [22]. Note, that signals other than LEO, such as 5 G, can be incorporated as individual channels. A complete list of the STAN components comprises a helix antenna, a Universal Software Radio Peripheral (USRP), MATRIX-SDR, IMU, plus the UAV's internal navigation system with a pressure altimeter and a GNSS

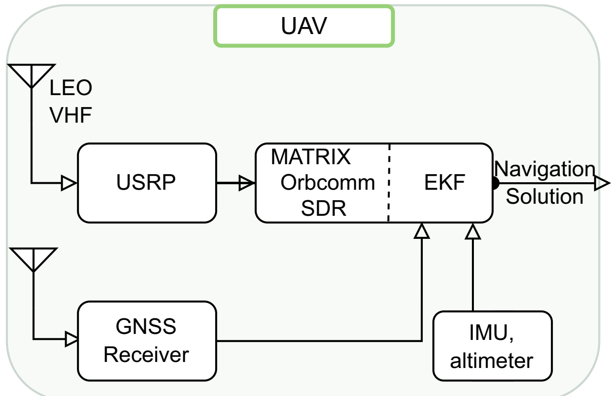

Fig. 5 "Simultaneous Tracking And Navigation" (STAN) [22] framework for positioning with LEO SOP with an Unmanned Aerial Vehicle (UAV)

receiver. Figure 5 shows a flowchart of these components from signal reception with a LEO VHF antenna to the navigation solution output. The analog signal is digitized and processed by a USRP and passed onto the custom MATRIX-SDR. Its EKF component finally performs the PNT computation. The EKF also takes in altimeter and GNSS measurements from the UAV's internal system when needed in experiments. In order to test the STAN framework, the log data of the IMU and altimeter were used as input to the framework, combined with the Orbcomm satellite's measurements.

The same type of SDR with EKF and altimeter set-up is applicable to available Starlink signals as SOP [31]. However, a commercial SDR is generally designed to process lower frequencies, requiring an additional downconverter to be added following the receiver antenna. Furthermore, the Starlink signal structure is unknown here and requires characterization on the user receiver end to extract positioning. The first step is to convert the signal from the time to the frequency domain by applying a FFT to the signal center frequency at 11.325GHz with a sampling bandwidth of 2.5MHz. The signal is now represented by peaks of individual frequencies. They are observed to vary along with the Doppler estimate, that was obtained using TLEs, with respect to unique satellites, forming the basis for positioning. The receiver's measurement is set to the peak of the highest amplitude f_P. The signal model and tracking loop are adjusted as follows. The model of the received and sampled signal $r(n)$ is described as

$$r(n) = \alpha \exp j(2\pi f_p n T_S + \bar{\theta}(n)) + \beta(n), \tag{4}$$

with n the sample number, α a real amplitude, sampling period T_S, noise β and the "beat carrier phase" Θ [31]. The adjusted beat carrier phase Θ is redefined as

$$\theta(n) \equiv \bar{\theta}(n) + 2\pi f_P n T_S, \tag{5}$$

with the remaining parameters definitions unchanged from Eq. 4 [31]. The adjusted beat carrier phase Θ is the target of the tracking loop, analogs to the PLL in regular GNSS receivers. Thus, a Kalman filter model is developed to estimate this quantity. Furthermore, Expressing the beat carrier phase in terms of time dependency results in an explicit dependence on clock bias, wavelength, and the true range between receiver and satellite, enabling the development of the beat carrier phase state vector. This includes the first- and second-time derivative of $\Theta(t)$, with a "kinematic model" stating the change in $\Theta(t)$. The Kalman filter performs time and measurement updates based on these models. Furthermore, the steps of coherent summation, or integration, and discrimination also need to be performed. An *atan*2 function as a discriminator is employed. Noise is again modeled as zero-mean white Gaussian, and its variance estimated by the Kalman filter. The measurement was performed with a USRP, a Ku antenna, and a low-noise block down-converter. The navigation data processing converts the beat carrier phase into a distance, corrects for the troposphere, and a WNLS estimator calculates the user position [31]. Another dynamic user receiver set-up focuses on an aircraft trajectory using the Iridium constellation signals [6]. A USRP is used to sample the Iridium signals, and range rates with the LEO satellites are calculated. Combined with an internal INS computed position, velocity, and attitude, they are fed into a navigation filter and the aircraft trajectory is estimated. The coupling of the different measurements and the Kalman filter implementations and update equations operate under the same assumptions as previously, and the details are found in [6].

Another possible SDR implementation receives signals from Multiple Constellations, MC-SDR [5]. Each channel performs Doppler positioning based on signals of various constellations. An EKF selects which channel's output to pass on to the next stage and the timing, referred to as mode switching. The acquisition stage differs from previous approaches, as it utilizes the "Welch method" for power spectral density analysis. The resulting signal peaks are the object of detection following acquisition. Burst signals, such as transmitted by Iridium, are also considered.

Improving acquisition loop performance is the aim of the QSA-IDE method [32]. It considers the burst signals of the Iridium constellation. First, the incoming signal is squared twice, then an initial estimate of the signal Doppler shift is obtained by an FFT. The resolution of the FFT sets the boundaries for the frequency search space. A MLE produces the fine Doppler shift estimation. The receiver produces replica signals aiming to match the incoming signal. The correlation is performed by multiplying both inputs via coherent integration and squaring. Once a threshold is crossed in output signal power, the acquisition is complete. The quadratic squaring distinguishes this method from other Iridium Doppler positioning and is the adjustment toward weak signal environments. The entire Iridium burst is used, "accumulating" signal power in a "weak signal environment by increasing the coherent integration time of MLE" [32].

3.2 Receivers for signal augmentation

Aiding GNSS with LEO satellites is offered as a service by the company called Satelles. The STL signal is designed for their own PNT solution, that complements the GNSS service in challenging environments. As such, it contains its own timing and frequency information, separate from GNSS. STL is received by the company's "Satelles Evaluation Kit (EVK2) STL receiver." Its components are "Maxim RF chip, Xylinx Spartan-3 FPGA, TI dual core DSP chip, and internal OCXO or external clock" [40]. The timing capability is crucial and differs for STL, as the broadcasting LEO satellites do not contain atomic clocks, that would facilitate transmitting precise timing information. Their set-up instead achieved high performance using a rubidium clock on the user end [7].

Correlation with locally replicated signals is performed by the receiver, comparable to GNSS receivers.

Aiding GNSS is also achieved by assisting its acquisition sensitivity. However, it is a concept tested only in simulation assuming the LEO satellites transmit GNSS ephemeris "through its communication channel" [8]. This receiver design is shown in Fig. 6. A GNSS and LEO module are combined into one receiver. It serves the purpose of sharing the acquired information from the LEO signal with the GNSS module. The LEO module performs Doppler positioning for an initial signal Doppler estimate on the carrier frequency, as well as a pseudorange. Furthermore, the ephemeris obtained via the LEO antenna is used to calculate the LOS toward the GNSS satellite. All parameters are passed onto the GNSS module in the receiver with the aim of aiding the GNSS signal acquisition. The frequency search space can be reduced with these initial values, rendering the acquisition more efficient. Moreover, the coherent integration time is extended, thereby the SNR increased. Relying on the reduced frequency search space, and the ephemeris passed on from the LEO module, GNSS signal reception is improved in weak signal environments. It is important to notice, that the two modules in the receiver share one oscillator as the frequency source.

Finally, studies on an actual signal from a LEO satellite for alternative PNT are being published. Luojia-1A is a test satellite for signal reception studies, and the arising challenges with respect to the best acquisition time range [35]. A USRP SDR architecture makes up the receiver. Figure 6 shows the signal flow of Cheng et al.'s receiver design. Commercial LEO and GNSS frontends are utilized, but noteworthy is the combination of both into one positioning solution. The LEO frontend passes on observed Doppler shifts to the GNSS part of the receiver to aid in frequency search space, and thus improve acquisition sensitivity [35].

3.3 Receivers for dedicated positioning signals

Signals from LEO dedicated to positioning set roughly the same requirements to the receivers as those decoding GNSS messages. This is assuming the same timing precision

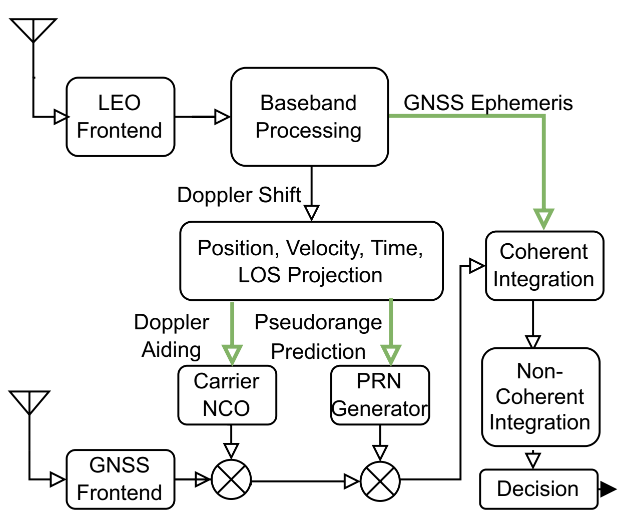

Fig. 6 Cheng et al.'s LEO augmented GNSS receiver design

measurement method is applied. The only suitable reference found in this area is the pending patent by Xona Space Systems [28]. The positioning information is incorporated into their own navigation message to be demodulated, obtaining transmit time, clock states, ranging values and ToA. The detailed demodulation in the receiver depends on the unknown frequency, and content of navigation message. Thus, it cannot be discussed further at the time of writing.

3.4 Discussion

3.4.1 Signals of opportunity

The common basis of current SOP methods is the knowledge of the signal's carrier frequency, with its Doppler shift being the center of measurements. The receiver architecture for SOP Doppler positioning is composed out of an antenna, RF, and a type of SDR including a navigation filter, not unlike a general GNSS receiver. However, challenges arise for SOP receiver designs and are discussed based on the previous works and references used. The challenges are as follows: unknown satellite state, unknown clock bias, accuracy, multiple signal processing, unauthenticated signal, and variable attenuation.

Information on the satellite state are missing parameters to be obtained from external sources. Pseudorange rates, plus the satellite's position, velocity and an error model, are required for a navigation filter to compute the user positioning solution. Common solutions are to rely on TLE files for the satellite's position and velocity. This information is fed to the orbit propagation model SPG4. This is a significant error source, as the TLE data itself may have errors of magnitude at km level [30]. Furthermore, additional sensors such as altimeters or INS may provide user altitude information. The noise model is assumed as zero-mean white Gaussian. It may contribute to the solution's overall error too if the signal propagation environment is not characterized well enough this way.

Causes of decreased accuracy have already been addressed in the discussion above. They are related to the unknowns of the satellite state, clock bias, and also the measurement precision. The appeal of SOP lies, among other factors, in the availability of lower cost COTS components, whose precision may also be expected to be of lower precision compared to laboratory grade equipment. Improvements in measurement performance may also be derived from the use of multiple constellations as SOP. This is the case, as currently constellations are composed out of few numbers of satellites in relation to their visibility due to the small footprint from LEO. Chances of a better measurement geometry improve with multiple constellation signals as well. However, additional measurement channels are required for multiple signals. Furthermore, multiple antennas are needed if the center frequencies are in different frequency bands. Consequently, cost is added, and receiver set-up flexibility reduced. However, alterations need to be made to suit frequency and signal processing. First, the antenna's size and power requirements are determined by the required frequency range. In the case of SOP, COTS components exist. This is a two-way street, as SOPs are by definition not dedicated PNT signals. As such, equipment from their primary purpose may exist, and this equipment availability may be the reason a signal becomes a SOP. This is due to lower cost equipment being a greater factor in non-dedicated signals. Hence, most satellite SOPs are Doppler shifted signals, that require relatively few receiver adjustments when compared to other methods, such as AOA, that may require complex, spacious, or less flexible antenna array set-ups. In the case of communication satellites, such as Orbcomm, common VHF dipole antennas suffice. SOP from Iridium broadcasts may even be received by the company's own manufactured antennas. Thus, only the frequency dictates which COTS antenna to use. Broadband signals require respective K-band antennas, for example a Ku-band antenna for Starlink's broadcast. The following parts of the RF need to be able to process the frequency of the incoming signal into digitized samples. To this end, another downconverter may be required for K-bands and above, used in the broadcast signals. This addition allows for the use of commercial SDRs for both broadband and narrowband signals, given the bandwidth is chosen small enough as well. The bandwidth needs to fit the size constraints of the chosen sampling COTS component, for example a SDR USRP, with enough of a margin to account for the signal's Doppler shift. Generally, this fits into a few MHz as an order of magnitude. Special considerations need to be given again to the case of broadband signals. The signal itself, as stated in the name, is of greater bandwidth than traditional navigation signals. Thus, characterizing the signal with the focus on containing sufficient positioning information may be a possible extra step for broadband SOPs. Sampling for a stationary receiver set-up can be performed by a commercial USRP, or even a low cost SDR dongle.

The final important component to consider within the RF is the source of the frequency reference. Components may already contain internal reference oscillators, such as a Temperature Compensated Crystal Oscillator (TCXO). External references may be added though. They could provide higher accuracy and stability, at the cost of increased complexity and price. A Rubidium clock is an example of such an external frequency reference. SOP used as augmentation for GNSS receiver signals, should consider using the same reference source, in order not to introduce further clock biases. The importance of the frequency reference is due to the measurement being entirely composed out of aspects of frequency, such as the phase and Doppler shifted center frequency. Their accuracy and that of the derived parameters are influenced by the resolution of the timing basis, as frequency is merely a number of cycles per unit of time. Herein lies a source of decreased accuracy compared to GNSS, that rely on atomic clock precision, and broadcast error estimates.

The measurements, namely the signal carrier's Doppler shift and phase, are obtained via the acquisition and tracking loops. Their implementation is customizable. The navigation filter processes the obtained parameters. A Kalman variant is suitable, as it is adjustable to modified loops. In a SDR, the navigation processing may be done on stored samples, for example with an algorithm developed in the software tool Matlab.

Signal strength is another appealing factor of LEO broadcasts. Path loss is reduced via the orbit's proximity, leading to higher power signal reception on Earth. Resilience is a consequence, as stronger signals are more difficult to spoof. As SOP, the signals are generally not authenticated though, making them not impervious to spoofing. Best performance is achieved for satellites in the zenith position. The path to the observer is the shortest of the satellite's overhead pass. Hence, higher elevation angles are preferable for best measurement performance. However, path loss is also a function of frequency.

Frequencies on the higher end of the spectrum are attenuated at a greater rate than lower ones. Its significance lies in the choice of SOP. Broadband constellations with their K-band transmissions are thus more affected by atmospheric attenuation, than the narrowband constellations. The user receiver's environment thus determines the SOP feasibility. High attenuation environments might not allow for high frequency signals to be detectable. Tackling the challenges described above can be achieved with a receiver architecture composed out of VHF and Ku antennas, a SDR, multiple tracking channels with an EKF implementation as switching mode and navigation processor. The antennas enable the receiver to benefit from the massive numbers of broadband satellites, as well as the better signal strength of narrowband constellations. The SDR enables algorithm flexibility, such that improvements for increased acquisition sensitivity can be included and updated. Along the lines of STL's service based on Iridium signals, there is room for code gain. Satellite information needs to be obtained with the help of TLE files. A TCXO as frequency reference is a cost-efficient option. Alternatively, the LEO receiver might be connected with a GNSS receiver, relying on the same frequency reference. The LEO signal part then serves the purpose of aiding the GNSS signal reception, while benefiting from the navigation system's precision. Due to the cost to performance ratio, utilizing LEO-SOP as such a back-up for GNSS signals in weak signal environments seems to be the most suitable receiver option.

3.4.2 Dedicated positioning signals

Dedicated positioning, or PNT, signals generally contain navigation parameters, so called ephemerides, as well as markers for acquisition. In the case of GPS, Pseudo Random Noise (PRN) codes signify a specific satellite and serve as an acquisition aid via the correlation with a local replica of the known PRN code. The STL service makes use of a continuous wave marker, that serves a similar purpose with lower complexity. Nonetheless, the achieved code gain is noteworthy. Ephemerides are also present in all GNSS signals. Their benefits to positioning are obvious, and their importance is underscored by SOP inaccuracies stemming from TLE dependency. However, LEO requires ephemerides adjusted to the higher drag environment. Their optimization is still undergoing research. Implications for the receiver design are an addition to the acquisition loop for locking onto a marker and the capability of demodulating an increased number of navigation parameters compared to traditional GNSS.

A suitable receiver architecture is a flexible SDR set-up with an additional correlation step in the acquisition process. Correlation is a significant difference to SOP, that brings with it increased precision. Correlation between a known signal and a replica further provides an opportunity for authentication, and thereby improved reliability. Although it requires specialized software, commercial SDRs might be a viable option, in case of a frequency allocation below 10GHz. Then an implementation of algorithms in Matlab, for example, enables easy access to creating specialized algorithms. Kalman filters are a suitable choice for such a navigation processor implementation. The Doppler shift of all LEO signals needs to be considered as well. The RF needs to support a large enough bandwidth, at least tens of kHz. This may serve as a coarse signal measurement, in the manner of SOP, and initialize the frequency search space. Moreover, the Doppler value itself changes relatively quickly, needing to be accounted for within the timing and type of acquisition and tracking algorithm. For example, the integration strategy chosen within a parallel code search acquisition algorithm, leads to improved acquisition timing performance [35].

The signal strength also varies with the changing LOS distance to the observer during a satellite's pass. Hence the elevation angle influences the signal strength, affecting the SNR, resulting in measurements of unequal quality. The receiver may need to set a definition of acceptable elevation angles for uniform measurement assurance, or the noise model may be adjusted. Furthermore, the antenna choice for a dedicated LEO PNT signal is of importance, especially in terms of knowing the satellite's transmission characteristics. The on-board antenna transmission pattern determines the most suitable receiver antenna, and thus also influences the user environment via size constraints. A satellite's wide beam footprint favors lower gain user antennas and vice versa for small beam signals. This choice also influences user receiver power consumption, whereas the frequency largely determines the antenna's ideal size.

Timing considerations within the user receiver are largely identical to the considerations presented in the previous section. In addition to the user segment, the satellite can provide timing and error estimates. These may be derived with the help of a GNSS on-board receiver, or with a Chip Scale Atomic Clock (CSAC). The obtained timing accuracy is relevant to the positioning solution in the user end because ranging is a timing navigation method.

Ultimately, a RF of large bandwidth and frequency range is needed, combined with a SDR, that enables adjustments to the receiver loops. Adjustments in the acquisition and tracking loops are required to tolerate faster changing Doppler than current GNSS. Ephemeris decoding is an additional step compared to SOP, and additional parameters compared to GNSS are required for correct orbit characterization leading to precision positioning solutions. Correlation and local replica components might be another addition for increased precision and authentication. Moreover, the details of the receiver architecture are dependent on the signal design. The signal design choices dictate all choices starting from the antenna to an algorithm implementation extracting positions from possible encryption.

4 Conclusion

This article reviewed developments in LEO satellite signals with respect to PNT user receiver architectures. In conclusion:

- The order of magnitude in positioning accuracy with SOP is generally tens of meters when unassisted.
- SOP can be received with COTS component receivers.
- The most common receiver architecture is a SDR set-up with signal customized EKF implementation
- In SOP processing, positioning signal analysis is the most demanding task due to the challenges in acquisition and tracking of a LEO satellite with signal specific characteristics, that are not in the public domain.
- Utilizing multiple channels for different signals is an option. However, multiple antennas may also be needed.
- The largest error source in SOP stems from the uncertainty of the satellite status, due to low precision of TLE files.

- Time keeping is critical in SOP. The precision of the user receiver clock is significant, especially when it is not disciplined by a precision clock such as in the GNSS system. Clock drift further degrades the possible positioning accuracy.
- Dedicated LEO-PNT receivers are unlikely to be a necessity, unless an upcoming PNT system will not strive for GNSS inter-operability. Instead settle on a less crowded frequency band, or a significantly different signal modulation scheme, in favor of a difficult user environment, such as indoors or dynamic users. Signal attenuation versus antenna size is a significant factor in such a design challenge and might involve connections via ground infrastructure.

Future developments may be the completion of several LEO-PNT systems. The receiver architectures will be adjusted to their respective signal structure. Early stages will likely see a focus on GNSS inter-operability, therefore receivers with the same type of set-up as GNSS receivers. As frequency bands get increasingly crowded and positioning services more numerous, there might be a market for receivers with more specialized features. It is conceivable for environments of limited access to but high demand for GNSS signals, such as mobile indoor users. Here commercial receiver set-ups of paid company services are conceivable. Noteworthy challenges are tackling frequency attenuation versus size of receiver, multipath mitigation, encryption and LEO specific ephemeris. In contrast to this scenario, SOP might have applications of low precision in part due to the accessibility of cheap COTS SDR receiver implementations.

Author contributions

CP was responsible for conceptualization, formal analysis, and the major contributor to the manuscript. FSP was a major contributor in reviewing, editing, as well as supervision. MZHB offered supervision, overall conceptualization and reviewed the manuscript. JP was the supervisor, supporting conceptualization. All authors read and approved the final manuscript.

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