ITIT-20

June 25-30, 2023
San Diego, CA

Absolute Total Electron Content (TEC) Estimation from Spire Global CubeSat Coherent GNSS-Reflectometry Measurements

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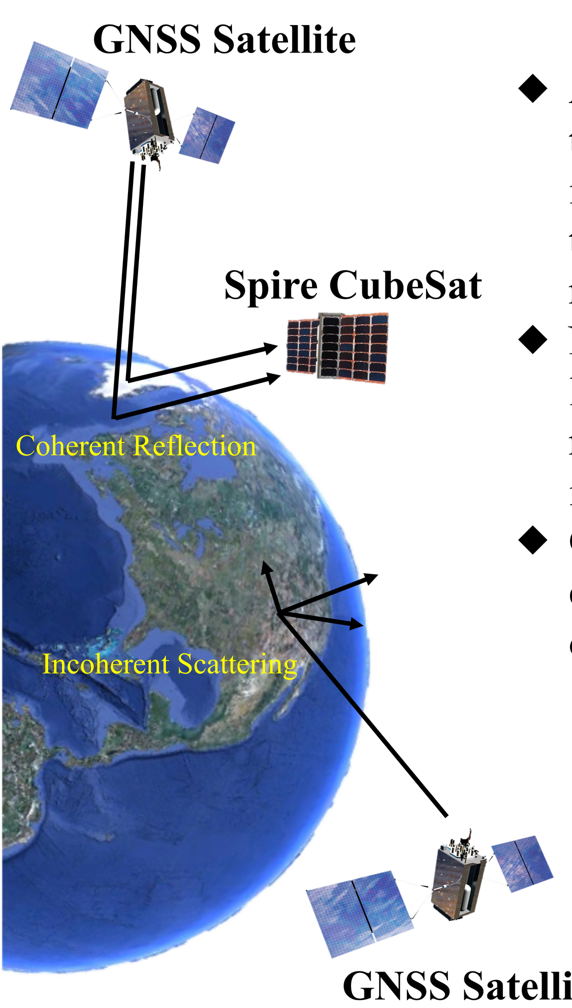
Introduction & Motivation

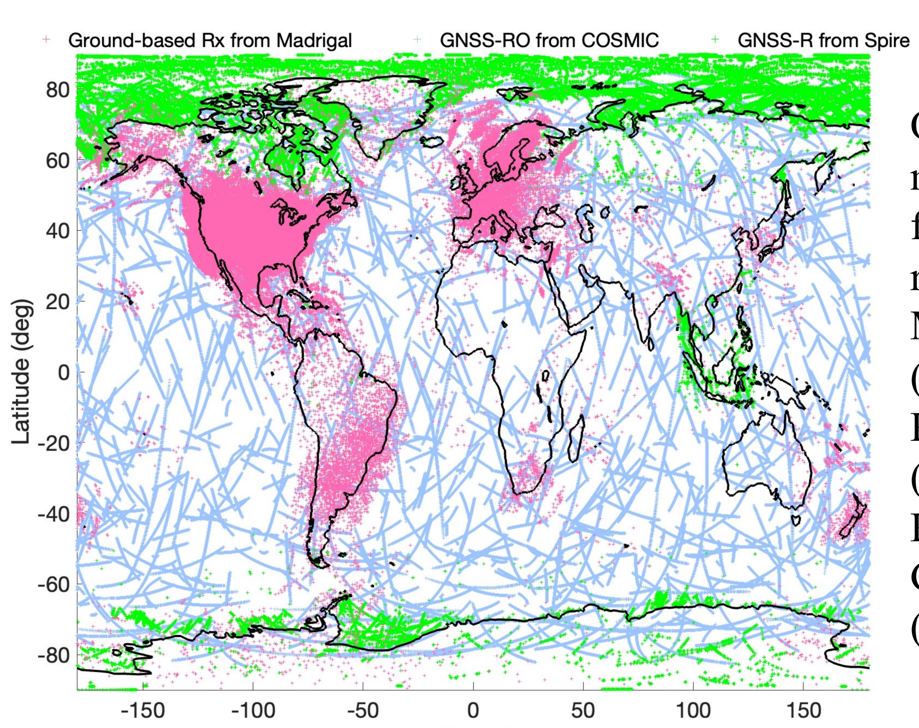
Total Electron Content (TEC) can be derived from GNSS receiver range measurements along the signal line-of-sight. Madrigal database collects ~8 k ground-based receivers which offers the observations with 1/30 Hz resolution. The coverage of these ground-based TEC measurements, however, is spotty over open oceans, polar caps, and unreachable terrains due to lack of receivers in-situ. GNSS Radio Occultation (RO) scan the ionosphere horizontally via a limb sounding geometry where the transmitter is a GNSS satellite and receiver is a satellite located on Low-Earth-Orbit (LEO). While the GNSS-RO has low horizontal resolution. Additional observations are desired to be ingested into the ionospheric data pool.

GNSS-Reflectometry (GNSS-R) shares similar configuration to GNSS-RO. The main difference is the LEO satellites receive the signal reflected by the Earth surface via nadir or side antenna which scan the ionosphere twice.



- As the GNSS signals are reflected by the Earth surface and go through the ionosphere twice, the measured TEC is the combination of TEC from incidence ray and reflection ray.
- Note that the Spire CubeSats are located at LEO orbit, hence, the reflected ray doesn't go through the ionosphere completely.
- GNSS-R signals contain adequate coherency when reflected over sea ice or calm waters [Wang & Morton, 2021]

SCAN ME



One day of TEC measurements from ground-based receivers from Madrigal (magenta), GNSS-RO from COSMIC (blue), and GNSS-R from Spire Global CubeSats (green).

Dataset & Methodology

Dataflow

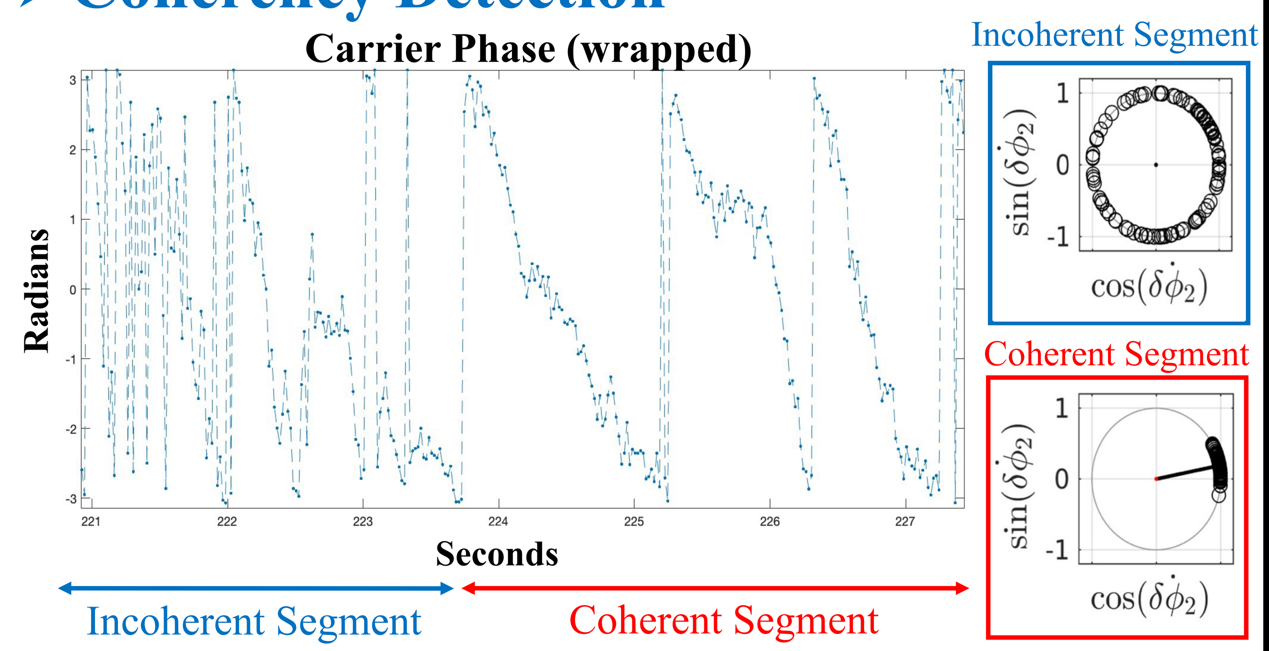
01 Coherency Detection — SCAN ME — [Roesler et al., 2020]

→ **02 Carrier Phase/ Pseudorange pre-processing** — SCAN ME — [Wang et al., 2020]

→ **03 TEC Retrieval**

1. Dual-frequency TEC retrieval
2. Differential Code Bias (DCB) estimation.

➢ Coherency Detection



Circular Statistics Method to identify the signal coherency.

➢ Carrier Phase/ Pseudorange Preprocessing

Spire provides 50 Hz open-loop (OL) carrier phase model and the residual carrier phase derived from I and Q channel. The OL carrier phase model is pre-processed and reported in range measurement while residual phase is in wrapped form.

$$\Phi_{tot} = \Phi_{OL} + \delta\Phi_{OL}$$

Φ_{tot} : Complete Carrier Phase.
Φ_{OL} : Open-loop Model.
$\delta\Phi_{OL}$: Residual Carrier Phase. (need to unwrap)

Residual Carrier Phase Unwrapping

$$\delta\Phi_i = \delta\Phi_i + 0 \text{ or } +2\pi \text{ or } -2\pi$$
$$\text{whichever minimize the } |\delta\Phi_i - \delta\Phi_{i-1}|$$

$\delta\Phi_i$: subscript i is the ith sample.

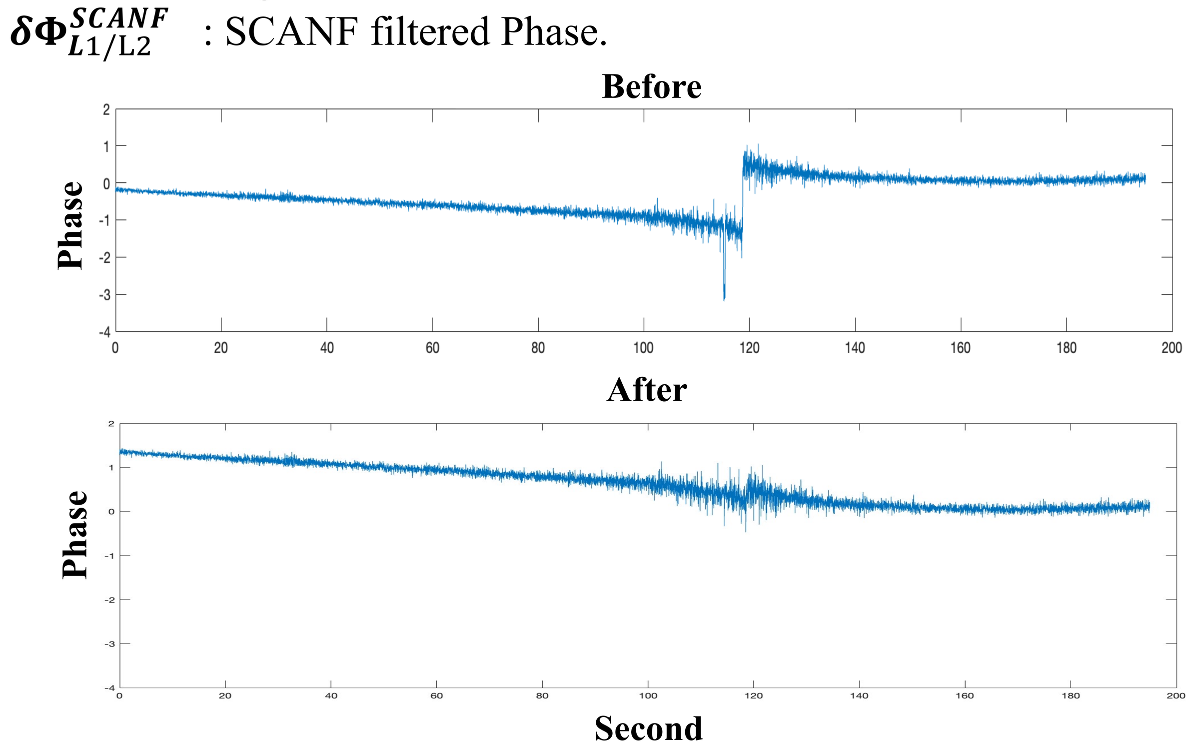
This method might still cause the discontinuities, also referred to as cycle slips, in the carrier phase time series due to signal amplitude fading.

Cycle Slip Correction

Simultaneous cycle slip and noise filtering (SCANF) method to correct the cycle slips. [Wang et al., 2020].

$$[\delta\Phi_{L1}^{SCANF}, \delta\Phi_{L2}^{SCANF}] = f_{SCANF}(\delta\Phi_{L1}^{OL}, \delta\Phi_{L2}^{OL}, SNR_{L1}, SNR_{L2})$$

SNR : Signal-to-noise Ratio.
$\delta\Phi_{L1/L2}^{SCANF}$: SCANF filtered Phase.



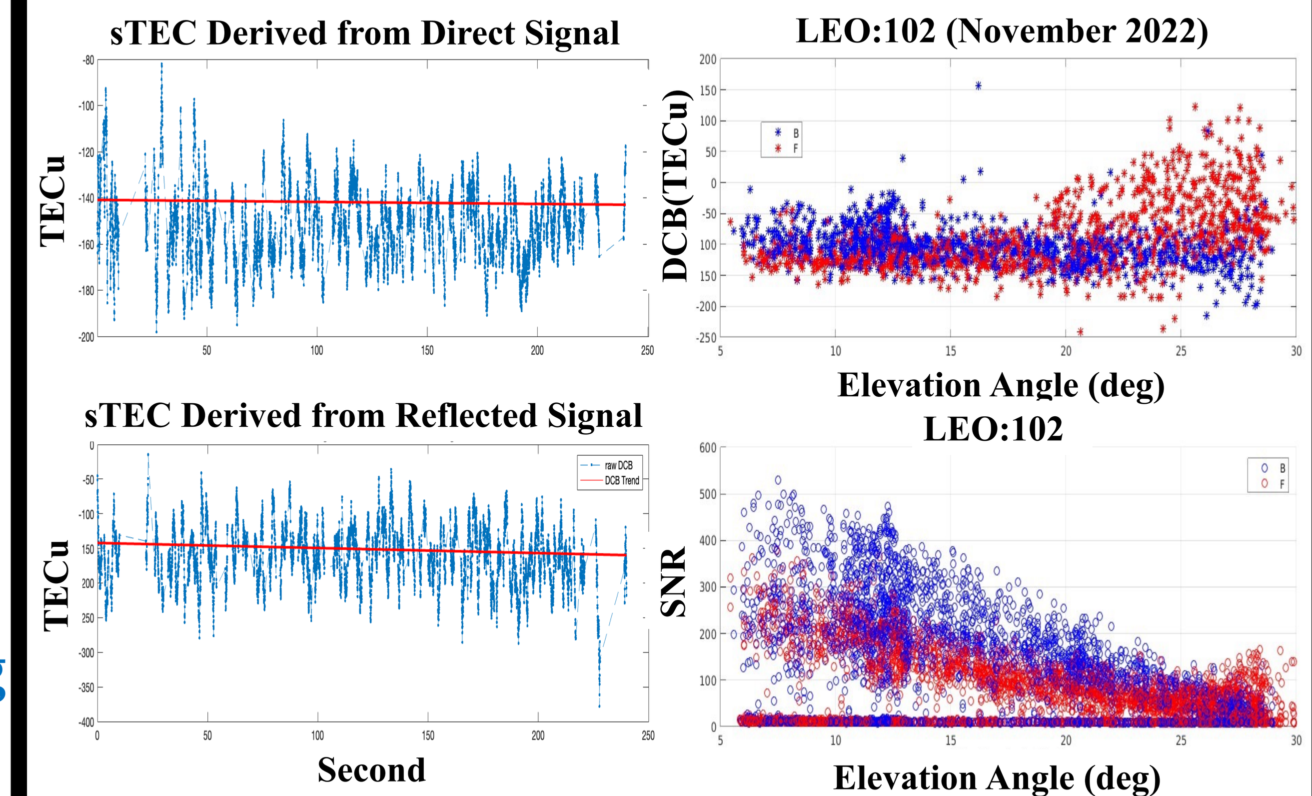
➢ TEC Retrieval

$$TEC = \frac{f_1^2 \cdot f_2^2}{40.3(f_2^2 - f_1^2)}(P_{L1} - P_{L2} - DCB_{GNSS} - DCB_{LEO} - \varepsilon_{P1} - \varepsilon_{P2})$$
$$= \frac{f_1^2 f_2^2}{40.3(f_2^2 - f_1^2)}(\Phi_{L2} - \Phi_{L1} + Z - DCB_{GNSS} - DCB_{LEO} - \varepsilon_{\Phi1} - \varepsilon_{\Phi2})$$

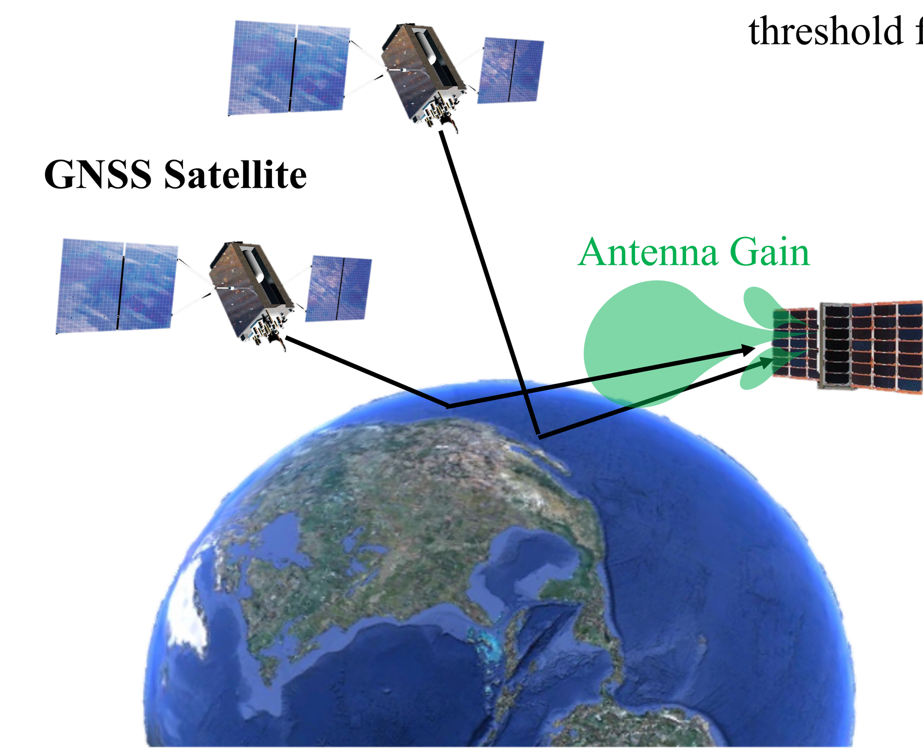
f_1 / f_2 : GPS L1 and L2 frequencies (f_1 = 1.575 GHz; f_2 = 1.227 GHz).
$P_{L1/L2}$: L1 & L2 band pseudorange measurements.
Z : Bias between pseudorange and carrier phase measurements.
DCB_{GNSS}: DCB of GNSS satellite ($DCB_{GNSS} = DCB_{C1C-C2W} + DCB_{C2W-C2L}$)
$\varepsilon_{1/2}$: noise.

Results

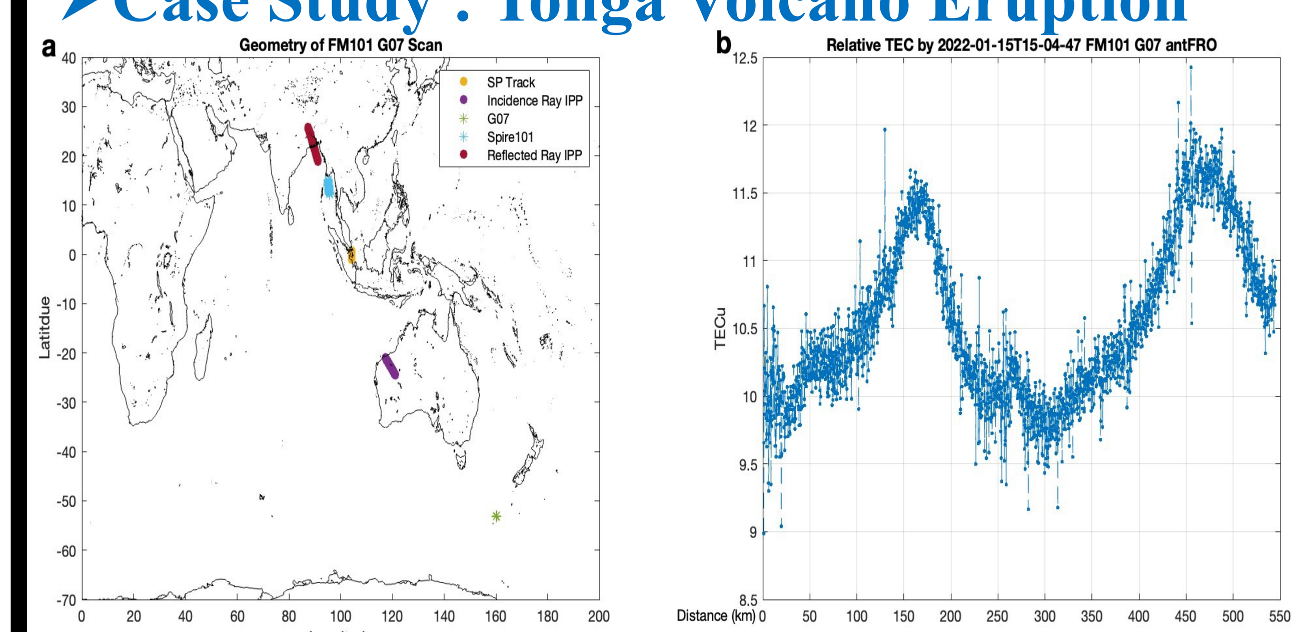
➢ Differential Code Bias (DCB) Estimation



Elevation Angle and SNR threshold for DCB estimation.

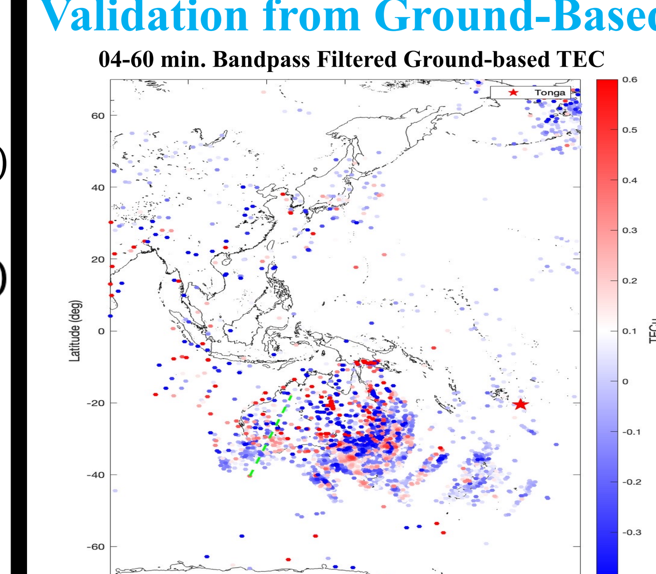


➢ Case Study : Tonga Volcano Eruption

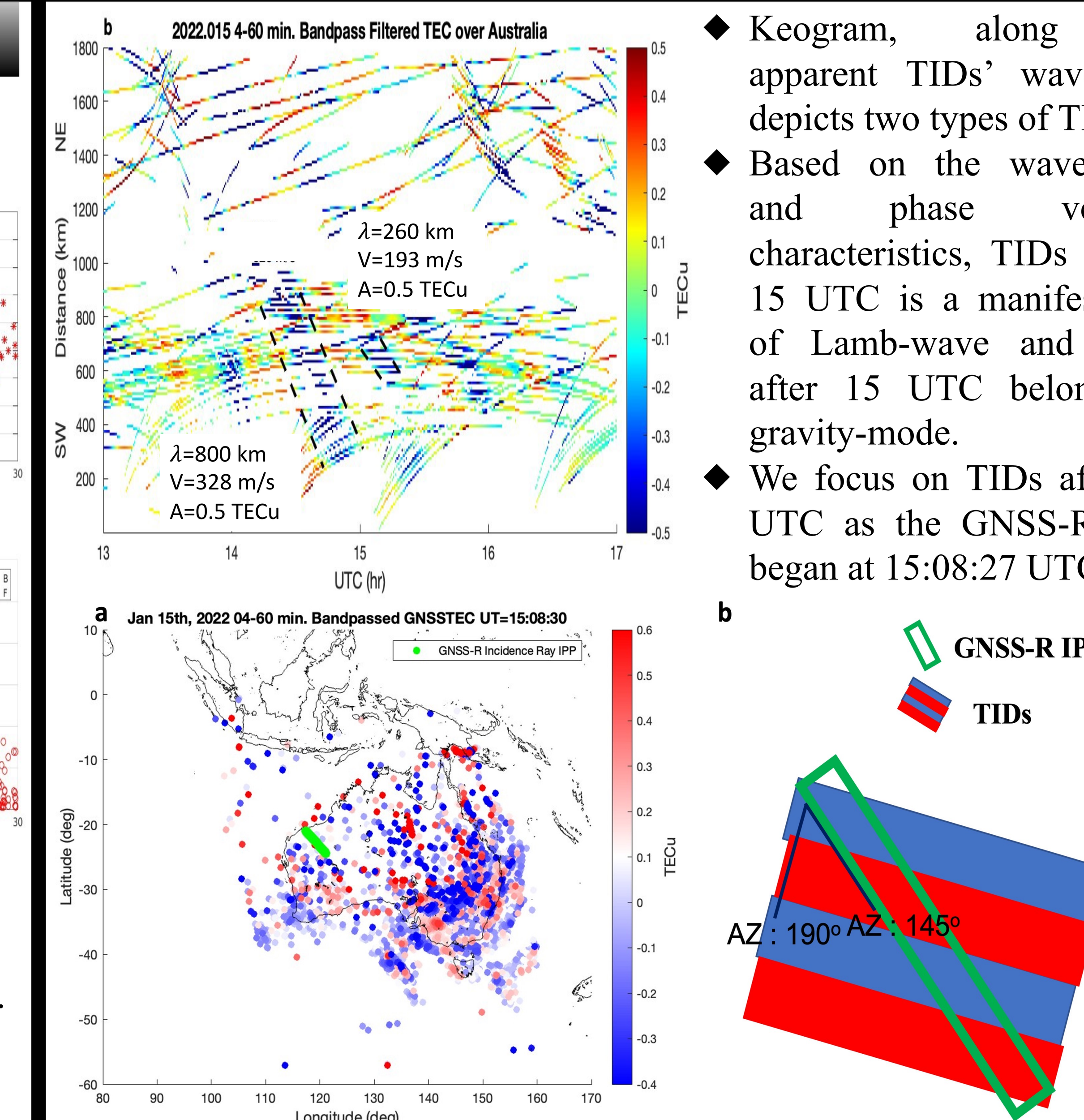


- The ionospheric piercing point (IPP) at 350 km altitude for both incidence and reflection rays.
- The GNSS-R scan offer nearly "frozen in time" observations. (15:08:27-15:09:12 UTC)
- The estimated wavelength and TEC magnitude of the ionospheric disturbances (TIDs) are ~330 km and 1 TECu.

Validation from Ground-Based Receivers' Observations



- We assume the GNSS-R reflection IPP, where the ground-based measurements are sparse, doesn't have apparent ionospheric disturbances.
- Around GNSS-R incidence IPP, clear TIDs are shown.



- Keogram, along the apparent TIDs' wavefront, depicts two types of TIDs.
- Based on the wavelength and phase velocity characteristics, TIDs before 15 UTC is a manifestation of Lamb-wave and TIDs after 15 UTC belongs to gravity-mode.
- We focus on TIDs after 15 UTC as the GNSS-R scan began at 15:08:27 UTC.
- The incidence IPP of GNSS-R is not aligned with the apparent wave normal, a ~45° angle between wave normal and GNSS-R scan.
- The 45° difference makes the wavelength observed by the ground-based network and by the GNSS-R scan in a ratio of 0.707 (cos(45°)) theoretically.
- The TIDs wavelength derived from GNSS-R and ground-based receivers network observations are ~330 km and ~260 km, respectively. The ratio of these two observed wavelengths is 0.787.

Conclusion & Discussion

This work presents the capability of absolute TEC retrieval and TIDs observations using GNSS-R. The Spire Global's fleet of CubeSats are used for our GNSS-R TEC retrieval work. The main findings are summarized below.

1. GNSS-R has high enough signal coherency over calm sea in Asia and sea ice in polar caps to offer the TEC measurements.
2. The pseudorange measurements are noisy (~100 TECu uncertainty), the relative stable DCBs can be estimated from low elevation angle scans associated higher antenna gain and SNR.

A case study of TIDs trigger by Tonga volcanic eruption on 15 January 2022 shows clear TEC disturbances observed by GNSS-R.

a) A coherent GNSS-R scan with its SPs over the ocean on the south of Singapore shows clear TEC disturbances after Tonga eruption. The identified horizontal wavelength is ~ 330 km and the TEC magnitude is ~1 TECu.
b) For the ground-based receivers' observations, two types of TIDs are discernable around 15 UTC over the Australia. The TIDs #1 with a horizontal wavelength of ~ 800km and phase velocity of ~328 m/s is likely a manifestation of Lamb-wave. The TIDs #2 with gravity-mode characteristics shows a horizontal wavelength of ~260 km and phase velocity of ~193 m/s. The TEC magnitude of these two TIDs are ~0.5 TECu.
c) Comparison results indicate that the GNSS-R scan is not aligned with the apparent wave normal of TIDs. The estimated angle between wave normal and GNSS-R IPP is 45°. Such angle makes the wavelength detected by GNSS-R longer than in reality. Further analysis suggests that the GNSS-R measured wavelength is consistent with our expectations.
d) Potential error sources of the usage of GNSS-R in this study are listed below.
   - The reflection ray of GNSS-R doesn't scan the topside ionosphere since the receiver is located at LEO orbit. The neglect of topside ionosphere might cause an ambiguity when comparing to ground-based TEC measurements.
   - We assume the reflection IPP didn't have apparent TEC disturbances as we don't have dense ground-based TEC observations around reflection IPP location. Further analysis of local TEC observations at refelction IPP location is needed.