Ionospheric Disturbances and Scintillations Observations through CubeSats Coherent GNSS-Reflectometry Measurements

IRRI-6

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Abstract

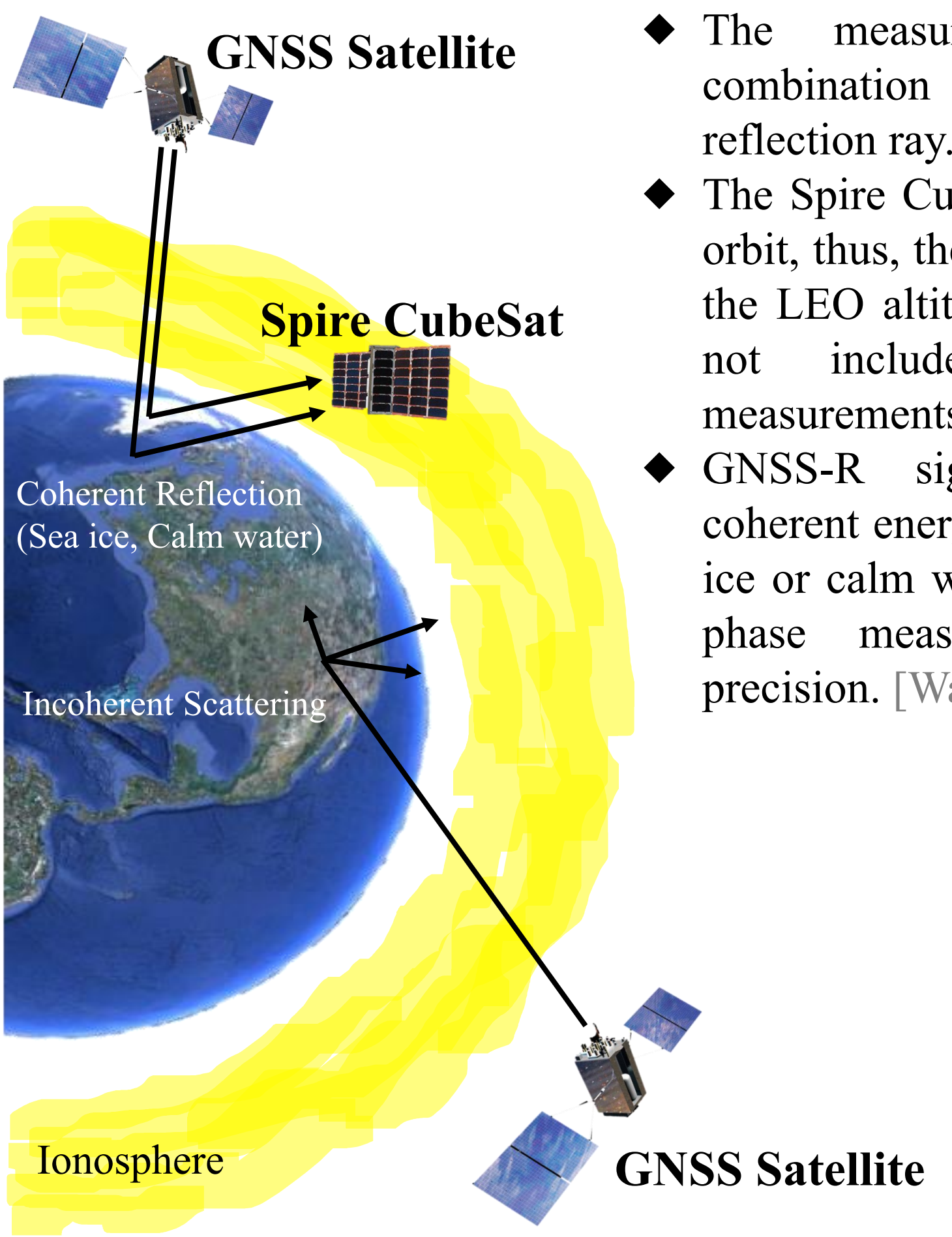
We present case studies of traveling ionospheric disturbances (TIDs) triggered by the 2022 Tonga volcanic eruption and a case study of ionospheric scintillation observed by low-cost CubeSat-based global navigation satellite system reflectometry (GNSS-R) measurements. The GNSS-R data used in this work are from Spire Global CubeSats. Our analysis shows that coherent GNSS signals reflected over the ocean can be used to derive precise phase measurements which can be translated into ionospheric total electron content (TEC) and scintillation index (S4). Clear TID structures with a TEC disturbance magnitude of ~1 TEC unit (TECu) and horizontal wavelength of ~330 km are shown over Northwest Australia on the day of Tonga volcanic eruption. The characteristics of observed TIDs are consistent with the co-location ground-based receivers' observations.

For the scintillation case, a GNSS-R event with its specular point track over the sea south of Singapore contains sufficient coherent energy that enables the ionospheric scintillation observations. Clear phase fluctuations are shown at the ionospheric piercing points (IPP) located over the sea south of Singapore. The phase fluctuations are quantified through the phase scintillation index (σ_ϕ), and S4. Our analysis indicates that the magnitudes of the filtered phase fluctuation are ~18 cm on L2-band and ~11 cm on L1-band and the obtained TEC shows a rate of TEC index (ROTI) value of ~0.4 TECu/s. The maximum values of σ_ϕ are ~6 cm and ~4 cm on L2-band and L1-band, respectively. Validation through nearby Radio Occultation (RO) measurements from FORMOSAT-7/COSMIC-2 indicates that the GNSS-R observed high S4 value is likely a sporadic E layer event.

Introduction & Motivation

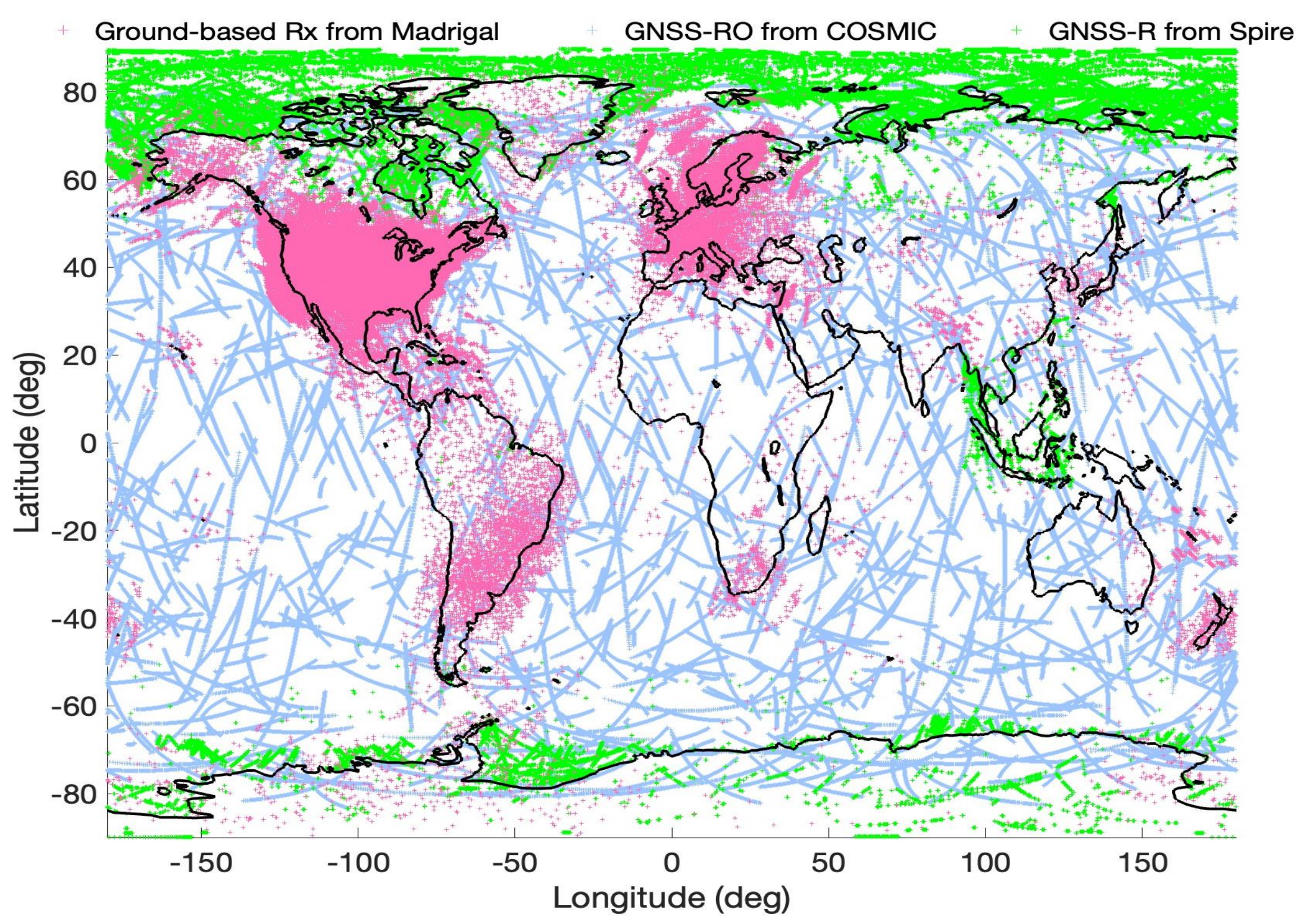
Total Electron Content (TEC) can be derived from GNSS receiver range measurements along the signal line-of-sight. Madrigal database collects ~8 k ground-based receivers worldwide. The coverage of these ground-based TEC measurements, however, is spotty over open oceans, polar caps, and unreachable terrains 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) has demonstrated feasibility to obtain TEC measurements over the region where ground-based observations are sparse. The main difference between RO and GNSS-R is that for GNSS-R, the LEO satellites receive the signal reflected by the Earth surface via nadir or side-looking antenna which scans the ionosphere twice.



- ◆ The measured TEC contains a combination of incidence ray and reflection ray.
- ◆ The Spire CubeSats are located at LEO orbit, thus, the topside ionosphere above the LEO altitude in the reflected ray is not included in the GNSS-R measurements.
- ◆ GNSS-R signals contain sufficient coherent energy when reflected over sea ice or calm waters which enable carrier phase measurement with cm-level precision. [Wang & Morton, 2021]

Paper Link

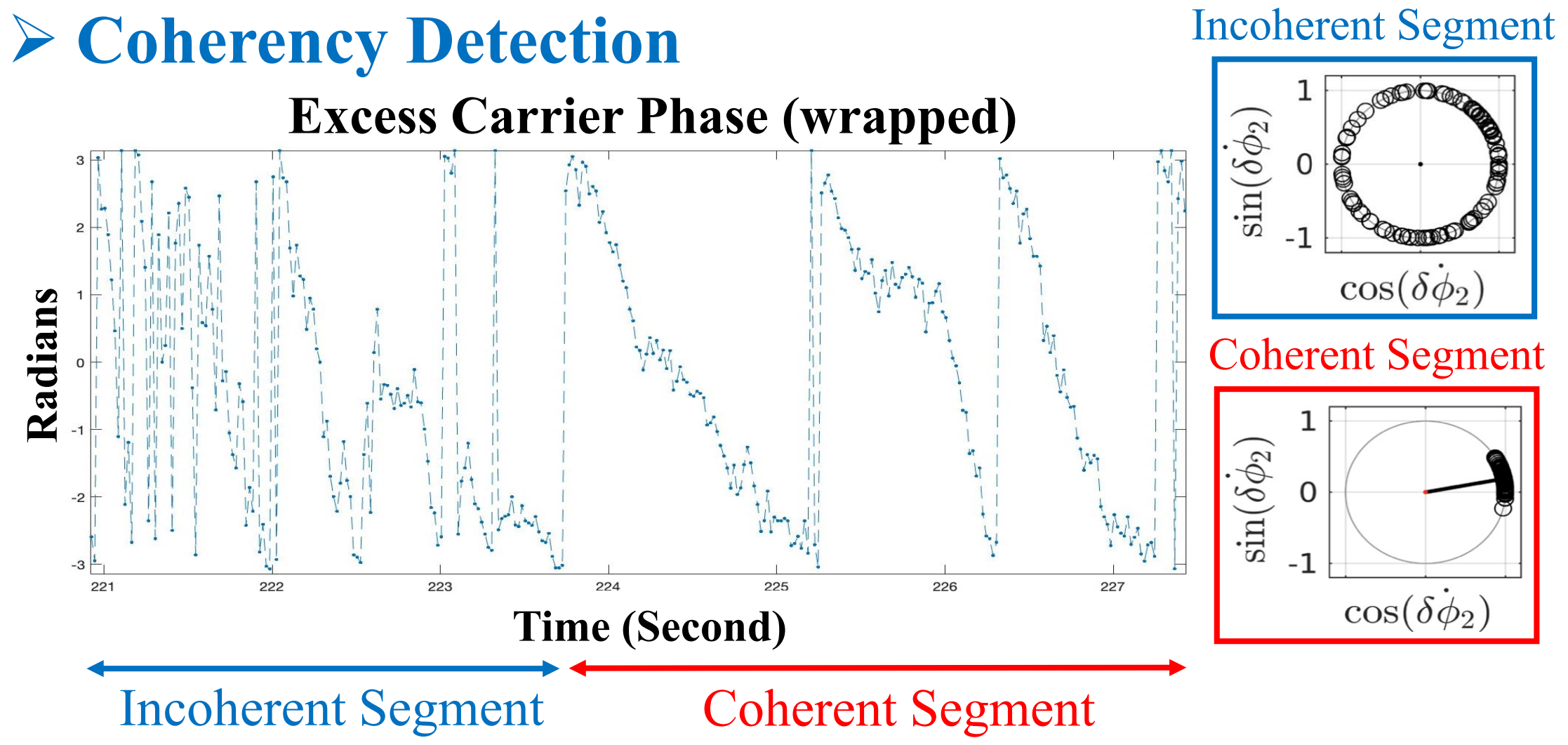


One snapshot of TEC measurements from ground-based receivers from Madrigal (magenta), and one day of GNSS-RO from COSMIC (blue), GNSS-R from Spire Global CubeSats (green).

- ◆ There are 20+ Spire CubeSats currently in operation which generate 3-4k GNSS-R data every day.
- ◆ The data mainly covers the polar and Asia-Oceania regions.

Dataset & Methodology

➢ Coherency Detection



Circular Statistics Method to quantify the signal coherency.

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➢ Residual Carrier Phase Unwrapping

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

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

$\boldsymbol{\Phi_{tot}}$: Entire Carrier Phase.
$\boldsymbol{\Phi_{OL}}$: Open-loop Model.
$\boldsymbol{\delta\Phi_{OL}}$: Residual Carrier Phase. (wrapped form)

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

$\boldsymbol{\delta\Phi_i}$: 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 Mitigation

Simultaneous cycle slip and noise filtering (SCANF) is a Kalman-filter-based method to mitigate the cycle slips. [Wang et al., 2020]

Initial States:

$$x^+[0] = [\widehat{\Phi}_{L1}[0] \quad \widehat{\Phi}_{L2}[0] \quad 0 \quad 0]^T$$
$$y[k] = Hx[k] + B[k] + v[k]$$

$\boldsymbol{B[k]}$: Integer Cycle Slip
$\boldsymbol{v[k]}$: Noise, $\sim N(0, R)$

Prediction:

$$x^-[k] = Ax^+[k-1]$$
$$P^-[k] = AP^+[k-1]A^T + Q$$

P : State Estimation Cov
Q : dynamic noise cov matrix, including surface roughness, troposphere, and ionosphere correction

Bias Estimation:

Find Integer B[k] that minimize
$|\, y[k] - Hx^-[k] + B[k] \,|$

Updates:

$$\mathbf{K}[k] = \mathbf{P}^-[k]\mathbf{H}^T\left(\mathbf{H}\mathbf{P}^-[k]\mathbf{H}^T + \mathbf{R}[k]\right)^{-1}$$
$$\mathbf{x}^+[k] = \mathbf{x}^-[k] + \mathbf{K}[k](\mathbf{y}[k] - \mathbf{H}\mathbf{x}^-[k] - \mathbf{B}[k])$$
$$\mathbf{P}^+[k] = (\mathbf{I} - \mathbf{K}[k]\mathbf{H})\,\mathbf{P}^-[k].$$

K: Kalman Gain

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$$\mathbf{Q} = \begin{bmatrix} \frac{T^3}{3}(q_s+q_i) & \frac{T^3}{3}(q_s+\beta q_i) & \frac{T^2}{2}q_s & \frac{T^2}{2}q_i \\ \frac{T^3}{3}(q_s+\beta q_i) & \frac{T^3}{3}(q_s+\beta^2 q_i) & \frac{T^2}{2}q_s & \frac{T^2}{2}\beta^2 q_i \\ \frac{T^2}{2}q_s & \frac{T^2}{2}q_s & Tq_s & 0 \\ \frac{T^2}{2}q_i & \frac{T^2}{2}\beta^2 q_i & 0 & Tq_i \end{bmatrix}$$

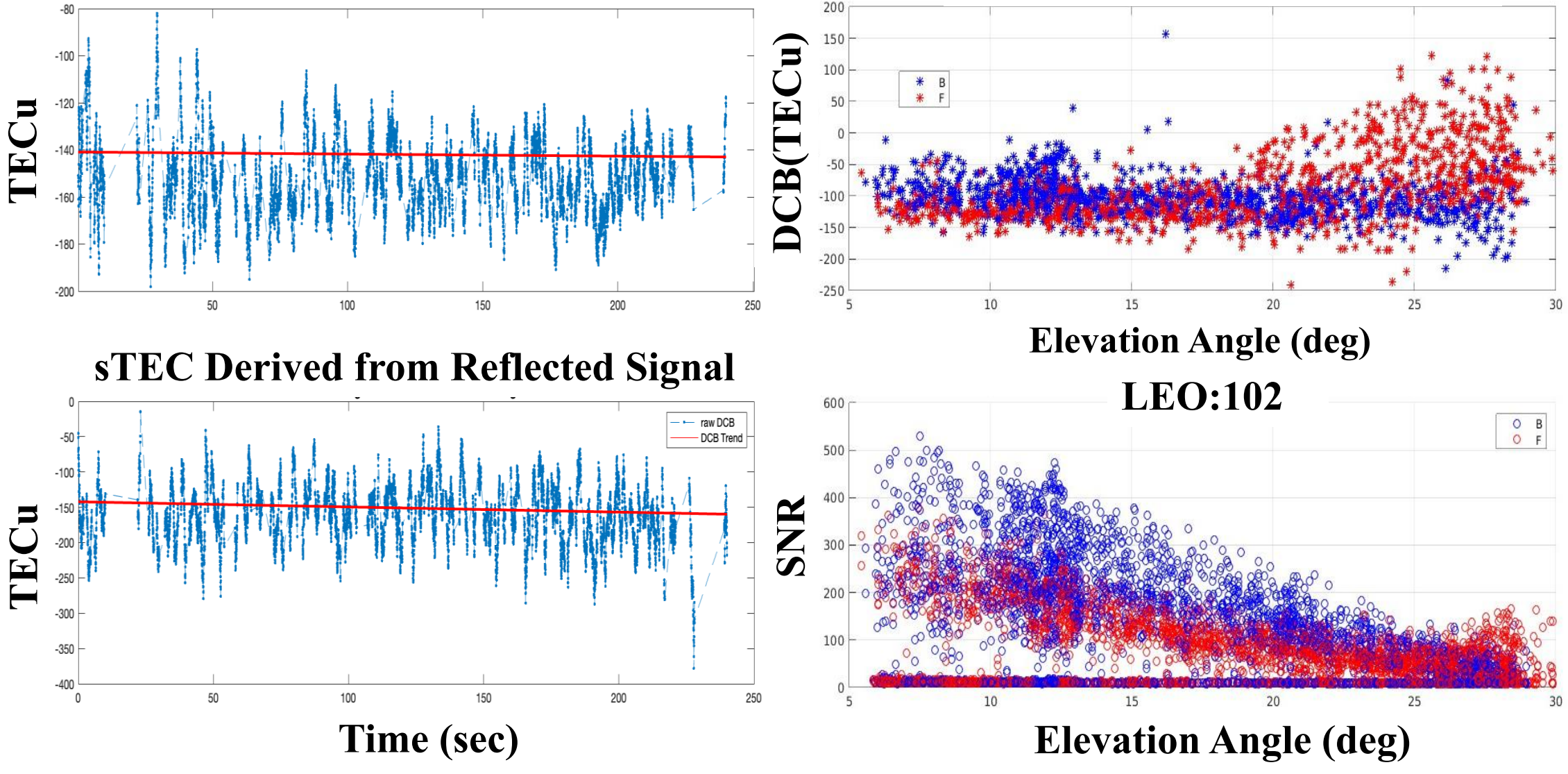
$\mathbf{q_s}$: PSDs of the frequency noise caused by tropospheric effects and reflection from the sea surface.
$\mathbf{q_i}$: ionospheric effects on the GNSS signal
$\boldsymbol{\beta}$: Ionospheric Factor $\left(f_{L1}^2 / f_{L2}^2\right)$

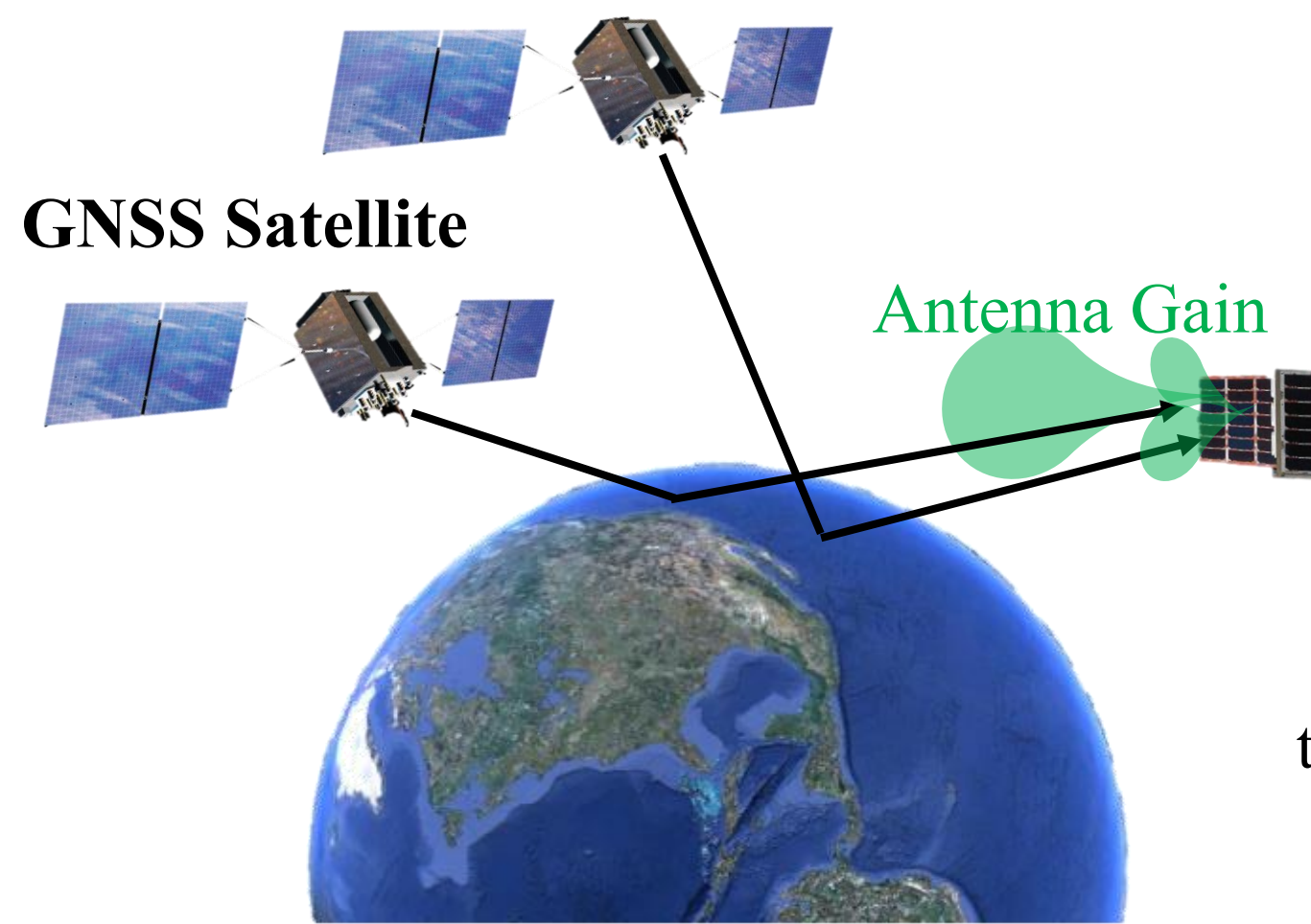
➢ TEC Retrieval

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

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

➢ Differential Code Bias (DCB) Estimation





Elevation Angle and SNR threshold for DCB estimation.

Results

➢ TIDs Triggered by 2022 Tonga Volcanic Eruption

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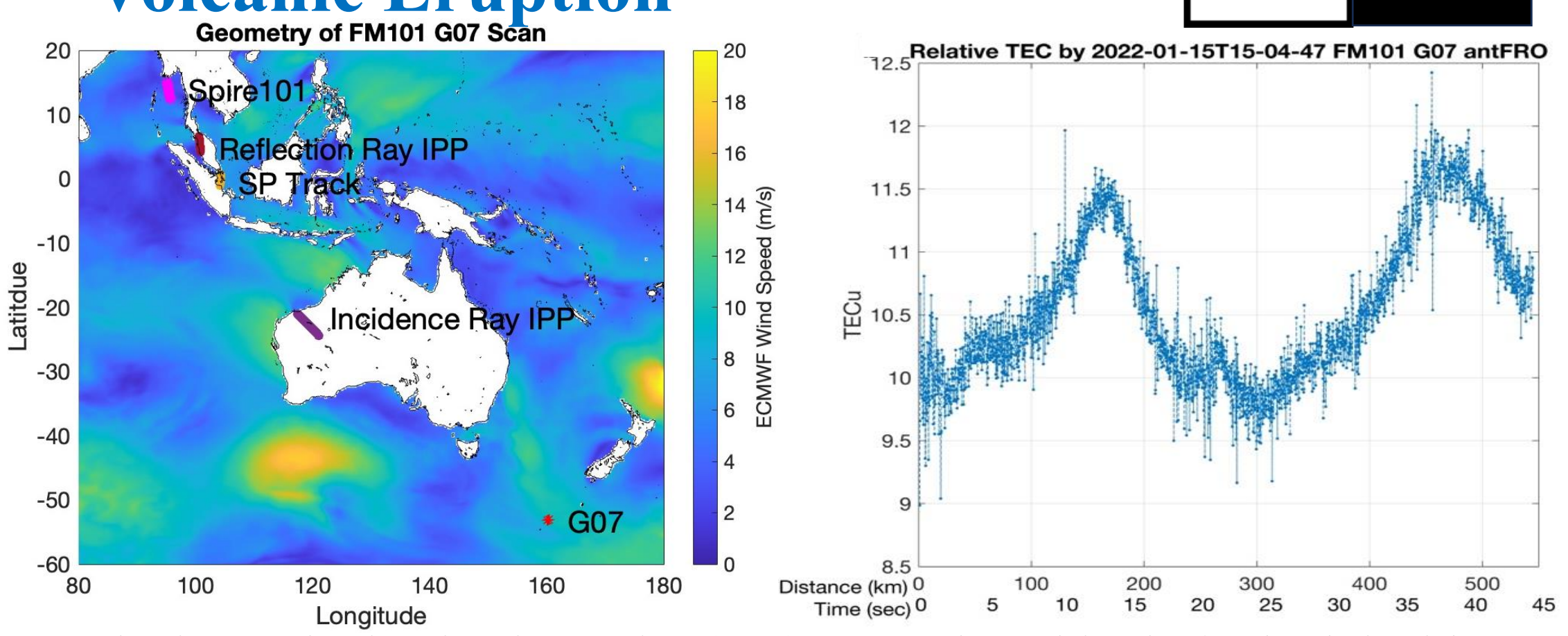
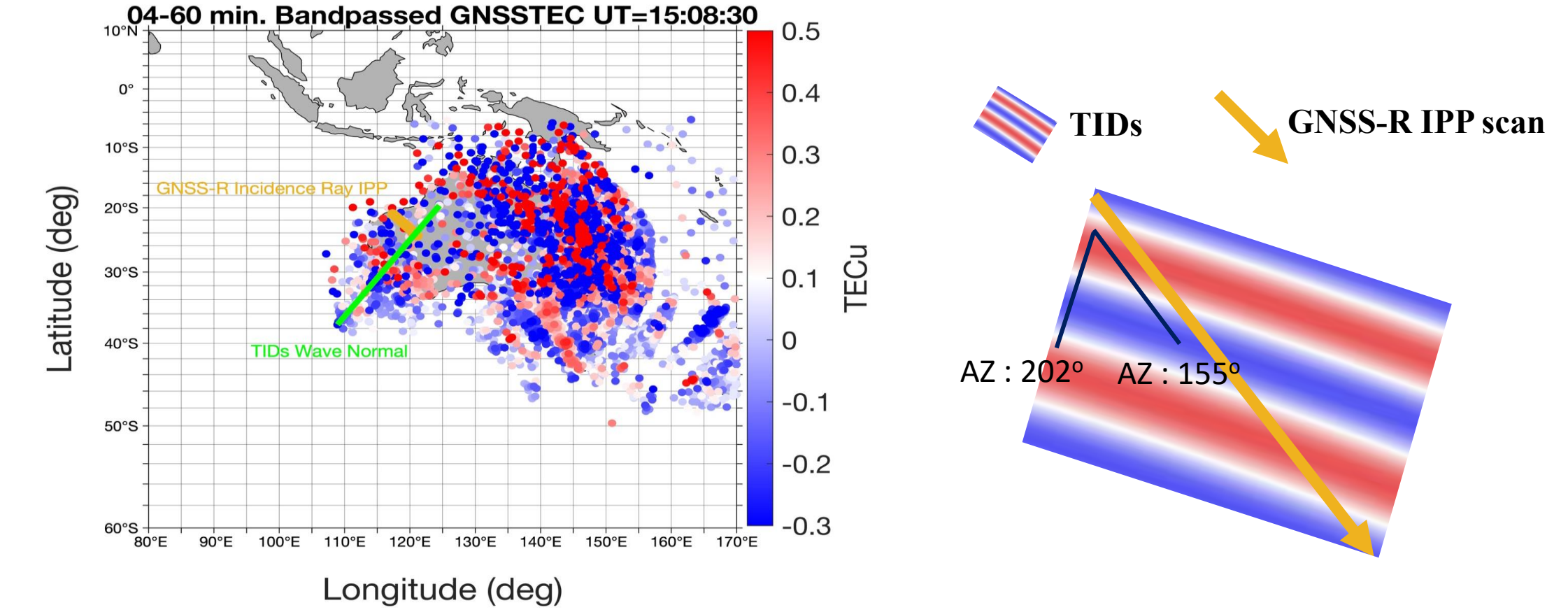


- ◆ The ionospheric piercing point (IPP) at 350 km altitude for both incidence and reflection rays.
- ◆ The GNSS-R scan offer nearly "frozen in time" observations. During 45 seconds (15:08:27-15:09:12 UTC), it scan 550 km horizontal distance.
- ◆ The estimated wavelength and TEC magnitude of the ionospheric disturbances (TIDs) are ~330 km and 1 TECu.

Validation through Ground-Based Receivers' Observations



- ◆ The incidence IPP of GNSS-R is not aligned with the apparent wave normal, a ~47° angle between wave normal and GNSS-R scan direction.
- ◆ The 47° offset makes the wavelength observed by the ground-based network and by the GNSS-R scan in a ratio of 0.682 (cos(47°)).
- ◆ The TIDs wavelength derived from GNSS-R and ground-based receivers network observations are ~330 km and ~250 km, respectively. The ratio of these two observed wavelengths is 0.758.
- ◆ The TEC magnitude measured by the GNSS-R and ground receivers is ~1 and ~0.4 TECu respectively, while the GNSS-R TEC is sTEC at a low grazing angle of ~6°.
- ◆ Apply a commonly used Mapping Function

$$MF = \frac{sTEC}{vTEC} = \frac{1}{\cos(z')}$$

The result indicates that the GNSS-R measured 1 TECu magnitude corresponds to 0.33 vertical TECu which is close to the ground-based receivers' observation.

➢ Ionospheric Scintillation : A Sporadic E-layer Event

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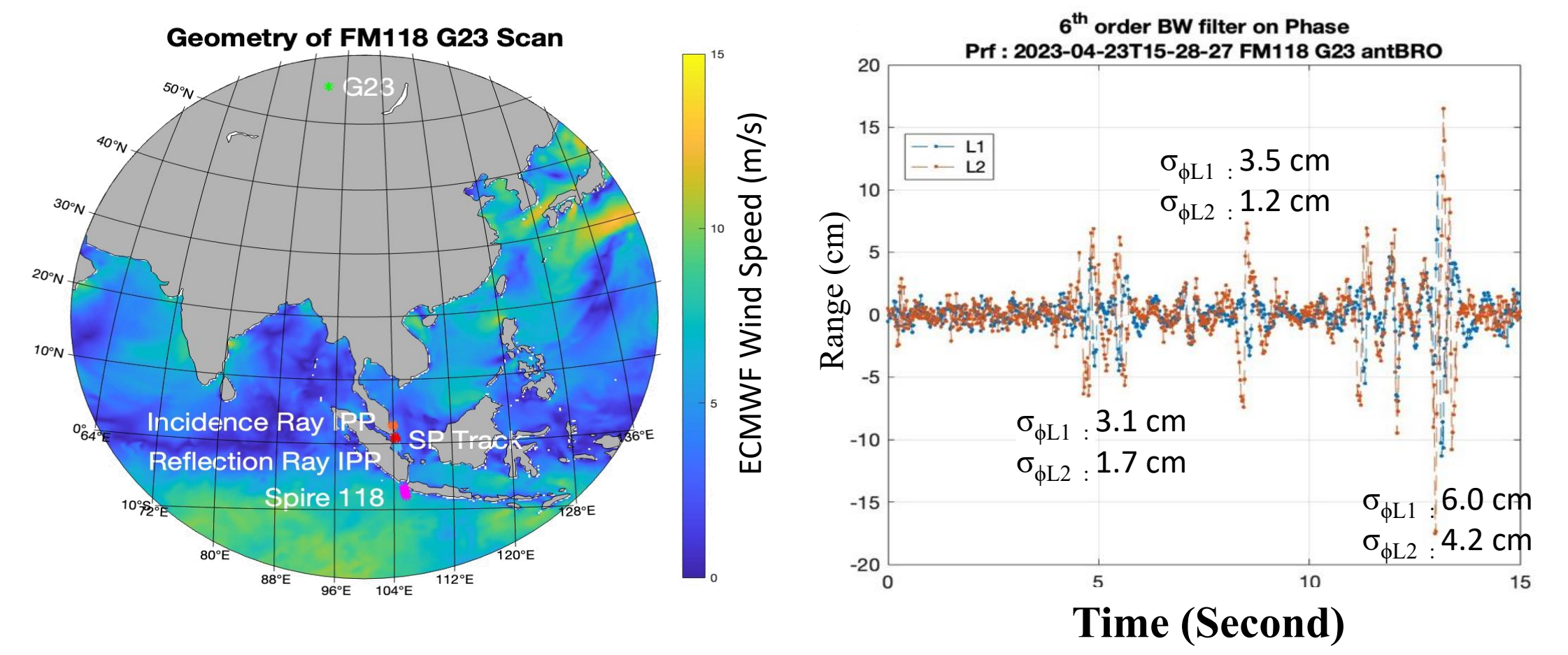
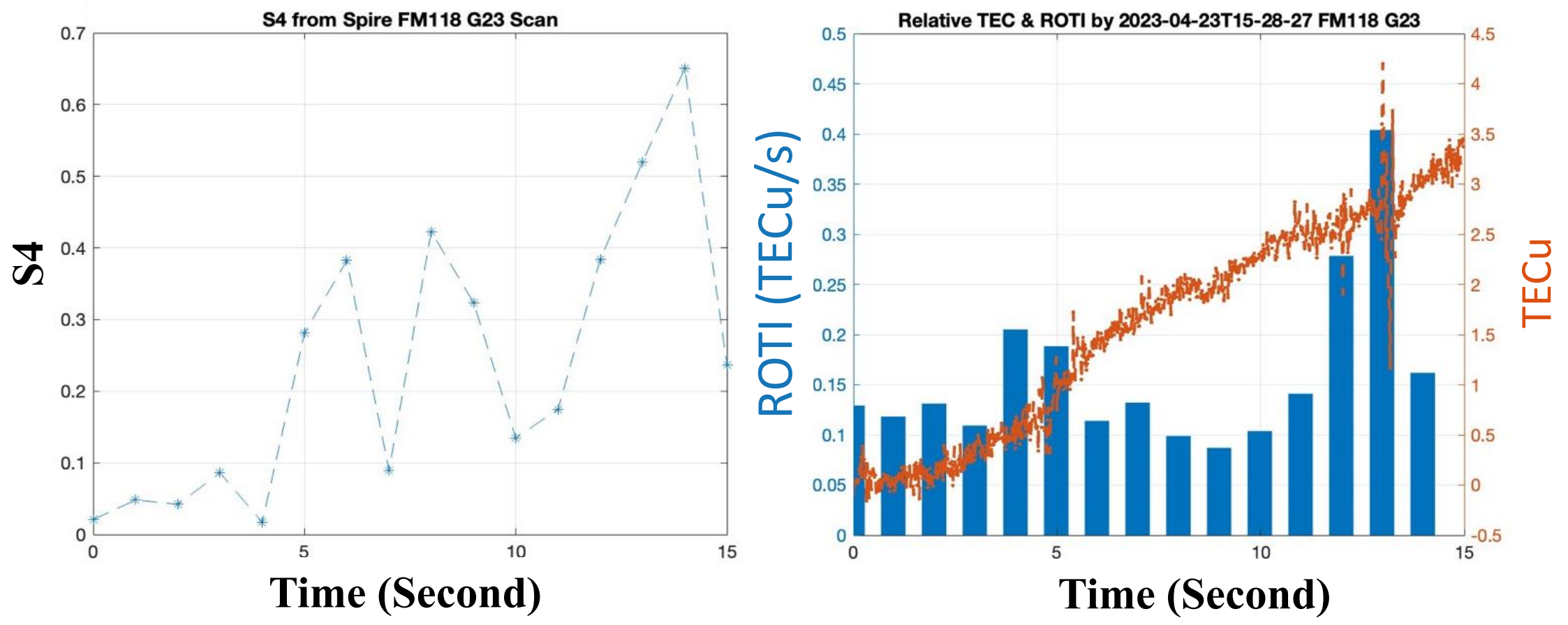


- ◆ The ocean surface wind speed is ~2 m/s around SP track which indicates a calm sea condition with low surface roughness.
- ◆ The phase fluctuation reaches its maximum at the 14th second where the magnitude of L1-band and L2-band are ~11 cm (σ_ϕ of 4.2 cm) and ~18 cm (σ_ϕ of 6.0 cm).
- ◆ The L2-band shows higher fluctuation than L1 which is consistent with the behavior of an ionospheric scintillation event.



➢ Scintillation Index (S4)

$$\boldsymbol{S4 = \frac{\sqrt{<I^2> - <I>^2}}{<I>}}$$

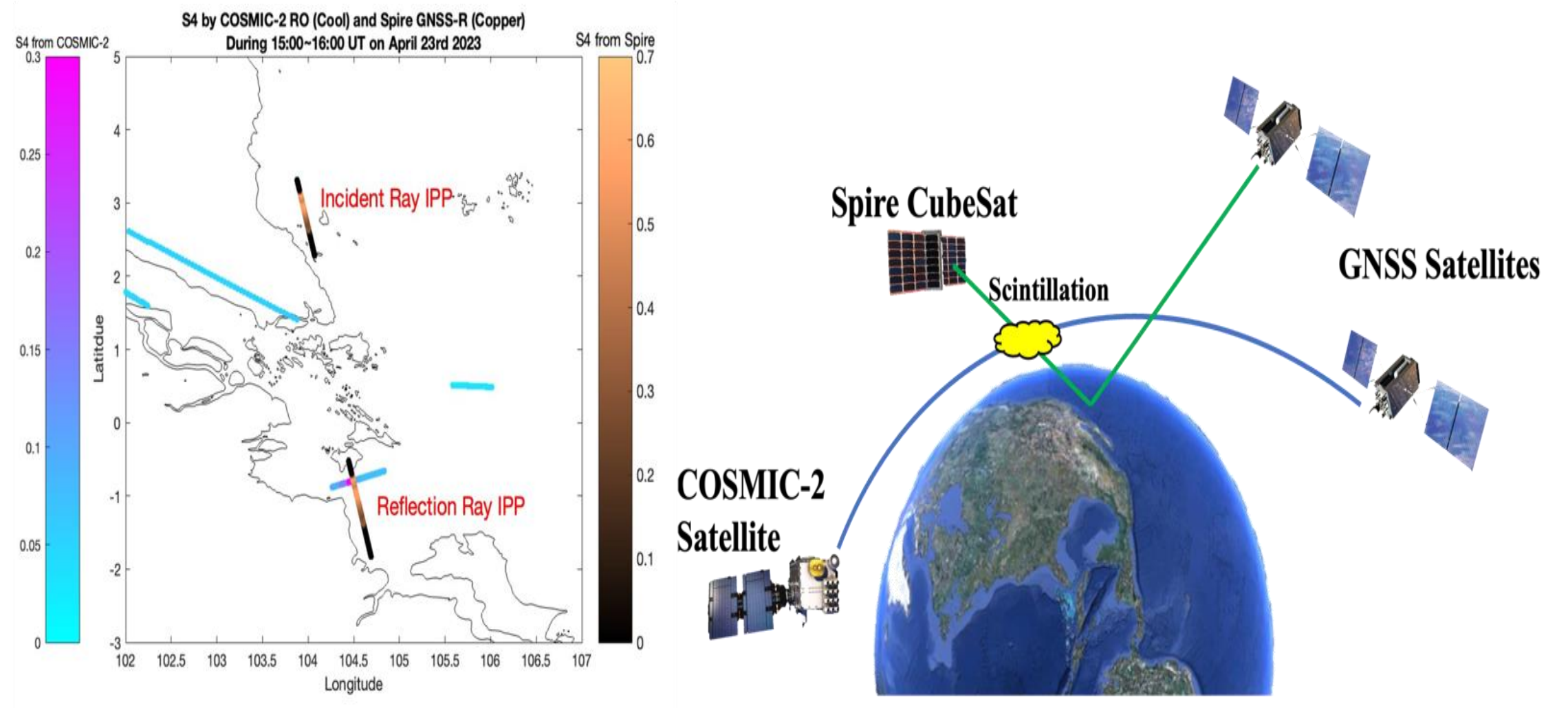
I : signal intensity derived from I (I_{corr}) and Q (Q_{corr}) correlators, $I = \sqrt{I_{corr}^2 + Q_{corr}^2}$

- ◆ S4 are calculated every second through 50 Hz I and Q correlator data since the signal scan across the ionosphere with a velocity about 60 times faster than a typical ground-based observations.
- ◆ Three clear peaks with S4 values > 0.3, maximum reaches 0.65 at 14th second.

➢ Rate of TEC Index (ROTI)

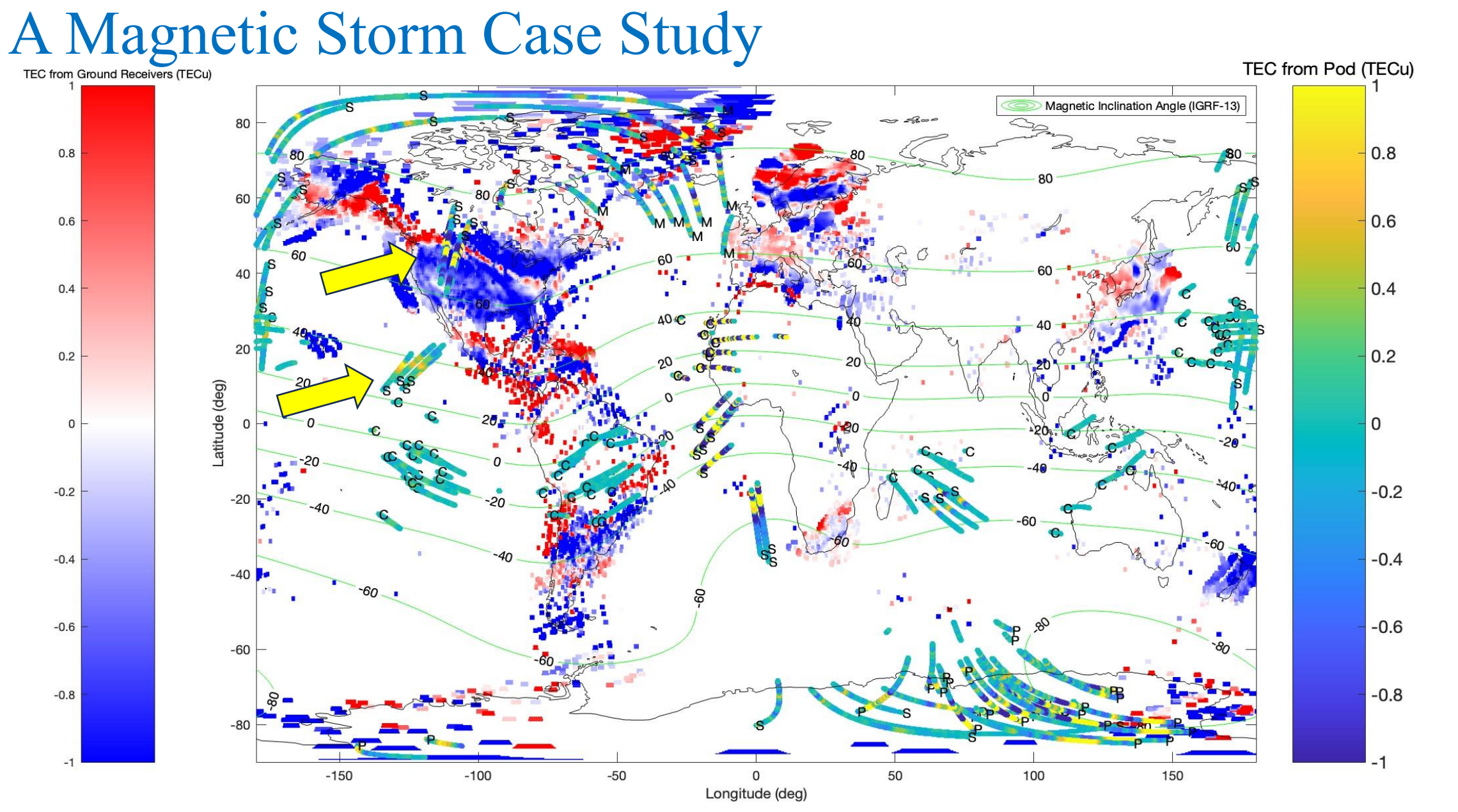
$$\boldsymbol{ROTI = \sqrt{<ROT^2> - <ROT>^2}} \qquad ROT = \frac{\Delta sTEC}{\Delta T}, \quad \Delta T = 1\ \mathrm{s}$$

- ◆ The maximum TEC fluctuation is 1.33 TECu at 14th second, corresponding to a ROTI value of 0.4 TECu/s; The 5th and 8th second phase fluctuations cause 0.19 TECu jumping which is too trivial to be discernable from the background TEC trend.



- ◆ The COSMIC-2 measured a S4 value of 0.37 among 103-123 km altitude which is likely a sporadic E event.
- ◆ Both incident and reflected ray IPPs of GNSS-R are at 100 km altitude.
- ◆ The location of the reflected ray IPPs are consistent with the location of a high S4 values' profile from COSMIC-2.
- ◆ S4 from Spire is 0.65 and from COSMIC-2 is 0.37. The discrepancy could be coming from different signal paths of R and RO.

➢ Other Observations That CubeSats Can Provide : Precise Orbit Determination (POD) TEC Measurements, A Magnetic Storm Case Study



- ◆ The POD antenna can provide the topside ionosphere TEC above the CubeSats' orbit (500~800 km altitude).
- ◆ The POD measured TEC disturbances are consistent with the ground-based observations over the US continent. While the POD observations over the region where receivers' coverages are sparse can be used as an augmentation of TEC observations.

Conclusion & Discussion

This work presents the capability of absolute TEC retrieval and TIDs/ scintillation 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 precise TEC measurements.
2. The pseudorange measurements are noisy (~100 TECu uncertainty), the relative stable DCBs can be estimated from low elevation angle scans associated with 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) The wave normal of TIDs measured by ground-based receivers are offset by 47° from that of the GNSS-R scan's directions. The offset results in the wavelength detected by GNSS-R appearing to be longer than that of the ground-based observations. The ratio between GNSS-R and ground-based receivers' observed wavelength matches the effects due to the angle offsets.
b) The difference in the magnitude of the TEC disturbance observed via GNSS-R and ground receivers is likely because the GNSS-R ray has a low elevation while the ground receiver data are dominated by high elevation signals. The low elevation signal traverses a much longer path through the ionosphere which amplifies the disturbance effects.

For the ionospheric scintillation event,

a) Clear phase fluctuations were shown by a profile over the sea south of Singapore. The magnitude of the phase fluctuations are ~11 cm (σ_ϕ of 4.2 cm) and ~18 cm (σ_ϕ of 6.0 cm) on L1-band and L2-band. The L2-band has greater phase fluctuation which is a behavior of an ionospheric scintillation.
b) Three clear peaks of S4 were shown with the maximum S4 value of ~0.65. The TEC jumping in this case is 1.33 TECu, corresponding to a ROTI value of 0.4 TECu/s.
c) Validation through co-location COSMIC-2 RO observations suggests that the GNSS-R measured high S4 value is likely a sporadic E layer event.

Pros & Cons of GNSS-R

Pros	**Cons**
I. Provide cm-level precision of phase observation over open but smooth ocean and polar sea ice areas where the ground base observations are sparse.	I. GNSS-R signals maybe incoherent when the surface is rough.
II. The high precision of the retrieved TEC will enable of capturing a continuous ionospheric structure.	II. Current GNSS-R measurements are relatively sparse due to the limited number of GNSS-R CubeSats in operation.
III. The rapid scan can measure thousands kilometers of ionosphere observations within a minute or two.	III. It is difficult to capture enough information of the ionospheric structures such as TEC magnitude when the reflection track is too short.
	IV. GNSS-R observations contain contributions from the incident and reflection signal ray path.