A First Look at the OneWeb LEO Constellation:
Beacons, Beams, and Positioning

Abstract—This paper is the first to examine OneWeb low Earth orbit (LEO) satellite signals. First, a blind beacon estimation framework is developed to estimate beacons present in the transmitted OneWeb Ku-band downlink signals. Second, a fast acquisition approach is proposed to reduce the computational complexity of acquiring LEO megaconstellation satellite signals. Third, the blindly estimated beacons are used to identify OneWeb’s beams and to characterize their carrier-to-noise ratio. Fourth, Kalman filter-based tracking loops are presented, enabling code and carrier phase tracking of 9 OneWeb satellites. Finally, a nonlinear estimator is formulated to demonstrate positioning exclusively with measurements from the 9 OneWeb satellites. Starting with an initial estimate 50 km away, the position was estimated with a two-dimensional error of 30.4 m.

Index Terms—Positioning, navigation, signals of opportunity, low Earth orbit satellite, OneWeb.

I. Introduction

Broadband communication providers have announced plans to launch tens of thousands of space vehicles (SVs) into low Earth orbit (LEO) over the next decade, ushering the era of LEO megaconstellations [1]. Currently, the two largest operational LEO constellations are SpaceX’s Starlink (≈6,000 SVs), followed by OneWeb (≈600 SVs). The potential of LEO SVs in augmenting or substituting global navigation satellite systems (GNSS) for navigation has been the subject of extensive recent theoretical and experimental studies [2]–[10].

While the spectrum allocation of LEO constellations is typically publicly available [11], little is known about the structure of their downlink signals. Without such knowledge, one cannot exploit these signals for positioning and navigation purposes [12]. Blind signal processing approaches [13], [14] have shown tremendous promise in acquiring and tracking downlink Starlink, OneWeb, Orbcomm, and Iridium LEO SV signals [15], [16] as well as in revealing salient properties of Starlink signals [17]–[20]. While previous work examined OneWeb signals for remote sensing and passive radar applications [21], [22], no comprehensive studies have been conducted to exploit...
OneWeb SV downlink signals for positioning, uncover their beaming pattern, and track their carrier phase.

This paper examines OneWeb SV signals by making the following contributions. First, beacons present in the transmitted Ku-band downlink signals are estimated in a blind fashion. Second, a fast acquisition approach to reduce the computational complexity of LEO SV acquisition is proposed. Third, the estimated beacons are used to empirically study the beam structure of OneWeb’s constellation and characterize its carrier-to-noise density ratio (C/N0). Fourth, Kalman filter (KF)-based tracking loops are developed, enabling code and carrier phase tracking of 9 OneWeb SVs. Finally, a positioning solution is generated exclusively with OneWeb signals and its error breakdown is discussed.

II. OneWeb Ku-Band Downlink Allocation

According to the Federal Communications Commission (FCC), the OneWeb constellation resides 1,200 km above the Earth’s surface, with the SVs traveling along the north-to-south direction [23]. The OneWeb user downlink signals are transmitted in the Ku-band (10.7–12.7 GHz). OneWeb employs a bent-pipe system in which the SVs receive signals transmitted by ground stations in the gateway uplink channels and redirect them to the users present in their service area through downlink channels. The downlink band is dissected into 8 contiguous channels of 250 MHz. Each OneWeb SV has 16 static highly-elliptical beams, and each beam transmits in only one of the 8 channels at any specific point in time. The term beam is adopted in this paper to contrast between the large beamwidth of OneWeb and other relatively smaller beamwidth (e.g., such as the one employed in Starlink) referred to as spotbeams. Moreover, each channel can be used by 2 geographically separated beams of the same satellite. Therefore, each OneWeb SV is capable of servicing multiple users simultaneously by multiplexing them in frequency division (8×250 MHz channels) and spatial division (16 beams), as depicted in Fig. 1.

Fig. 1. Diagram showing OneWeb’s Ku-band downlink signal allocation. Different users can receive data from a single OneWeb SV at the same time while being multiplexed in frequency division (8×250 MHz channels) and spatial division (16 static beams).

III. Blind Beacon Estimation Framework

This section describes a blind beacon estimation framework capable of extracting useful information from OneWeb downlink signals, which in turn will be used to reveal the characteristics of the constellation and generate a positioning solution opportunistically.

A. Received Baseband Signal Model

Let \( x(t) \) be the baseband signal transmitted by OneWeb SVs at a specific channel. It is assumed that \( x(t) \) can be written as \( x(t) = s_{\text{SI}}(t) + n_d(t) \), where \( s_{\text{SI}}(t) \triangleq \sum_{k=-\infty}^{\infty} s(t - kT_0) \) is the repetitive beacon stream, \( s(t) \) is the deterministic beacon, and \( n_d(t) \) is a random signal driven by the user data. The beacon present in OneWeb’s downlink signals contains, but is not limited to, the synchronization sequences that are broadcasted repetitively by the satellite to the users. Moreover, the beacon and the user data co-exist in the transmitted signal with the use of multiplexing scheme(s) that are employed by OneWeb. This paper assumes that \( s(t) \) is: (i) confined in the interval \([0, T_0]\), (ii) uncorrelated with the data \( n_d(t) \), and (iii) zero-mean \( \mathbb{E}[s(t)] = 0 \) and has a stationary power spectral density (PSD) \( \mathbb{E}[s^*(f)] \mathbb{E}[s(f)] = S_s(f) \).

The signal is modulated by a carrier frequency \( f_c \) and transmitted in a noisy channel. The received signal after baseband mixing and filtering can be expressed as

\[
r(t) \triangleq x(t - \tau(t)) \exp [j\theta(t)] + n_c(t)
\]

\[
= s_{\text{SI}}(t - \tau(t)) \exp [j\theta(t)] + n_c(t),
\]

where \( \tau(t) \) denotes the apparent delay between the transmitted signal and the received signal at the receiver’s antenna; \( \theta(t) \) is the carrier phase of the received signal; \( n_c(t) \) is the additive channel noise; and \( n(t) \triangleq n_d(t - \tau(t)) \exp [j\theta(t)] + n_c(t) \) is the combined channel and random user data noise, modeled as a complex white noise with a two-sided PSD of \( \frac{\Delta}{2\pi} \) in the interval \([-\frac{\Delta}{2}, \frac{\Delta}{2}]\), where \( \Delta \) is the sampling frequency of the device. The apparent delay and carrier phase consist of: (i) the time-of-flight along the line-of-sight between the transmitter and receiver, (ii) the combined effect of the transmitter’s and receiver’s clock biases, (iii) the ionospheric and tropospheric delays, and (iv) other unmodeled errors.

Using the Taylor series expansion (TSE), the carrier phase at time instant \( t_k = t_0 + kT_0 \), where \( k \in \mathbb{N} \) is a discrete-time index (referred to as the sub-accumulation index) and \( t_0 \) is some initial time, is approximated up to its second-order term by \( \theta_k(t) \triangleq \theta(t + t_k) \approx \theta(t_k) + \dot{\theta}(t_k) t_k + \frac{1}{2} \ddot{\theta}(t_k) t_k^2 \). By definition, \( f_D(t) \triangleq \frac{\partial \theta(t)}{\partial t} \) is the apparent Doppler frequency and \( f_D(t) \) is the apparent Doppler rate. On the other hand, the code phase is approximated by its zero-order value at the \( k \)-th sub-accumulation, i.e., \( \tau_k(t) \triangleq \tau(t + t_k) \approx \tau(t_k) = \tau_k \).

Finally, the expression of the received signal at the \( k \)-th sub-accumulation can be written as

\[
r_k(t) \triangleq r(t + t_k) w_{\tau_k}(t)
\]

\[
= s_{\text{SI}}(t - \tau_k) \exp [j\theta_k(t)] w_{\tau_k}(t) + n_k(t),
\]

where \( w_{\tau_k}(t) \) is a window function that is unity within the interval \([0, T_0]\) and zero elsewhere, and \( n_k(t) \triangleq n(t + t_k) w_{\tau_k}(t) \).
For a given estimate of the carrier phase \( \hat{\theta}_k(t) \) and code phase \( \hat{\tau}_k \), the output after modulating the incoming signal with a numerically-controlled oscillator (NCO) at the \( k \)-th accumulation is given by

\[
\hat{r}_k(t) \triangleq r(t + k + \hat{\tau}_k) \exp \left[-j\hat{\theta}_k(t)\right] w_{T_k}(t) \tag{1}
\]

where \( \hat{\theta}_k(t) = \theta_k(t) - \hat{\theta}_k(t) \) is the carrier phase error, \( \hat{\tau}_k = \tau_k - \hat{\tau}_k \) is the code phase error, and \( \hat{n}_k(t) \triangleq n(t + k + \hat{\tau}_k) \exp \left[-j\hat{\theta}_k(t)\right] w_{T_k}(t) \). The phase modulation of the received signal \( r(t) \) by the estimated carrier phase \( \hat{\theta}_k(t) \) is the discrete-time version of the beacon circularly shifted by \( \hat{\tau}_k \) in (1) referred to as the code phase wipe-off. The code phase wipe-off in this case is simply a time shift. The carrier and code phase estimates are generated by the tracking loop discussed in Section IV.B.

It is important to note that, unlike GNSS, the blindly estimated beacons from OneWeb does not have a specific time reference. Therefore, the start of the periodic sequence can be considered to be any value in the range \([0, T_0] \) without affecting the delay locked-loop (DLL) operation, which is invariant to a constant initial time shift in the beacon.

After sampling at a rate \( F_s = 1/T_s \), the received signal at the \( k \)-th sub-accumulation is given by

\[
r_k[n] = (s \otimes \tau_k)[n] \exp \left[j\hat{\theta}_k[n]\right] + n_k[n],
\]

where \( n \in \mathbb{N}, (s \otimes \tau)[n] \triangleq s_{\text{sw}}(nT_s - \tau)w_{T_0}(nT_s) \) is a discrete-time version of the beacon circularly shifted by \( \tau \) seconds, \( \theta_k[n] \triangleq \theta_k(nT_s) \) is the discrete-time carrier phase sequence, and \( n_k[n] \triangleq n_k(nT_s) \) is the discrete-time noise sequence. Finally, the discrete-time version of \( \hat{r}_k(t) \) is given by

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\]

where \( \hat{\theta}_k[n] \) is the discrete-time carrier phase error sequence and \( \hat{\tau}_k \) is code phase error.

**B. Blind Navigation Beacon Estimation**

To capture OneWeb’s downlink signals, a stationary National Instrument universal software radio peripheral (USRP) 2945R with a receiver bandwidth of 2.5 MHz was equipped with a consumer-grade low-noise block downconverter with feed horn (LNBF) with conversion gain of 50 dB and a noise figure of 2.5 dB to receive OneWeb signals in the Ku-band. The hardware setup is summarized in Fig. 2.

![Hardware setup for capturing OneWeb LEO SV signals.](image)

The blind Doppler estimator in [16], [24] is used to estimate and wipe off the time-varying parameters \( (\theta_k[n] \) and \( \tau_k \) that modulates the beacon sequence. After wipe off, the signal in (2) simplifies to \( \hat{r}_k[n] \approx s[n] + \hat{n}_k[n] \), where \( s[n] \triangleq (s \otimes 0)[n] \) is the discrete-time version of the un-shifted beacon \( s(t) \). At this point, the beacon length \( T_0 \) can be estimated by examining the autocorrelation function (ACF) for a sufficiently large coherent processing interval (CPI). Fig. 3 shows the circular ACF for 0.5 seconds of the data. The ACF indicates that \( T_0 = 10 \) ms for OneWeb SVs signal. Note that during the blind beacon estimation phase, the receiver’s clock was disciplined by GPS to have a precise estimate of the beacon duration.

![Circular autocorrelation function of 0.5 seconds of the received signal after Doppler wipe off.](image)

The output after modulating the incoming signal with a numerically-controlled oscillator (NCO) at the \( k \)-th accumulation is given by

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r_k[n] = (s \otimes \tau_k)[n] \exp \left[j\hat{\theta}_k[n]\right] + n_k[n],
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with others; thus, unlocking the capability of detecting which beam is servicing the receiver’s cell. On the other hand, a prominent peak in the ACFs shows that the estimated beacons are suitable for SV signal acquisition and tracking purposes. It is important to note that the beacons estimated using the blind framework are modulated by a real-valued Doppler ambiguity that has been estimated and corrected for using the method proposed in [16]. The Doppler ambiguity present in the estimated beacon comes from the arbitrary initial intermediate frequency that the receiver had when the blind beacon estimation was initiated. This intermediate frequency captures the value of the error between the receiver’s and true center frequency of the transmitted beacon.

IV. OneWeb Receiver Design

This section discusses the implementation of the receiver to acquire and track OneWeb signals using the navigation beacons estimated in Section III.B.

A. Fast LEO Acquisition

In contrast to the acquisition tractability of traditional medium Earth orbit (MEO) GNSS, the acquisition of LEO SVs transmitting in the Ku-band presents some challenges. The maximum expected Doppler frequency present in a given dynamic channel can be mainly predicted by: (i) the relative speed v between the transmitter and receiver and (ii) the carrier frequency fc using the formula \( f_{D,\text{max}} \approx \frac{v}{c} f_c \). For a OneWeb SV orbiting at a speed of 7.2 km/s and transmitting at 11.325 GHz, the expected Doppler frequency present in the downlink signals can reach up to \( f_{D,\text{max}} \approx 270 \) kHz, which is much greater than the maximum Doppler shift observed in GNSS that can only reach up to \( f_{D,\text{max}} \approx 10 \) kHz. Note that the maximum Doppler shift was empirically found to be around 200 kHz due to the beaming pattern of OneWeb SV that reduces the received signal power near the horizon. The larger acquisition search grid imposed by the high LEO Doppler frequencies, combined with the large number of SVs and navigation beacons given a specific LEO megaconstellation, renders the acquisition task formidable for real-time purposes. To address this challenge, this paper proposes a fast LEO acquisition algorithm to reduce the computational complexity of the acquisition stage.

The acquisition stage for GNSS is well-known in the literature and is based on a joint 2–D search for the Doppler \( \hat{f}_{D,k} \) and code phase \( \hat{\tau}_k \) as follows

\[
\{\hat{f}_{D,k}, \hat{\tau}_k\} \triangleq \arg \max_{f,\tau} |\{r_k[n], (s \tau)[n] \exp[j2\pi f n T_s]\}|^2.
\]

It can be shown that for a CPI of \( T_0 \), the granularity of the Doppler search should be at least \( \Delta f_D = 1/(2T_0) \). For OneWeb SV signals, \( T_0 = 10 \) ms leads to \( \Delta f_D = 50 \) Hz. To accelerate the search, a two-step beacon subsampling-based Doppler search is proposed (see Algorithm 1), where \( (f \ast g)[n] = \sum_{m=-\infty}^{\infty} f^*[m]g[m+n] \) is the discrete-time cross-correlation operator, and \((\cdot)^*\) denotes the complex conjugate. Denote by \( P \in \mathbb{Z}^+ \) the subsampling factor; \( L_P = T_0/(PT_s) \) the subsampling length; \( w_p[n] \) the subsampling window function that is unity within the interval \( \{0, \ldots, L_P - 1\} \) and zero elsewhere; and \( \Delta f_p^P = P\Delta f_D \) is the new minimum Doppler search granularity.

**Algorithm 1 Two-step subsampling-based Doppler acquisition**

**Input** \( r_k[n], s[n], T_0, T_s, f_{D,\text{max}}, P \)

**Output** \( f_{D,k}, \hat{\tau}_k \)

\[
L_P \leftarrow \frac{T_0}{(PT_s)}; \quad \Delta f_D \leftarrow \frac{1}{2(T_0)}; \quad \Delta f_p^P \leftarrow \frac{P}{(2T_0)}
\]

\[
M \leftarrow \left\lceil \frac{f_{D,\text{max}}}{\Delta f_p^P} \right\rceil
\]

\[
s_p^m[n] \leftarrow \sum_{k=0}^{M-1} s[n] \exp[j2\pi k \Delta f_p^P T_s] w_p[n-kL_P]
\]

\[
m \leftarrow \{-M/2, \ldots, M/2\}
\]

\[
\mathcal{L}_m[m] \leftarrow \max_{\tau} |\{r_k \ast s_p^m \exp[j2\pi m \Delta f_p^P T_s]\}|^2
\]

**end for**

\[
m^* \leftarrow \arg\max \mathcal{L}_m \mathcal{L}_m[m]
\]

\[
s^m[n] \leftarrow s[n] \exp[j2\pi m \Delta f_p^P T_s]
\]

**for** \( p = \{0, \ldots, P - 1\} \)

\[
\mathcal{L}_p[p] \leftarrow \max_{\tau} |\{r_k \ast s^m \exp[j2\pi p \Delta f_D T_s]\}|^2
\]

**end for**

\[
\hat{f}_{D,k} \leftarrow \hat{m} \Delta f_p^P + \hat{p} \Delta f_D
\]

The subsampling reduces the number of search bins by an approximate factor of \( P \) at the expense of degrading the detection performance in the acquisition stage. In this paper, setting \( P = 5 \) reduced the number of Doppler search bins from 4,000 to 805, while retaining the signal detection capability for the estimated beacons.

B. Kalman Filter-Based Tracking Loops

A joint phase locked-loop (PLL) and DLL KF-based tracking loop is used to track OneWeb SVs’ signals to generate code and carrier phase observables. Let \( x(t) \triangleq [\theta(t), \dot{\theta}(t), \ddot{\theta}(t), \tau(t)]^T \) be the state vector whose dynamics is modeled as

\[
\dot{x}(t) = Ax(t) + B\ddot{w}(t), \quad (3)
\]

\[
A \triangleq \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \quad B \triangleq \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}, \quad \ddot{w} \triangleq \begin{bmatrix} \dddot{\theta}_0 \\ \dddot{\theta}_r \end{bmatrix},
\]

where \( \dddot{\theta}_0(t) \) and \( \dddot{\theta}_r(t) \) are zero-mean white noise processes with PSD \( \dddot{\theta}_0 \) and \( \dddot{\theta}_r \), respectively (tuned in this
paper to be \( \tilde{Q} = (2\pi 0.5)^2 \) and \( \tilde{r} = (0.01)^2 \). The continuous-time dynamics in (3) is discretized with a sampling period \( T_0 = LT_s \), leading to \( x_{k+1} = F x_k + u_k \), where \( x_k \triangleq [\theta_k, \mu_k, \sigma_k, T_k]^\top \). \( F \triangleq e^{A T_0} \) is the state transition matrix, and \( u_k \) is a discrete-time zero-mean white random sequence with covariance \( Q = \int_0^{T_0} e^{At} B Q (e^{At} B)^\top dt \), where \( Q \triangleq \begin{bmatrix} \tilde{q}_o & \tilde{q}_r \\ 0 & \tilde{q}_r \end{bmatrix} \). The KF’s observation model is given as \( z_k = C x_k + v_k \), where

\[
C \triangleq \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad v_k \overset{i.i.d.}{\sim} \mathcal{N} \left( \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \sigma_\theta^2 & 0 \\ 0 & \sigma_\tau^2 \end{bmatrix} \right).
\]

Finally, the innovation term of the KF \( \nu_k = [\tilde{\theta}_k, \tilde{\tau}_k]^\top \) is calculated from the unambiguous four-quadrant arctangent and early-minus-late envelope discriminators [25] as

\[
\begin{align*}
\tilde{\theta}_k & \triangleq \text{atan}2 (\Re \{ Z_P(k) \}, \Im \{ Z_P(k) \}), \\
\tilde{\tau}_k & \triangleq \frac{1}{2} \left| Z_E(k) - |Z_L(k)| \right|
\end{align*}
\]

where \( Z_P(k) \triangleq \langle \tilde{r}_k[n], \sigma[n] \rangle, Z_E(k) \triangleq \langle \tilde{r}_k[n], (s \otimes \hat{\Delta}_E)[n] \rangle, Z_L(k) \triangleq \langle \tilde{r}_k[n], (s \otimes -\hat{\Delta}_E)[n] \rangle \), are the prompt, early, and late correlations, respectively, and \( \Delta_i \) is the chip length, in seconds. In this paper, the estimated beacon from OneWeb at \( F_s = 2.5 \text{ MHz} \) had a value of \( \Delta_i = 0.4 \mu \text{s} \). The measurement standard deviations tuned to \( \sigma_\theta = 0.006 \text{ rad} \) and \( \sigma_\tau = 0.01 \text{ s} \).

C. Beam Switching

Modern LEO megaconstellations make use of beam-forming strategies [26] and handover schemes [27] with their phased antenna arrays to be able to support their high capacity and low latency broadband communication applications [28]. During the SV passing, the blind navigation beacon estimator could identify 11 different active beams, 8 of the them transmitting at 11.075 GHz (CH1) while the other 3 were transmitting at 11.575 GHz (CH3). Fig. 5 shows on top the theoretical 4 dB contours of OneWeb Ku-band’s highly elliptical 16 beams, as shown in the FCC documentation [23], and on the bottom the empirical \( C/N_0 \) for the tracked beams. Note that in Fig. 5, beams 1, 3, 5, 7, 9, 11, 13, and 15 were observed at CH1, beams 4, 8, and 12 were observed at CH3, and beams 2, 6, 10, 14, 16 were observed to be inactive up until the time of writing this paper.

The beam handling block, illustrated in Fig. 6, was designed to acquire and track the beams in the following fashion:

1) Acquisition stage: The receiver sweeps over all the possible values of the beam-specific beacons \( s_i[n], i \in \{1, \ldots, 16\} \), and performs the acquisition described in Section IV.A that outputs the carrier power for the \( i \)-th beam denoted by \( C(i) \triangleq |\langle \tilde{r}_k[n], s_i[n] \rangle|^2 \). Once the \( C/N_0 \) at a given beam passes a preset threshold \( \eta \) (chosen to be 25 dB in this paper), the receiver flags a successful acquisition and starts the tracking loops.

2) Tracking stage: The receiver monitors the \( C/N_0 \) of the current beam (whose index is \( i \)); if the \( C/N_0 \) falls below \( \eta \), the receiver stops the tracking and switches back to acquisition mode, otherwise, if the power at the next predicted beam \( C(i^+) \) is greater than the current one \( C(i) \), the receiver triggers a beam switch. The next beam index prediction formula is \( i^+ = \text{mod}(i + 1, 16) \).

Note that in this paper, the beam-specific beacons \( s_i[n] \) for \( i \in \{1, \ldots, 8\} \) were populated using the estimated beacons from CH1 as discussed in Section III, while \( s_i[n] \) for \( i \in \{9, \ldots, 16\} \) were set to zero.

V. Positioning with OneWeb LEO constellation

This section provides the first results for carrier phase positioning with OneWeb signals exclusively.

A. Tracking results

The sampling rate \( F_s \) of the USRP was set to 2.5 MHz and the carrier frequency was set to 11.075 GHz (CH1). The USRP was set to record for 30 minutes. During this period, a total of 9 OneWeb SVs passed over the receiver, one at a time. The samples of the signal were stored for offline processing. Fig. 7 summarizes the tracking results (solid lines) and compares them with simulated results (dashed lines) generated by propagating the SV ephemerides using the simplified general perturbation 4 (SGP4) initialization by the two-line elements (TLE) file [29]. Note that repetitive pattern present in the code phase and carrier phase error in Fig. 7 is due to the beam switching that temporarily drops the \( C/N_0 \) and increases the tracking error variance.

B. Carrier Phase Measurement Model

The tracked carrier phase \( \theta_i(k) \), where \( i \in \{1, \ldots, 9\} \) represents the SV’s index, and \( k \) is the sub-accumulation
summarizes the position results. The breakdown order TSE which allows (i) C/No, (ii) estimated Doppler (solid) versus Doppler profile generated from TLE-SGP4 propagated ephemeris, (iii) estimated code phase (solid) versus code phase profile generated from TLE-SGP4, (iv) carrier phase error, and (v) code phase error.

index defined earlier, was used to localize a stationary receiver. In order to simplify the formulation of the weighted nonlinear least squares (WNLS) estimator, this paper assumes that the signal time of flight has negligible effect on the i-th SV position and on the clock bias terms. However, the errors resultant from this approximation will be lumped and estimated as described in the following section. Using this assumption, the carrier phase observable model can be written as

\[ \theta_i(k) = \| \mathbf{r} - r_{SV_i}(k) \|_2 + c\delta t_i(k) + \lambda_i N_i + \nu_i(k), \]

where \( \mathbf{r} \) is the stationary receiver’s three-dimensional (3-D) position vector; \( r_{SV_i} \) is the i-th SV’s 3-D position vector; \( \delta t_i \) is a term modeling the lumped effects of the clock bias mismatch between the receiver and the i-th SV’s clock biases and the atmospheric delays caused by the signal propagation in the ionosphere and troposphere; \( c \) is the speed of light; \( \lambda_i \) is the wavelength of the i-th SV’s signal; \( N_i \) is the carrier phase ambiguity between the receiver and i-th SV; and \( \nu_i(k) \) is the measurement noise which is modeled as a discrete-time zero-mean white sequence with variance \( \sigma^2_{\nu_i} \) retrieved from the first entry of the KF estimation error covariance (see Section IV.B). The term \( \delta t_i(k) \) will be approximated as a first-order TSE which allows (4) to be approximated as

\[ \theta_i(k) \approx \| \mathbf{r} - r_{SV_i}(k) \|_2 + a_i + b_i k T_0 + \nu_i(k), \]

where \( a_i \) and \( b_i \) are the zero- and first-order TSE terms, respectively, of the lumped clock and atmospheric errors.

C. Batch WNLS Estimator

Next, define the state vector \( \mathbf{x} \triangleq [r_r^T, a_1, b_1, \ldots, a_9, b_9]^T. \) Let \( z(k) \) denote the vector of carrier phase observables from OneWeb SVs, available at time-step \( k \), stacked together, i.e., \( z(k) \triangleq [\theta_1(k), \ldots, \theta_9(k)]^T. \) The vector of all available observables is defined as \( \mathbf{z} \triangleq [z(0), \ldots, z(M)]^T, \) where \( M \) is the total number of observations during the SV’s pass. Let \( \mathbf{v}_z \) denote the vector of all measurement noises stacked together; \( \mathbf{v}_z \) is zero-mean Gaussian random vector with a diagonal covariance matrix \( \mathbf{R} \) whose diagonal elements are given by \( \sigma^2_{\nu_i}(k). \) Then, one can readily write the measurement equation given by \( \mathbf{z} = \mathbf{g}(\mathbf{x}) + \mathbf{v}_z \), where \( \mathbf{g}(\mathbf{x}) \) is the nonlinear mapping from the state space \( \mathbf{x} \) to the measurement space \( \mathbf{z} \) according to (5). A WNLS estimator with weighting matrix \( \mathbf{R}^{-1} \) is implemented to obtain an estimate of \( \mathbf{x}. \) The SV positions were obtained from TLE-SGP4 propagation. It is important to note that the TLE epoch time was adjusted a priori such that it minimizes the range residuals for each SV to account for ephemeris errors. The receiver position was initialized 50 km away from the true position with a vertical error of 10 km. The final 2-D position error was found to be 30.4 m. Fig. 8 summarizes the position results. The breakdown of the error in the east-north-up (ENU) frame was 30.4 m, 7 cm, and 60 cm respectively. The large error in the east direction is explained by the geometry of OneWeb constellation which is north-south oriented. This specific configuration renders the east direction, which is the projection of the cross-track direction of the SV onto Earth’s surface to be poorly observable [30].

![Fig. 7. Figure showing the tracking results of 9 OneWeb SVs from top to bottom: (i) estimated C/No, (ii) estimated Doppler (solid) versus Doppler profile generated from TLE-SGP4 propagated ephemeris, (iii) estimated code phase (solid) versus code phase profile generated from TLE-SGP4, (iv) carrier phase error, and (v) code phase error.](image)

![Fig. 8. Positioning results with OneWeb LEO constellation: (a) OneWeb SV trajectories, (b) initial position estimate vs. receiver’s true position, and (c) final errors relative to receiver’s true position.](image)

VI. Conclusion

This paper examined OneWeb LEO SV signals. OneWeb’s downlink beacons were estimated via a proposed blind navigation beacon estimation framework. A fast acquisition framework reduced the number of Doppler search bins by nearly 80%. The blindly estimated beacons were used to identify the beams of the OneWeb
constellation and to characterize its C/N₀. The developed KF-based tracking loops successfully tracked the code and carrier phase of 9 OneWeb LEO SVs, which were used to localize a stationary receiver. Starting with an initial estimate 50 km away from the true position, the proposed approach achieved a 2-D error of 30.4 m.

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