Mitigating Receiver Code Bias in Wideband Low-Elevation TEC Retrievals from GNSS Ground Stations

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Abstract

Accurate estimation of ionospheric total electron content (TEC) is essential for improving GNSS performance and understanding space weather. Our work investigates the use of wideband GNSS pseudorange data to recover low-elevation TEC measurements, which are typically discarded due to high noise and multipath. Wideband signals like GPS L5 offer improved code resolution and reduced noise, making them promising for single-frequency TEC retrieval. Our past work shows that noise in wideband pseudorange-derived TEC is significantly lower than that of narrowband signals, especially below 30° elevation.

Ongoing work focuses on unbiased sTEC retrieval by using data from high-latitude IGS stations. We apply receiver code bias (CB) estimation methods that use dual-frequency high-elevation measurements and spatial TEC gradients. This bias correction methodology will enable the retrieval of absolute slant TEC from low-elevation wideband signals. We plan to test this methodology using electron density data from the Poker Flat ISR (PFISR) and compare computed CBs to published data from IGS. This work aims to expand low-elevation GNSS signal usage, a critical step toward mitigating ionospheric data gaps and improving global ionospheric models.

Background and Motivation

Most ground-based GNSS monitoring stations impose a masking angle to eliminate measurements from low satellite elevation angles, removing noisy signals and signals corrupted by multipath errors. However, low-elevation signals are abundant, especially at high and mid latitudes. These signals carry rich environmental information, as they travel longer distances through the ionosphere's active layers. Utilizing low-elevation signals would greatly increase the number of available TEC observations while offering more diverse signal geometries for 3-D TEC mapping algorithms.

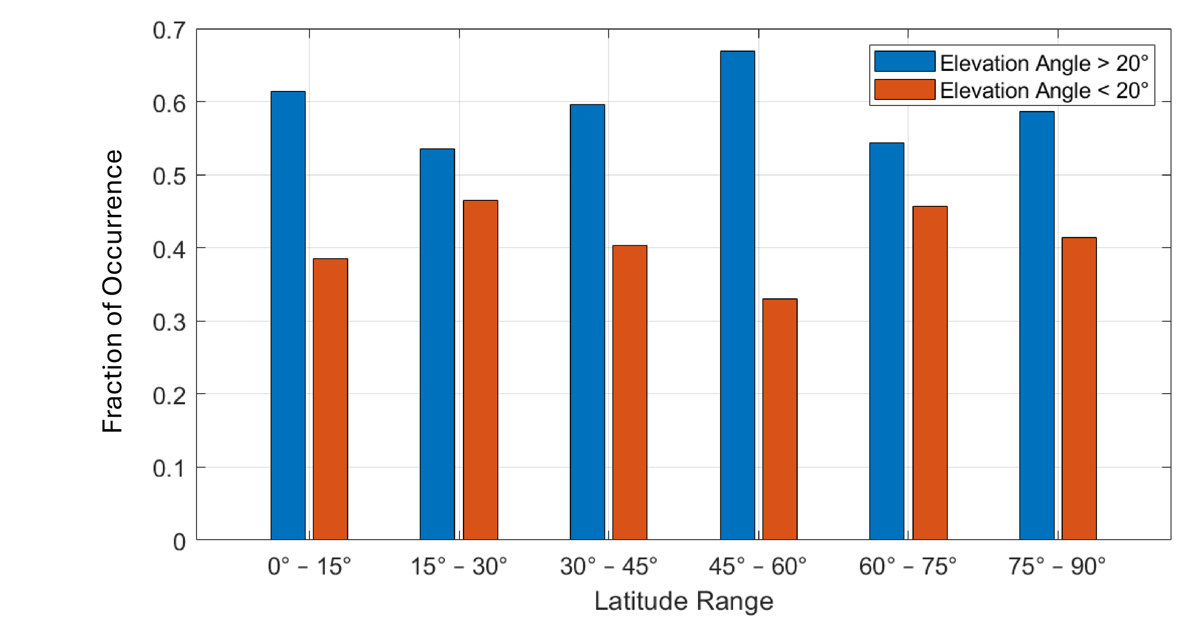

Figure 1. Fraction of occurrence of received narrowband GPS signals below and above 20° satellite elevation angle binned by latitude range.

Wideband GPS signals such as the L5 civil signal are less susceptible to multipath errors due to their code chipping rate, which is 10x higher than the L1 C/A and L2 C signals. Additionally, wideband signals result in less pseudorange measurement noise than their narrowband counterparts, providing better low-elevation signal quality. Currently, more than half of GPS satellites transmit L5 civil signal.

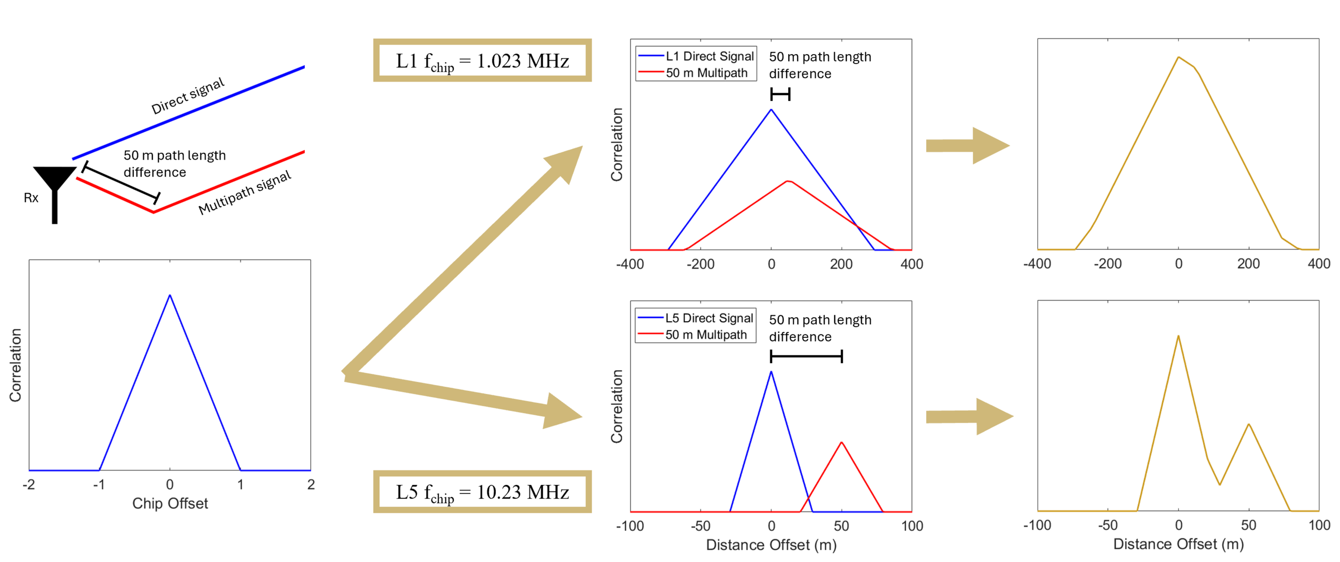

Figure 2. Illustrates binary phase-shift keying (BPSK) correlation waveform and how a higher-bandwidth signal (e.g. GPS L5) has better multipath rejection compared to a lower-bandwidth signal (e.g. GPS L1CA).

Motivation: Single-Track TEC Estimation

Currently, the estimation of ionospheric TEC is most-commonly achieved using dual-frequency narrowband GNSS signals. Figures 3 and 4 illustrate TEC estimate noise quality improvements using a wideband signal-frequency method. As satellite elevation angle decreases, dual-frequency TEC noise greatly increases, as single-frequency wideband TEC noise remains more consistent. Our work has shown <u>L5 single-frequency estimates improve signal noise by a factor of ~3–5 at high satellite elevation and by a factor of ~3–7 at elevations below 30 degrees when compared to dual-frequency methods. Receiver code bias is still present in these measurements.</u>

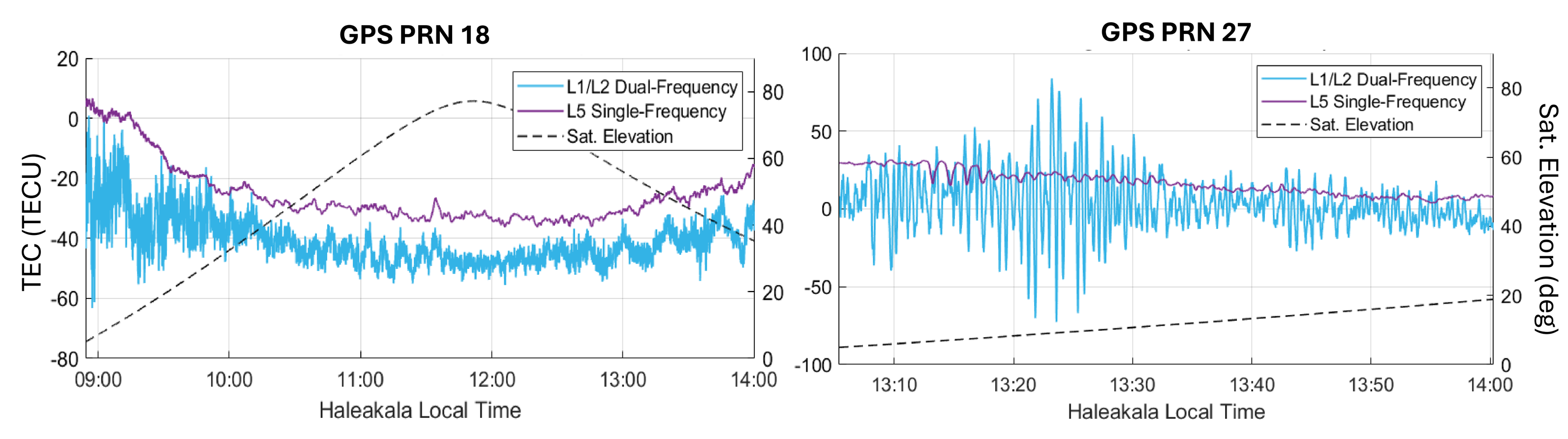

Figure 3. Comparison of wideband single-frequency and narrowband dual-frequency TEC estimates from single satellite passes over Haleakala, HI on 10-June-2021.

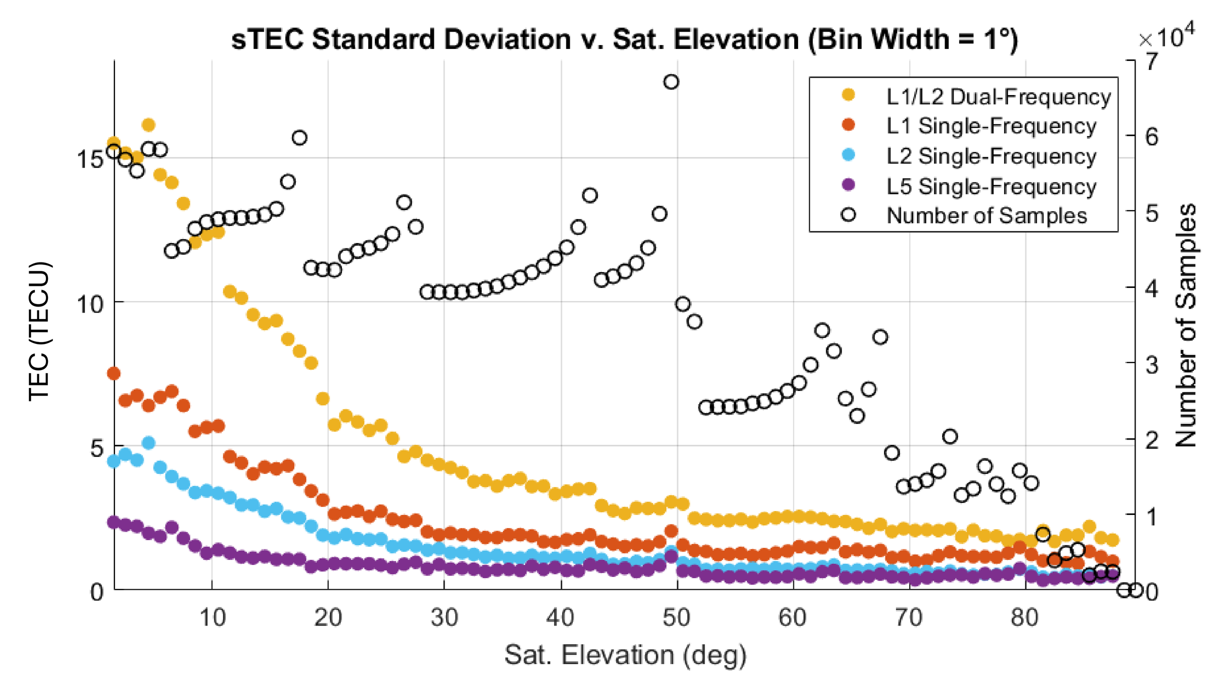

Figure 4. Standard deviation of TEC estimates from one week of satellite passes binned by 1° satellite elevation angle from a receiver in Haleakala, HI.

Methodology: Receiver Code Bias Estimation using TEC Gradients

Receiver code bias (CB) estimation is essential for retrieving absolute (unbiased) TEC from low elevation satellite signals. Figure 5 shows a block diagram and signal geometry depiction for the CB correction methodology. This approach uses high-elevation dual-frequency relative slant TEC (sTEC) measurements to derive vertical TEC (vTEC) and the receiver differential code bias (DCB). With the knowledge of the vTEC and DCB, we can derive the single frequency wideband signal CB, which we then apply to correct the low elevation satellite TEC obtained using wideband single frequency signal.

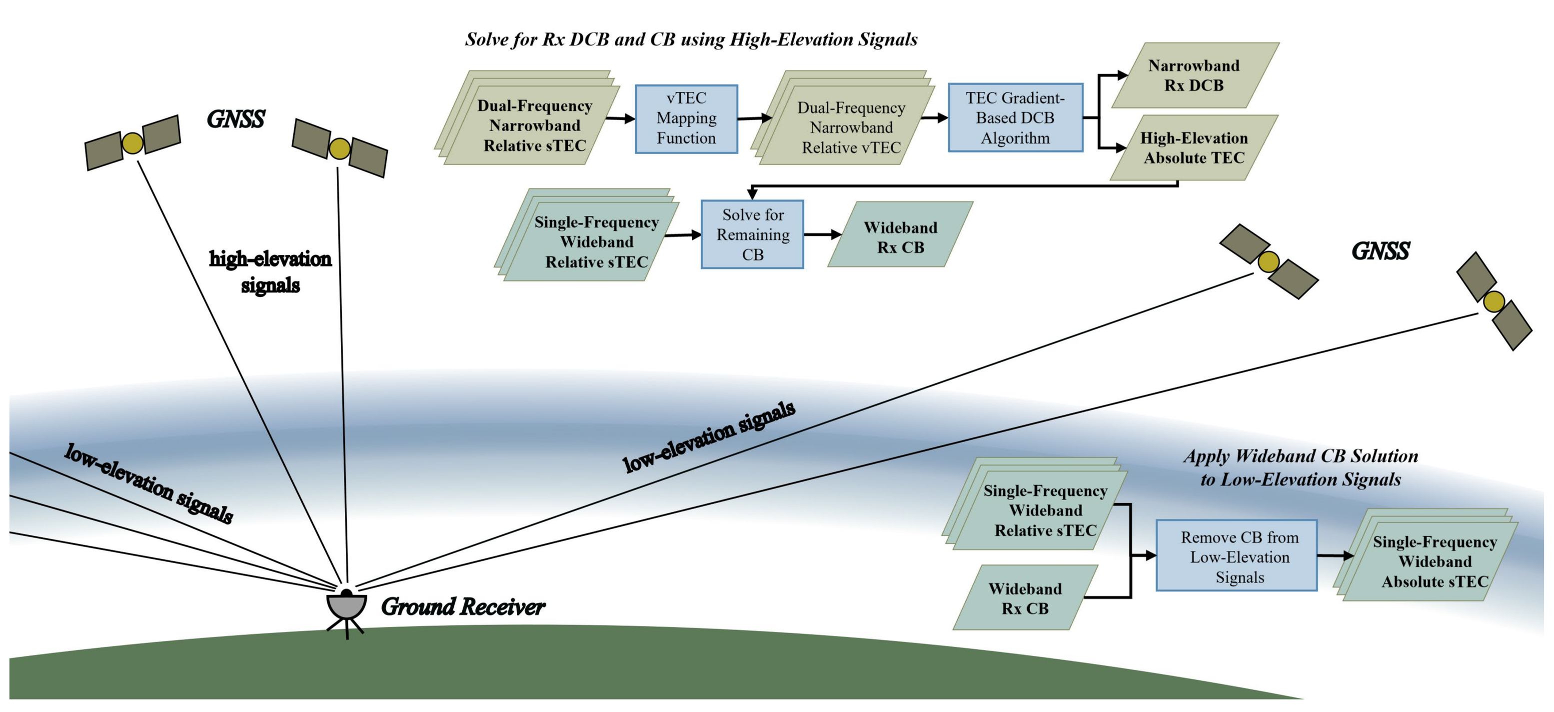

Figure 5. Diagram depicting high- and low-elevation signal geometries at ground receivers. Block diagrams describe using high-elevation measurements to aid in the retrieval of absolute sTEC from low-elevation signals.

Methodology: TEC Gradient Based Rx Code Bias Solution

This equation set models dual-frequency GNSS pseudorange differences to estimate vertical total electron content (vTEC), its spatial gradients, and receiver differential code bias (DCB) at high elevation angles. By linearizing ionospheric delay as a function of pierce point location, it can enable estimation of ionospheric structure and receiver bias from high-elevation, slant-path GNSS observations.

$$\rho_{L2,i} - \rho_{L1,i} - DCB_i^{SV} =$$

$$\frac{40.3}{MF(el_i)}\left(\frac{f_{L1}^2 - f_{L2}^2}{f_{L1}^2 f_{L2}^2}\right)\left(VTEC_0 + \frac{\partial VTEC}{\partial \lambda}\Delta\lambda_{IPP,i} + \frac{\partial VTEC}{\partial \phi}\Delta\phi_{IPP,i}\right) + DCB_{RX}$$

TEC, spatial gradients, and Rx CBs can be solved for using a least squares approach.

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{x}$$

$$y_i = \rho_{L2,i} - \rho_{L1,i} - DCB_i^{SV}$$

$$\boldsymbol{H}_i = \begin{bmatrix} ab_i & ab_ic_i & ab_id_i & 1 \end{bmatrix}$$

$$\boldsymbol{x} = \begin{bmatrix} VTEC_0 & \frac{\partial VTEC}{\partial \lambda} & \frac{\partial VTEC}{\partial \phi} & DCB_{RX} \end{bmatrix}^T$$

$$a = 40.3\left(\frac{f_{L1}^2 - f_{L2}^2}{f_{L1}^2 f_{L2}^2}\right)\text{x}10^{16} = 0.10505$$

$$b_i = \frac{1}{MF(el_i)} = [0.57, 1]$$

$$c_i = \Delta\lambda_{IPP,i} = [-11.23, 11.23](deg)$$

$$d_i = \Delta\phi_{IPP,i} = [-4.8, 4.8](deg)$$

$\rho_{L1,i}$, $\rho_{L2,i}$: Pseudorange measurements on the L1 and L2 frequencies.

DCB_{RX}, DCB_i^{SV}: Receiver, satellite differential code biases.

$VTEC_0$: Vertical Total Electron Content (VTEC) at the reference IPP.

$\frac{\partial VTEC}{\partial \lambda}$, $\frac{\partial VTEC}{\partial \phi}$: Longitudinal, latitudinal gradients of VTEC.

a: Frequency-dependent constant for dual-frequency GNSS ionospheric delay, where f_{L1} and f_{L2} are carrier frequencies.

b_i: Slant-to-vertical TEC mapping function, where el_i is the satellite elevation.

c_i, d_i: Longitude, latitude deviation of the IPP.

Future Work: Experimental Setup

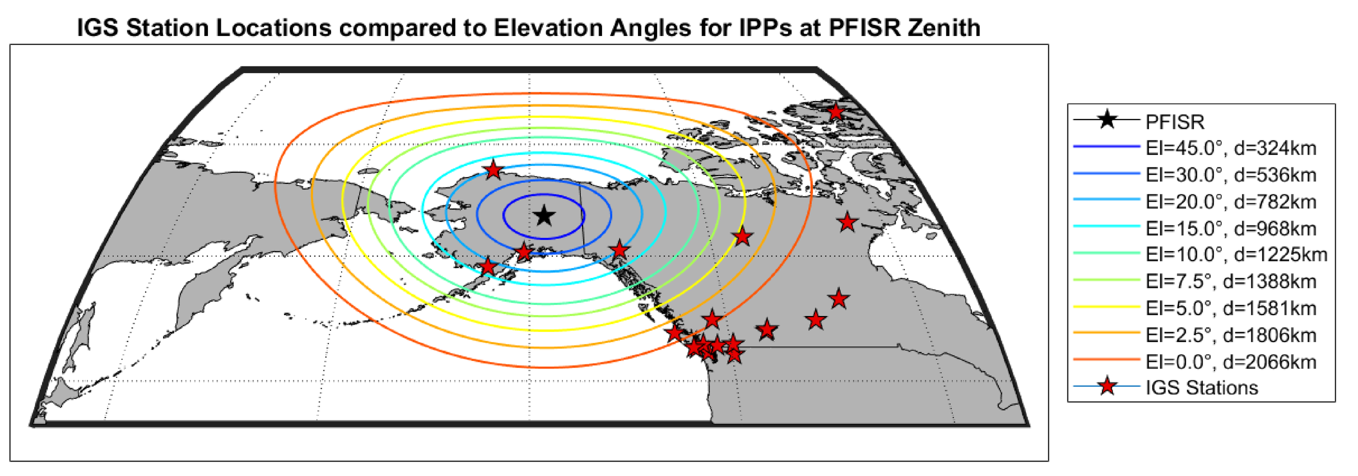

Figure 6. Map of high-latitude area surveyed for validation experiment. The black star denotes the Poker Flat ISR (PFISR) which generates electron density data. IGS stations are shown using red stars. Concentric circles around PFISR denote the approximate distance between PFISR and a ground station which would have a 350 km IPP directly above PFISR at the elevation angles shown in the legend.

Large-Scale High Latitude Validation Experiment

- Compare retrieved sTEC with electron density profiles from PFISR.
- Assess TEC retrieval accuracy across elevation angles and geomagnetic conditions.
- Quantify improvement in regional TEC maps and model residuals using wideband-corrected sTEC.

References

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