Estimating Ionospheric TEC Using Single-Frequency Wideband Low-Elevation GNSS Signals

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Abstract

Accurate estimation of ionospheric total electron content (TEC) is crucial for mitigating GNSS ranging errors and ensuring the reliability of navigation and positioning systems. TEC is also a fundamental parameter that describes the state of the ionosphere for space science research. This study investigates the ability to expand TEC measurement capability by the reduction of multipath and measurement noise by utilizing single-frequency wideband GNSS signals. Narrowband GNSS signals are characterized by increased multipath errors and higher measurement noise, especially for low-elevation satellites. For this reason, most ground-based GNSS monitoring stations impose a masking angle to eliminate low-elevation measurements. The purpose of this study is to make use of these low-elevation satellite signals for TEC estimation. Our results show that the utilization of the wideband signals can reduce measurement noise by a factor of approx. 3–5 at high satellite elevation, and 3–7 at elevation below 30 degrees when compared to dual-frequency methods. The technique presented here could enable wideband single-frequency receivers to produce better TEC estimates than standard dual-frequency methods.

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.

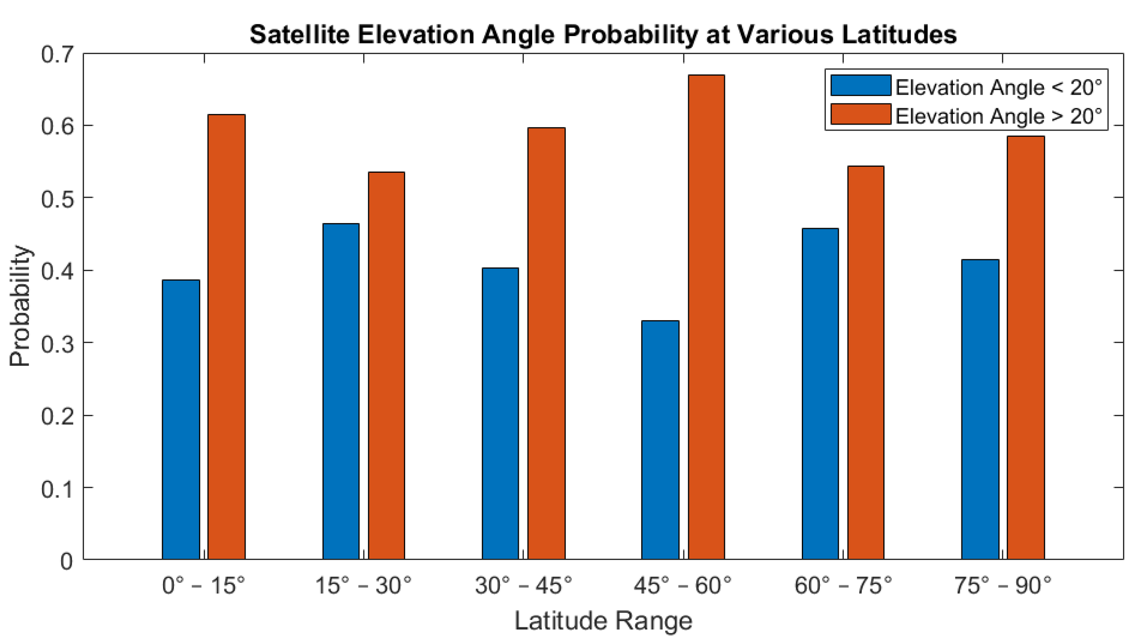

Figure 1. Probability of received narrowband GPS signals below and above 20° satellite elevation angle binned by latitude range.

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.

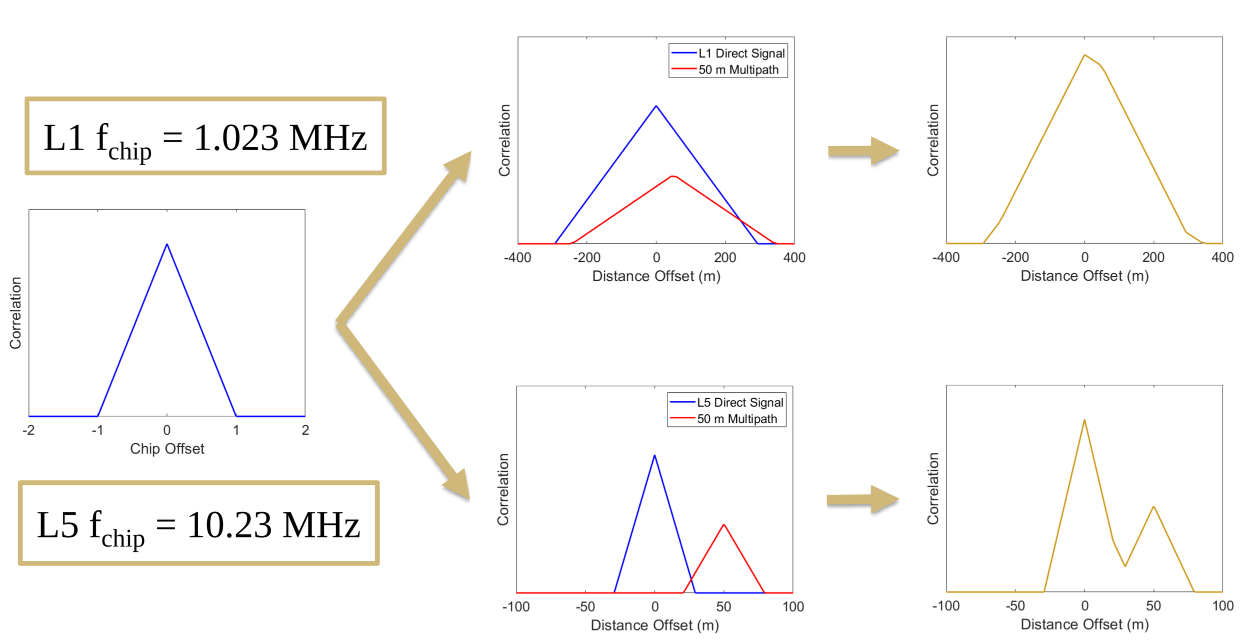

Figure 2. Comparison of GPS signal correlation peak for GPS L1 and L5 signals. Notably, the L5 correlation has a much higher precision and can easily be distinguished from a 50 m multipath error, while the L1 signal is degraded by multipathing.

Experimental Setup

Data used in this study are sourced from zenith-facing Septentrio receivers located at stations in Haleakala, HI and Toolik Lake, AK. Surveyed receiever station coordinates are 20°42'23"N, 156°15'25"W, 3,060 m and 68°37'39"N, 149°35'53"W, 737 m, respecttively. Data used in analyses are GPS L1C/A, L2C, and L5C pseudorange measurements. Both receiver stations are located in latitude ranges where close to half of incident GPS signals within view are below 20° elevation angle. Note that the Haleakala station has ambient structures which act as multipath variables during low-elevation satellite passes.

Methodology: Single-Frequency TEC Estimation

Single-frequency wideband TEC computations are produced using receiver pseudorange, pseudorange error calculations, and an estimate of the receiver clock bias. Notably, a dual-frequency TEC estimate is produced using high-elevation GPS satellite passes as an intermediate step to estimate the receiver clock and hardware biases.

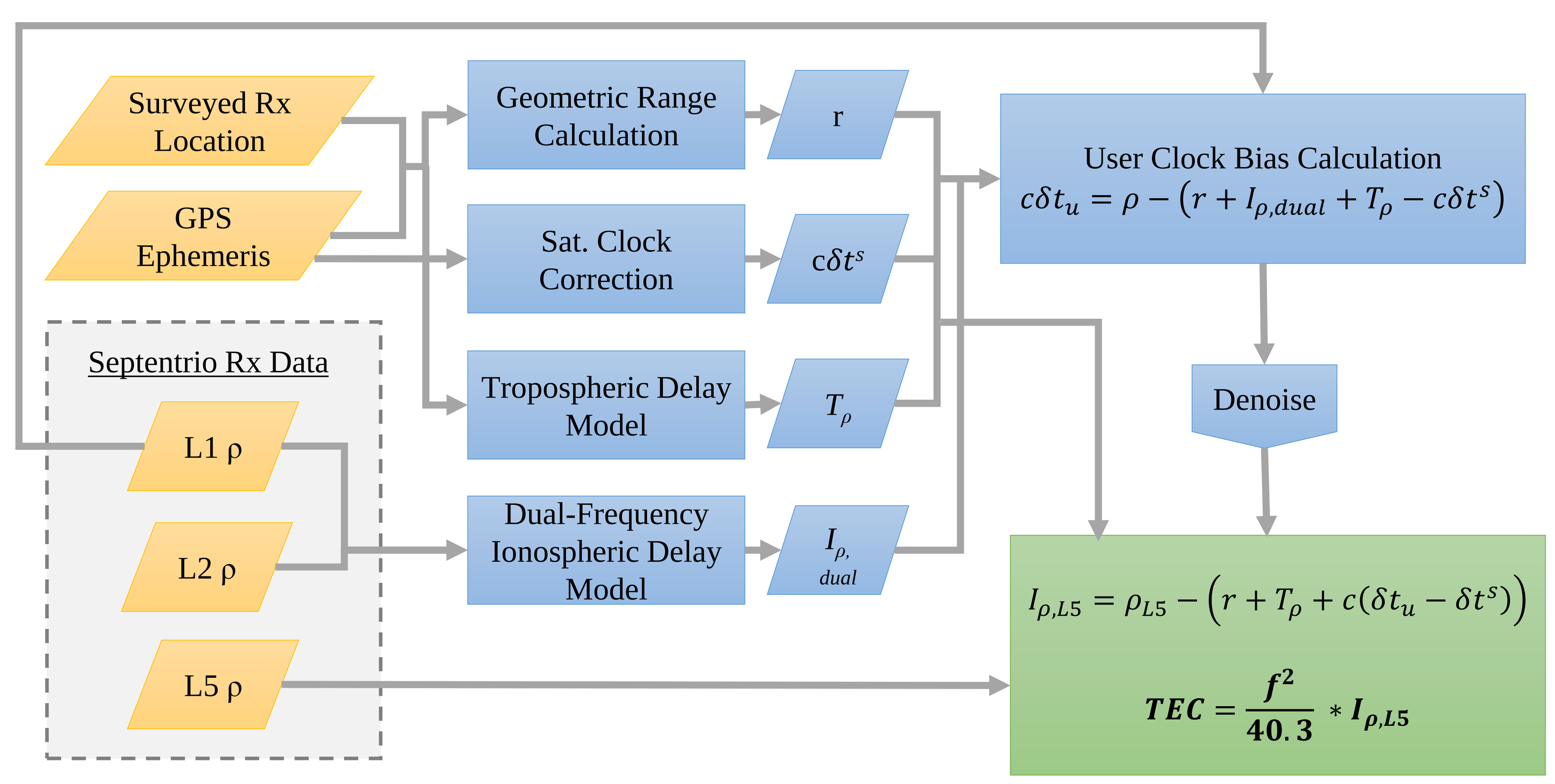

Figure 3. Block diagram of TEC estimation methodology for single-frequency wideband signals. Yellow parallelograms denote input data, while blue rectangles and parallelograms show intermediate calculations necessary to obtain final ionospheric range delay and TEC estimate, denoted by the green rectangle.

Results: Single-Track TEC Estimation

Currently, the estimation of ionospheric TEC is most-commonly achieved using dual-frequency narrowband GNSS signals. Figures 4 and 5 illustrate TEC estimate noise quality improvements using our wideband signal-frequency method. As satellite elevation angle decreases, dual-frequency TEC noise greatly increases, as single-frequency wideband TEC noise remains more consistent.

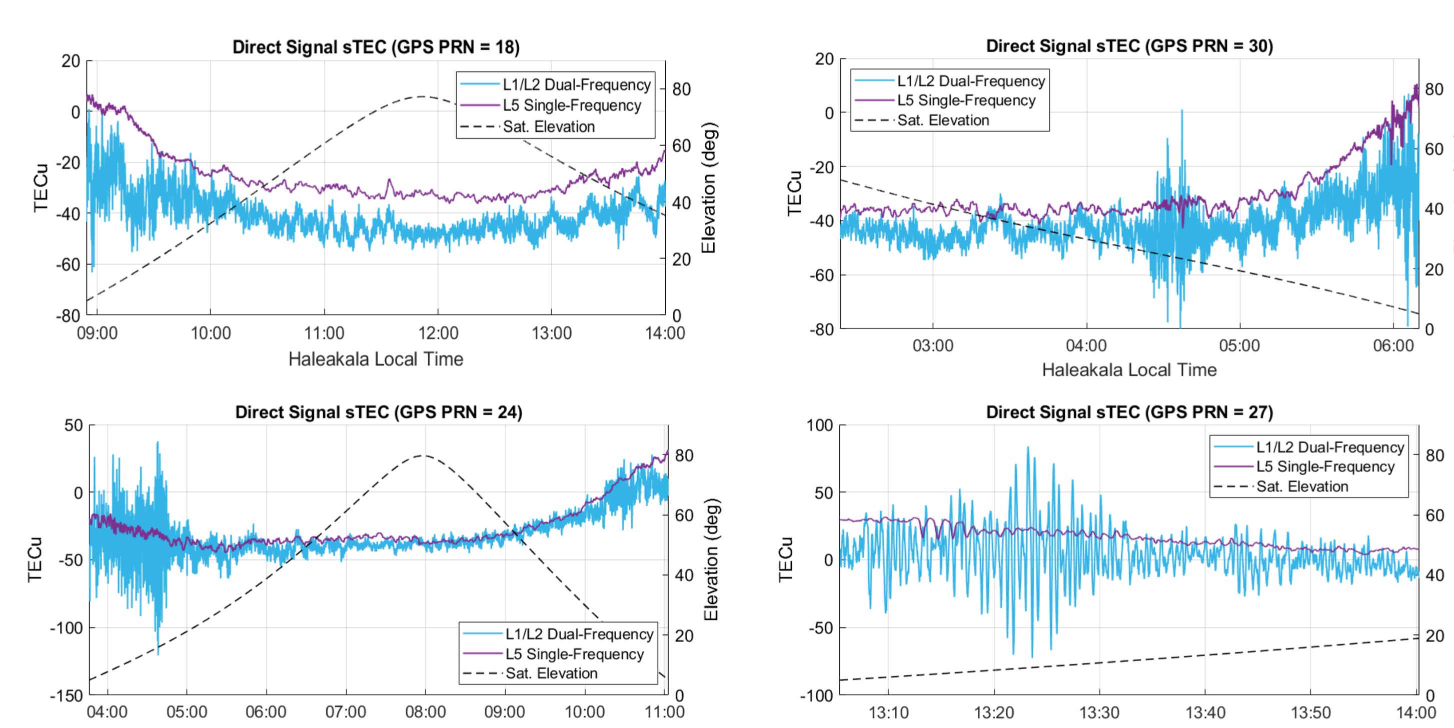

Figure 4. Comparison of wideband single-frequency and narrowband dual-frequency TEC estimates from single satellite passes over Haleakala, HI on 10-June-2021.

Results: Single-Frequency TEC Elevation Analysis

Our single-frequency methodology is used to estimate relative sTEC with one-week datasets of L1C/A, L2C, and L5C signals collected by receivers stationed in HI and AK. Figure 5 shows the TEC estimate noise-quality improvements using the wideband signal-frequency method binned by elevation angle. Number of samples is also plotted below, showing the frequency of received signals by elevation angle. Notably, the high-latitude station has more numerous received signals at low satellite elevation angles.

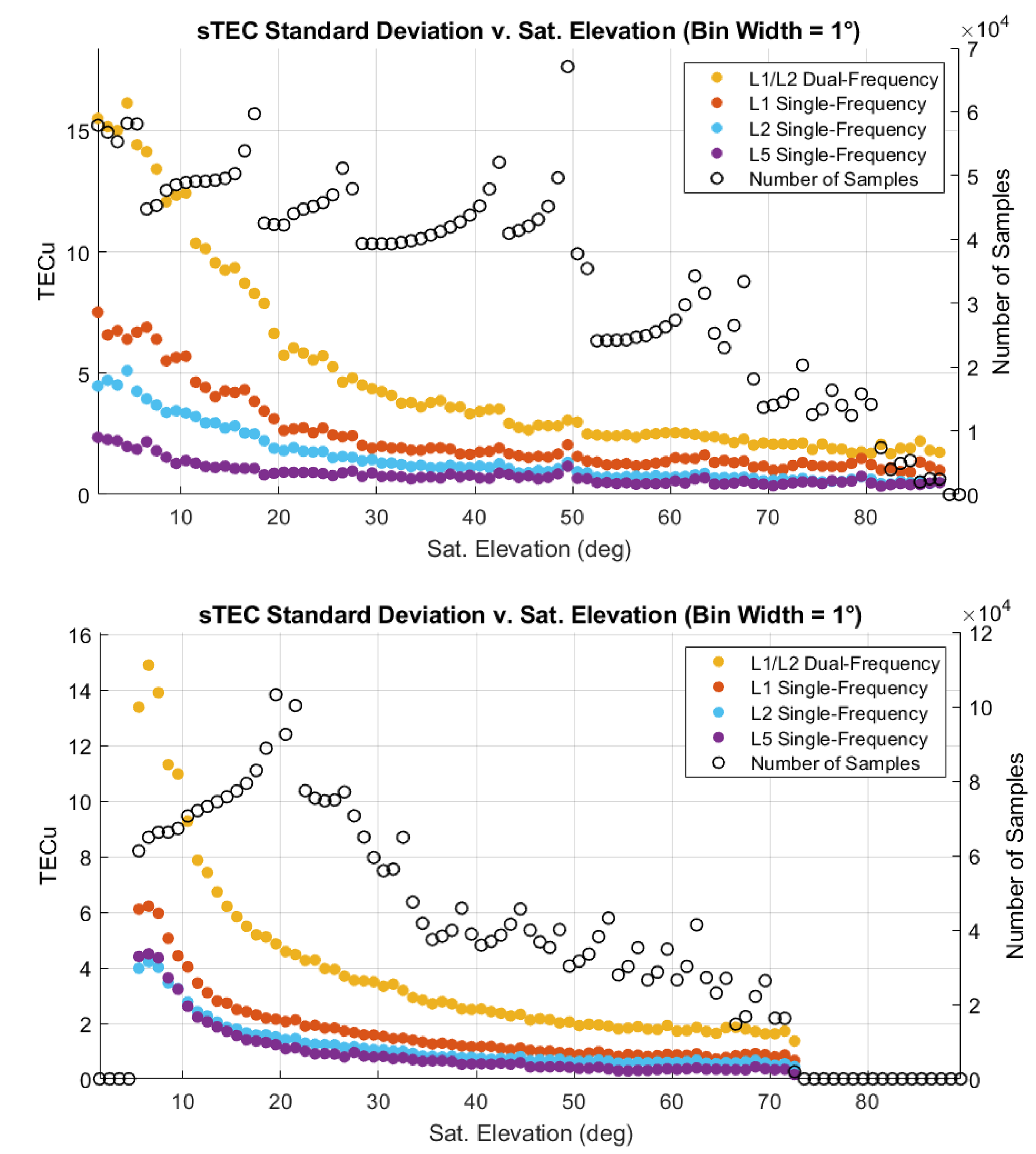

Figure 5. Standard deviation of TEC estimates from one week of satellite passes binned by 1° satellite elevation angle. L5 single-frequency estimates improve signal noise by a factor of ~3–5 at high satellite elevation and by a factor of ~3–7 at elevations below 30 degrees when compared to dual-frequency methods. The top plot shows results from the Haleakala, HI station, while the bottom plot shows results from Toolik Lake, AK.

Conclusion

Benefits

- Usage of L5 signals reduced multipath and pseudorange noise
  - Dual frequency TEC estimates dominated by L1/L2 noise at low elevation angles, washing out signals
- Low-elevation measurements enable more diverse signal geometry
  - Better for advanced tomography TEC mapping techniques

Challenges

- Difficult to calibrate Rx clock/hardware bias
  - Currently found using high-elevation L1/L2 signals as an intermediate computation
- Single-frequency methodology is more computationally intensive
- Multipath errors are not completely-eliminated by using wideband signals

References

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