

利用臺灣高頻都卜勒探測系統和電離層探測儀觀察 2025年7月29日堪察加半島規模8.8地震引起的 地震和海嘯電離層擾亂+燦樹颱風

Seismo- and tsunami-traveling ionospheric disturbances of the 29 July
2025 M8.8 Kamchatka Earthquake observed by CW-HF Doppler
sounding systems and ionosondes in Taiwan and Japan
+ 2021 Chanthu Typhoon

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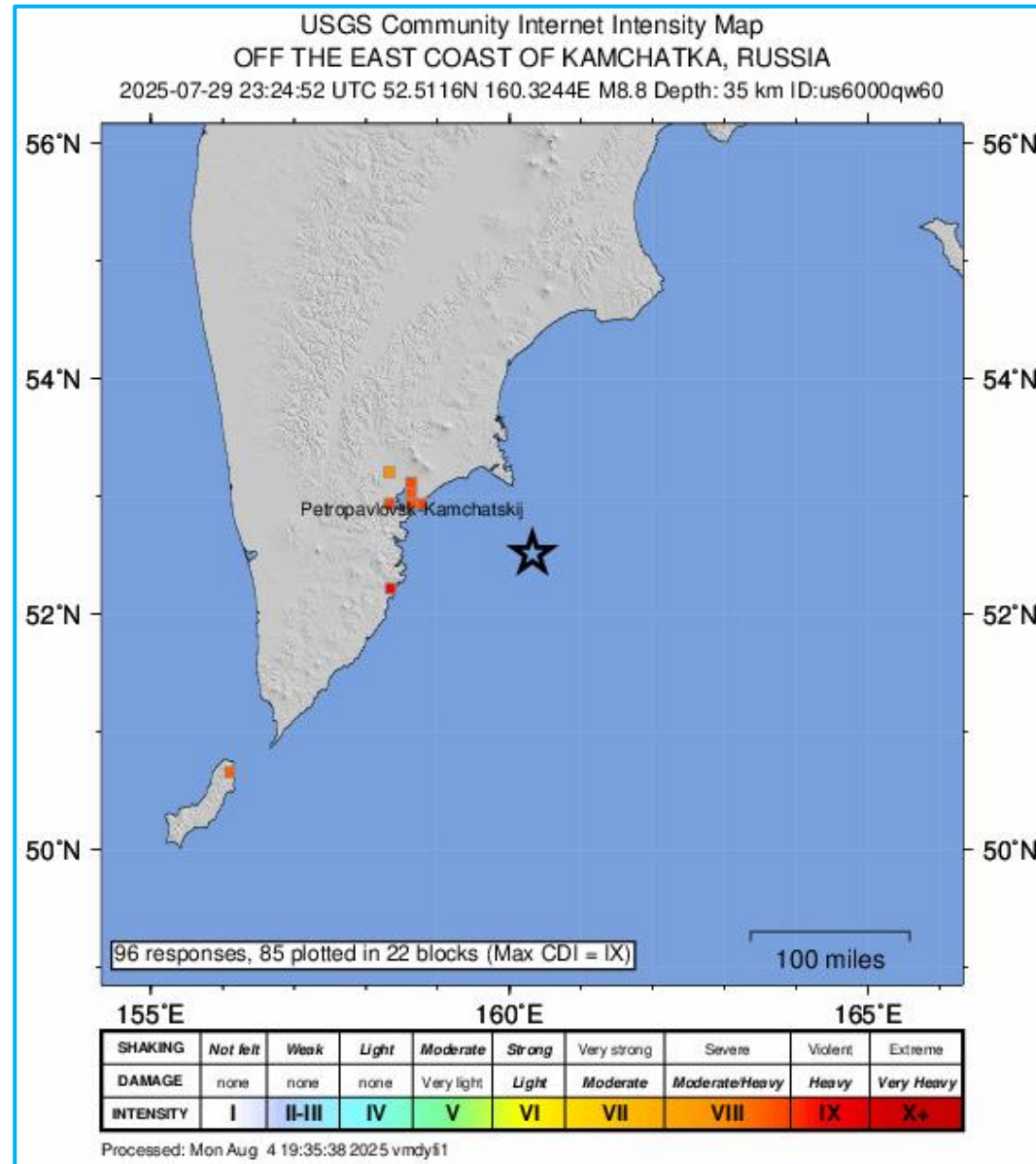
摘要

2025年7月29日，堪察加半島近海發生強烈地震，引發強烈地震動和海嘯。這些擾動不僅影響了固體地球和海洋，也擾動了地面上的空氣層。大氣波向上传播，最終進入電離層。本研究利用臺灣高電離層探測儀觀測數據，顯示地震和海嘯波到達後不久出現的擾動，並迅速遠離震源傳播。地震相關的擾動在電離層中也觀測到了結果，表明電離層可以作為大型地震和海嘯的靈敏放大偵測器。因此，利用高頻都卜勒探測系統和電離層探測儀觀測電離層擾動的資訊，並確認地震和海嘯波的抵達。

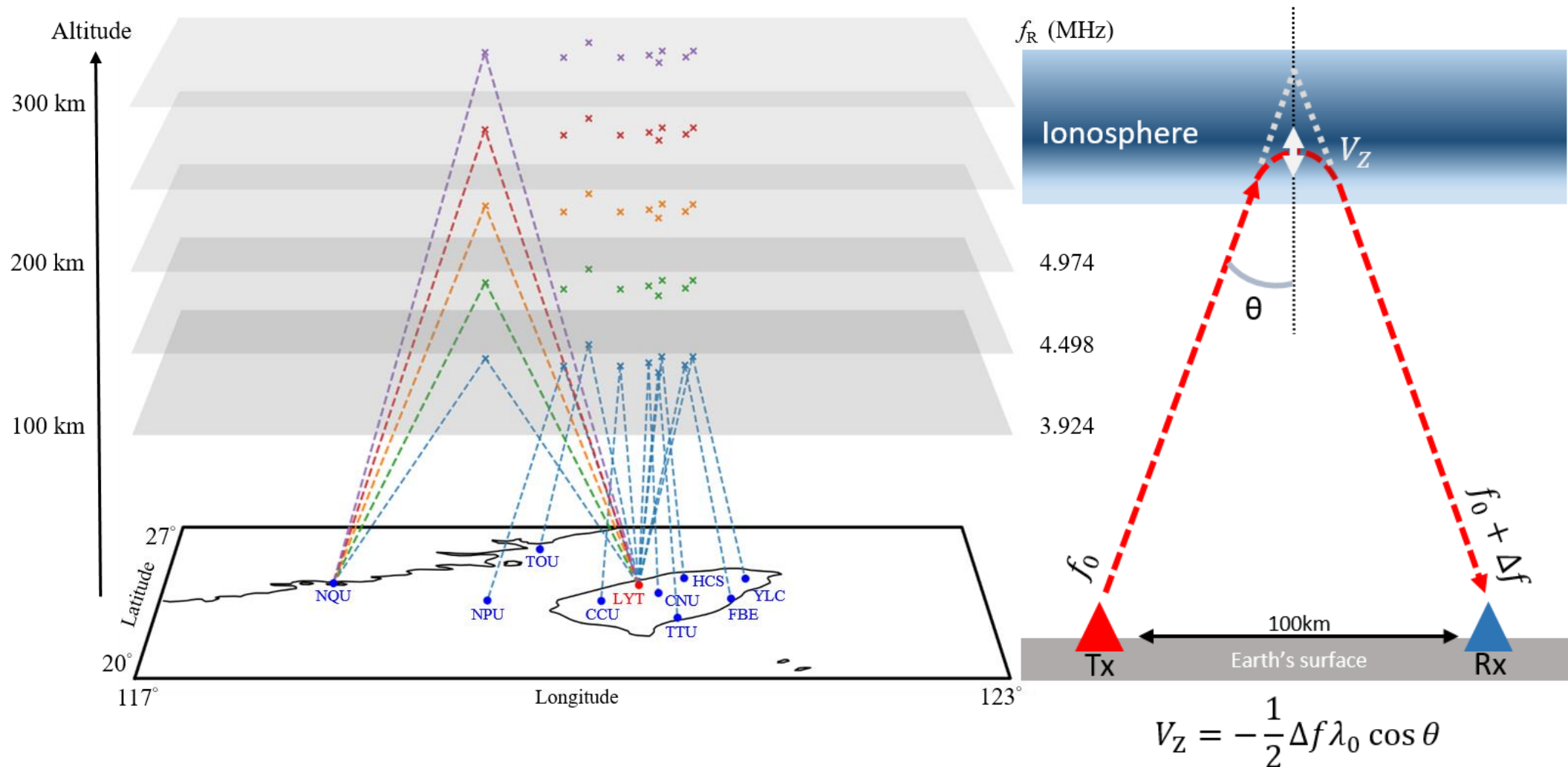
Content

- 2025 Mw 8.8 Kamchatka Earthquake precursors
 - CW-HF (continue wave-high frequency) Doppler sounding systems
 - global ionosphere map of total electron content (GIM TEC)
 - FORMOSAT-5/AIP in-situ ion density/velocity
- 2025 Mw 8.8 Kamchatka Earthquake ionospheric disturbances
 - seismo traveling ionospheric disturbance (STID)
 - tsunami traveling ionospheric disturbance (TTID)
 - ionograms and CW-HF Doppler Frequency Shifts
- Conclusion
- 2021.09 Chanthu typhoon

The 2025 Mw 8.8 Kamchatka earthquake

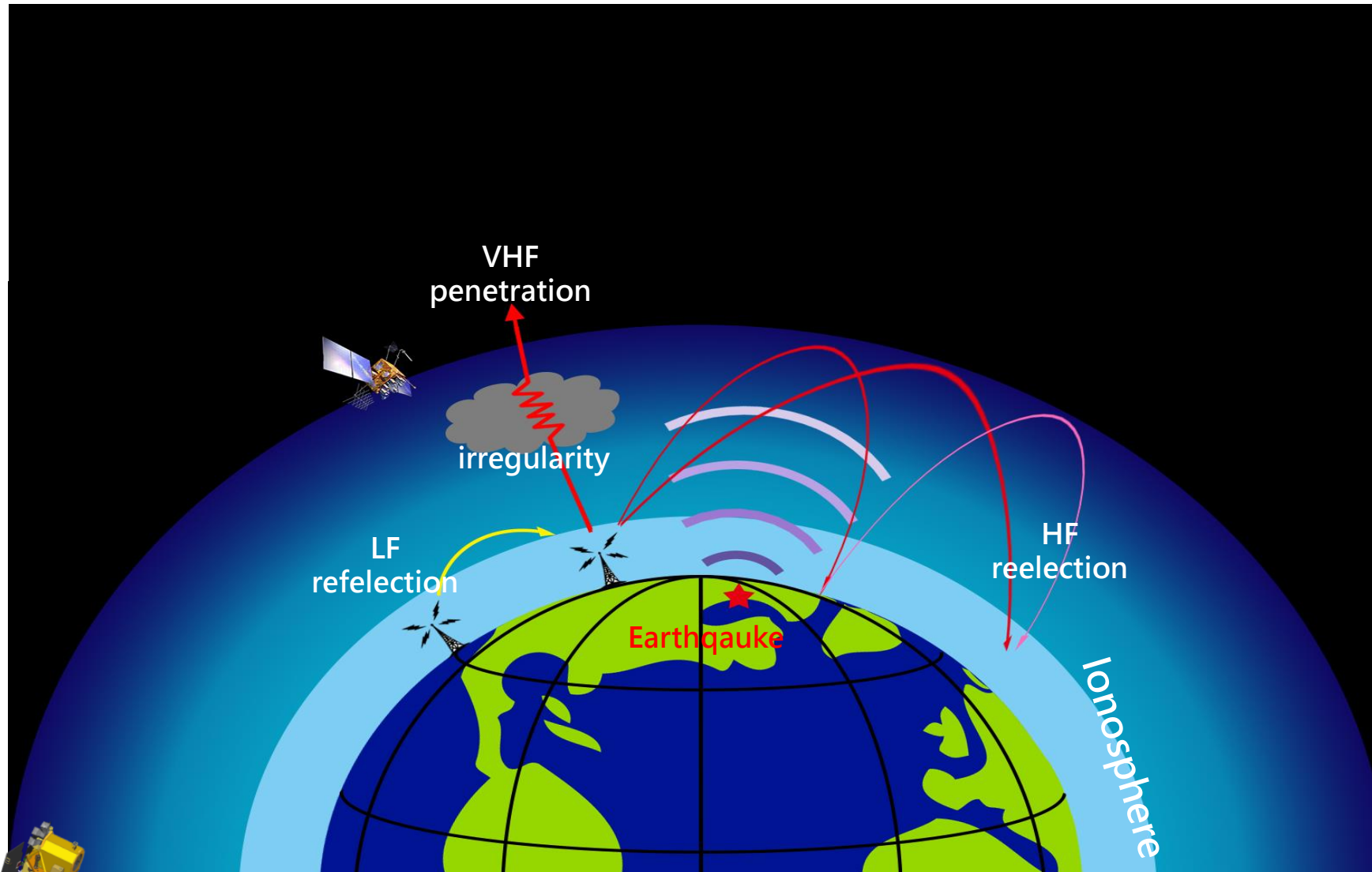


CW-HF (continue wave-high frequency) Doppler sounding systems



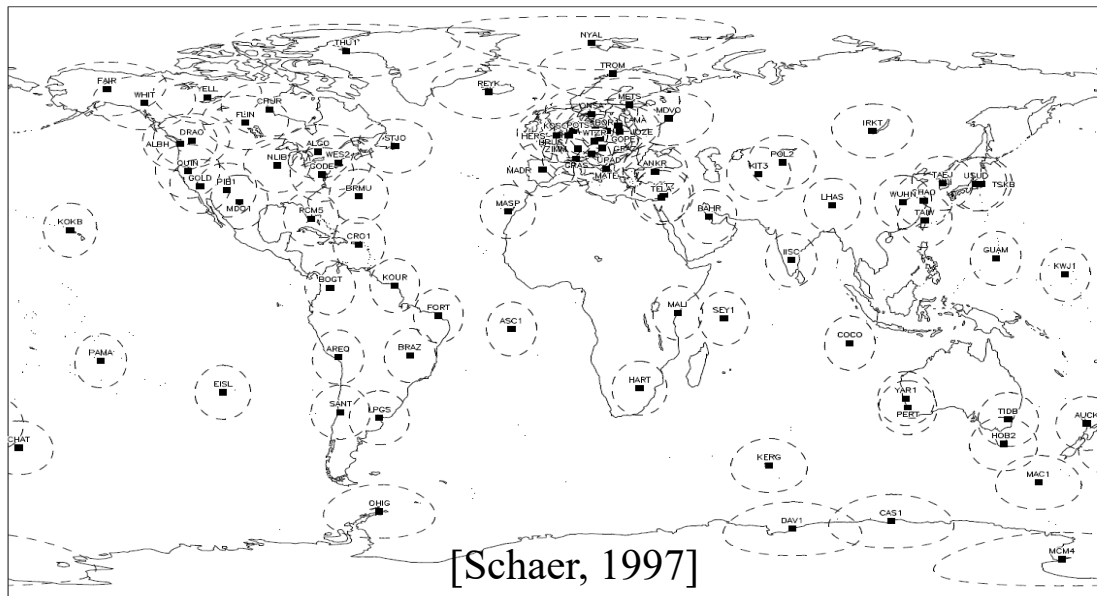
FORMOSAT-5/AIP (Advanced Ionospheric Probe, 2017-)

- Ionospheric Weather-Irregularity (Communication 、 Position 、 Navigation)
- Seismo-Ionospheric Precursor-**ion Density/Temperature/Velocity**)



Global Ionosphere Map (GIM)

Worldwide 200 IGS GPS receivers



$$UB = M + k(UQ - M)$$

$$LB = M - k(M - LQ)$$

LQ : first quartile (25%)

M : second quartile (50%)

UQ : third quartile (75%)

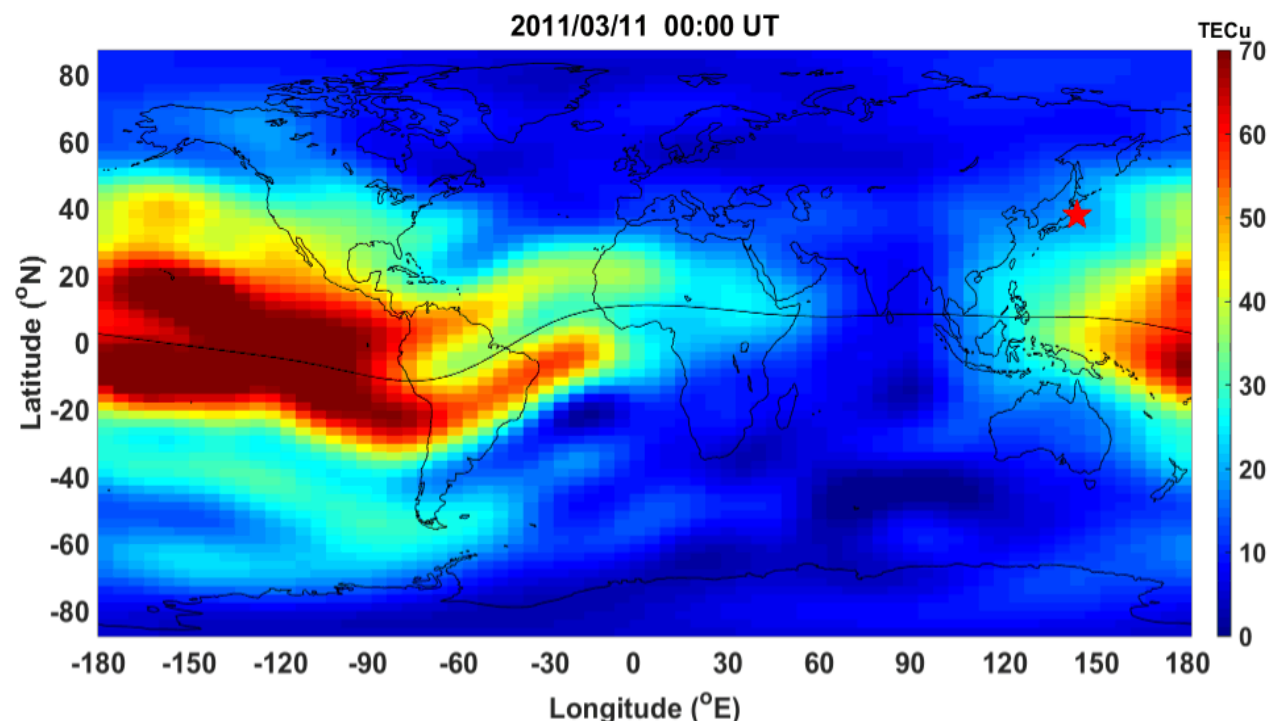
k : threshold constant

Center for Orbit Determination in Europe (CODE)

Time resolution: 1-hour

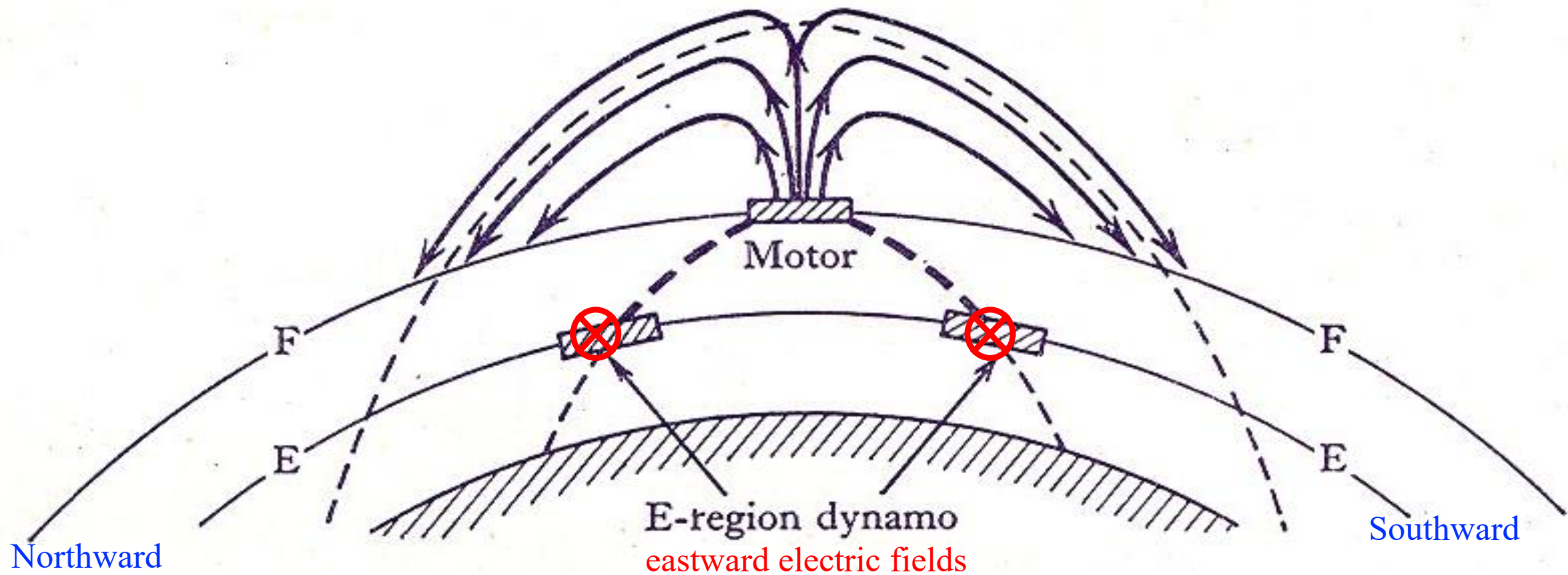
Spatial resolution: 2.5° latitude $\times$ 5° longitude

5183 (=73 x 71) lattices

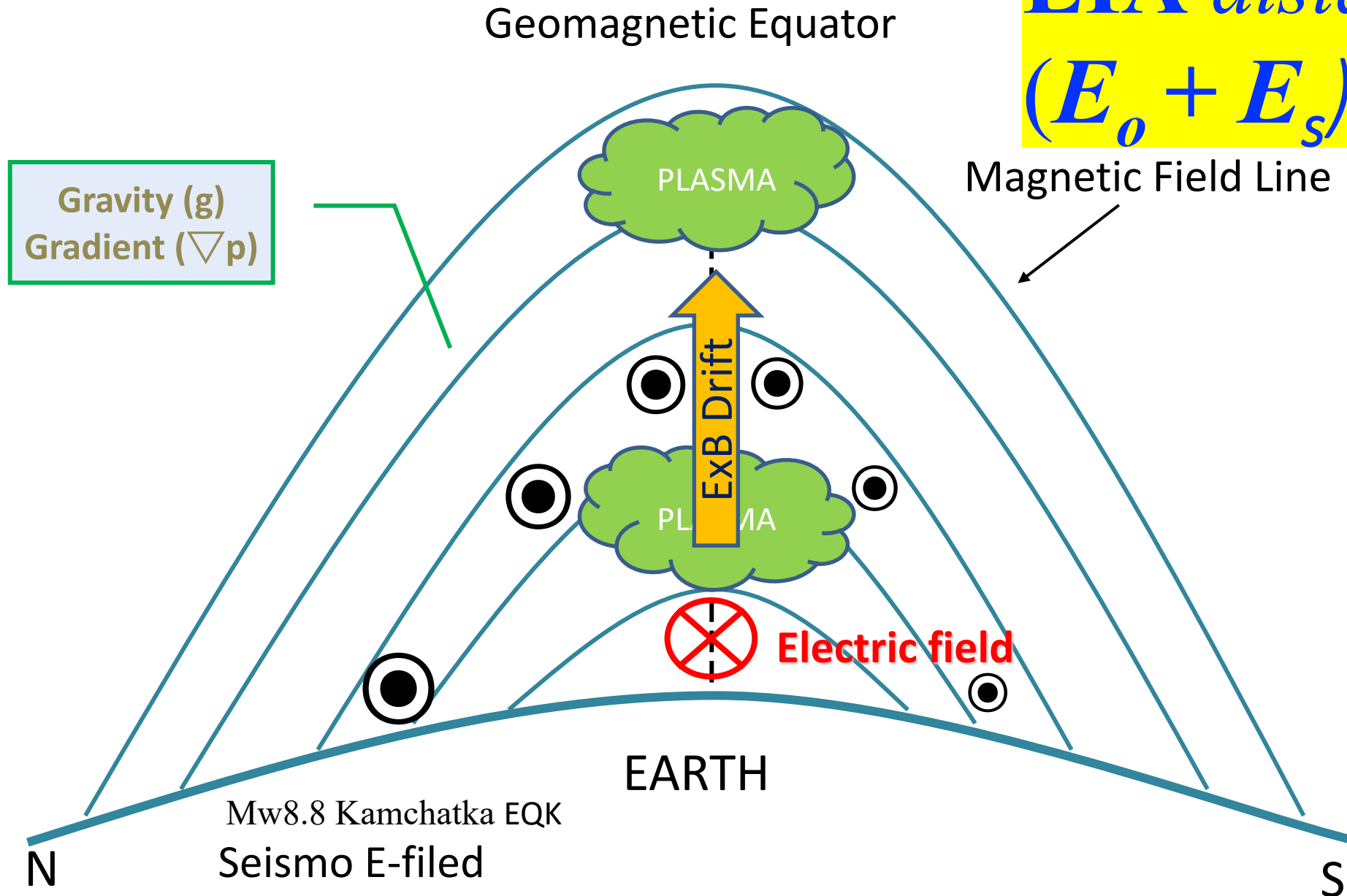


Equatorial Ionization Anomaly, EIA

$$\mathbf{V} = \mathbf{E}_o \times \mathbf{B} / B^2$$



EIA distance $\propto$
 $(E_o + E_s) \times B/B^2$



EIA crest distances response to electric fields

Center for Orbit Determination in Europe (CODE)

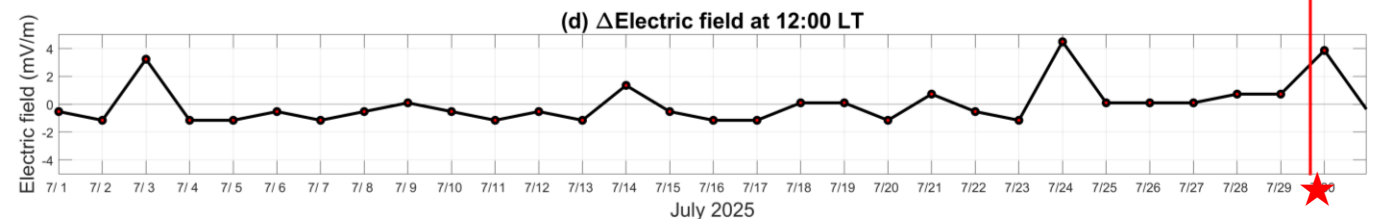
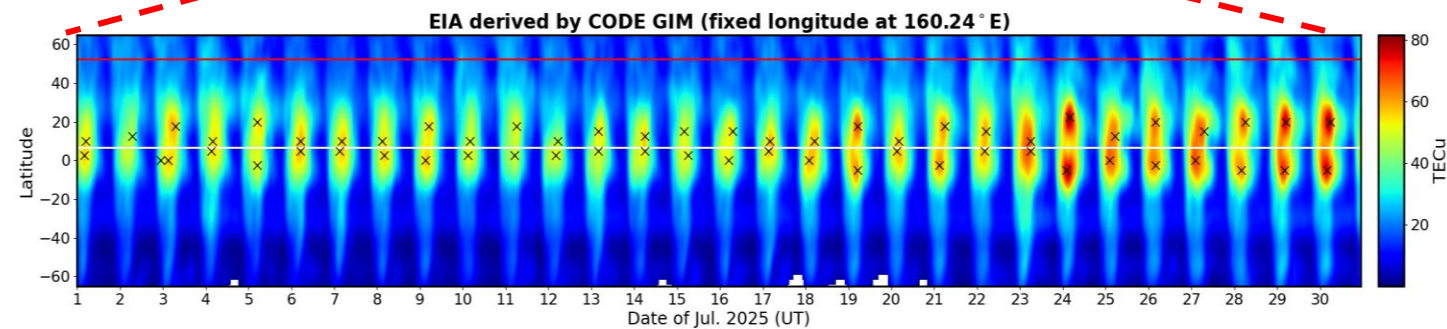
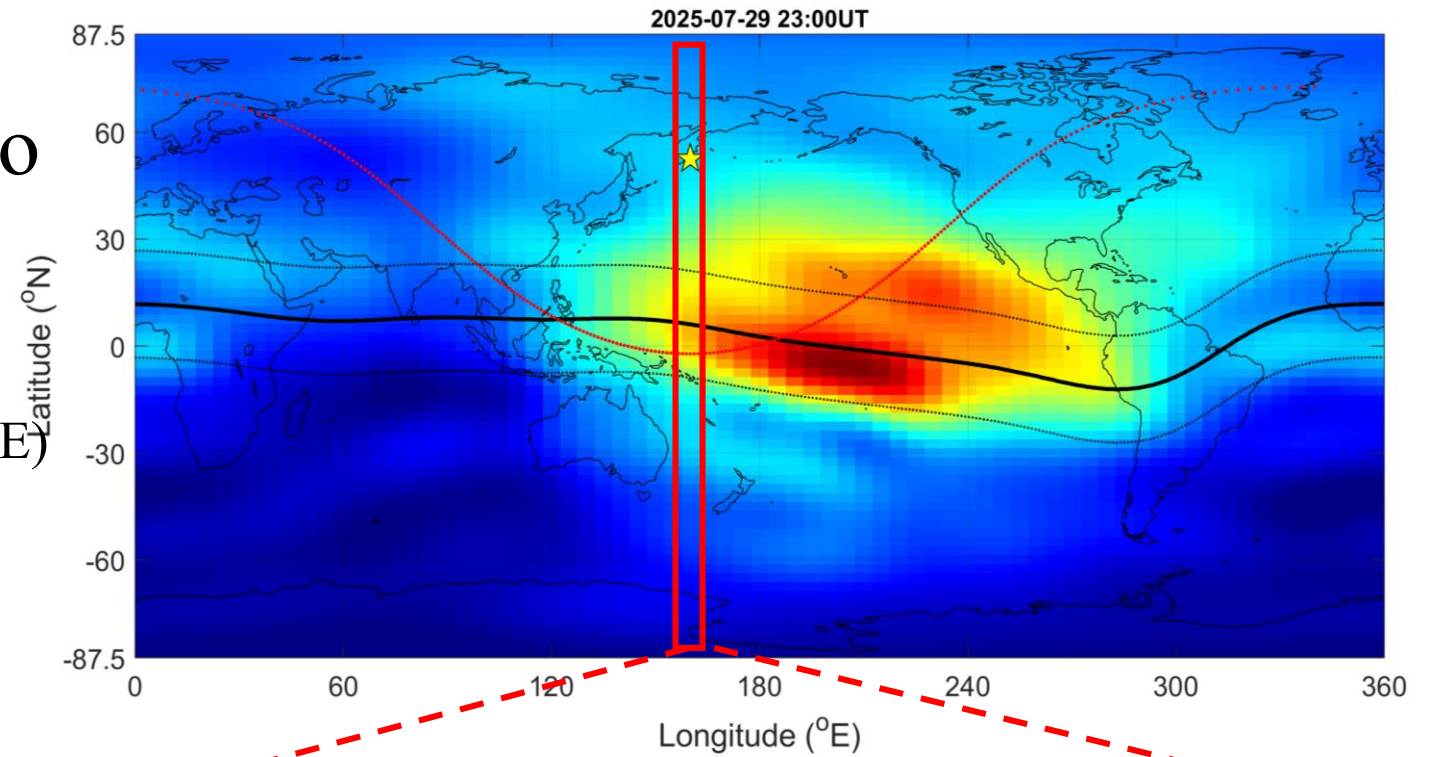
Time resolution: 1-hour

Spatial resolution: 2.5° latitude $\times$ 5° longitude

5183 (=73 x 71) lattices

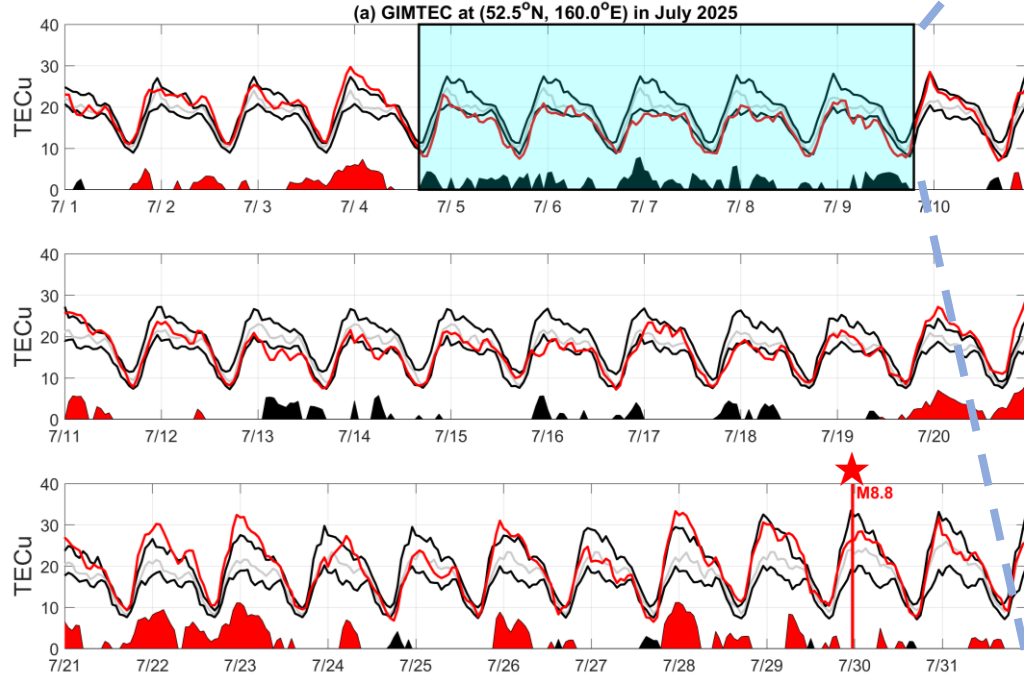
Cheng et al. (2022)

Cheng, C.-C., Liu, J.-Y., Lin, C. C. H., & Cheng, Y.-C. (2022). Daily dynamo electric fields derived by using equatorial ionization anomaly crests of the total electron content. *Space Weather*, 20, e2022SW003073. <https://doi.org/10.1029/2022SW003073>



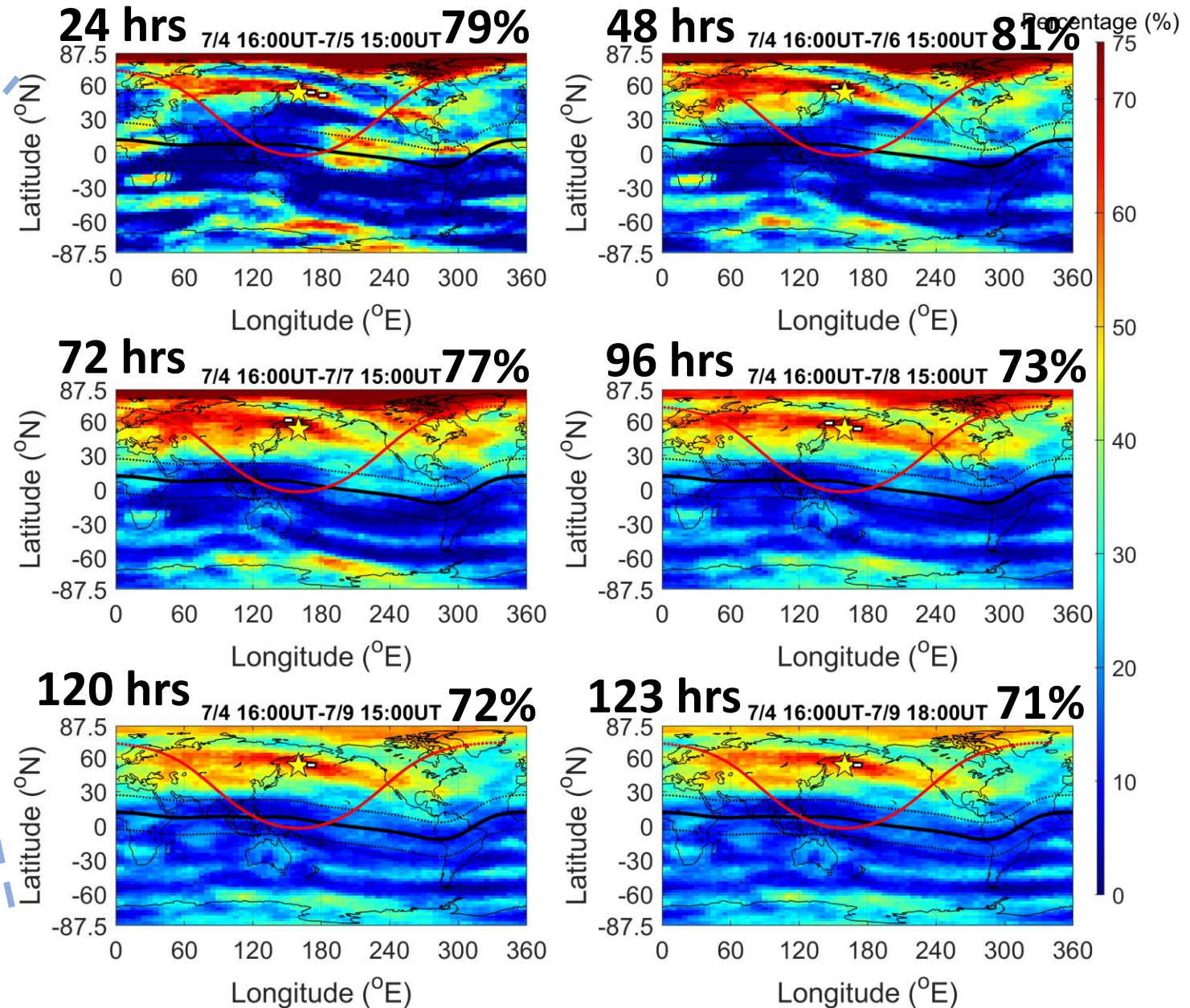
M8.8

GIM TEC over the epicenter distances on day 21-25 before



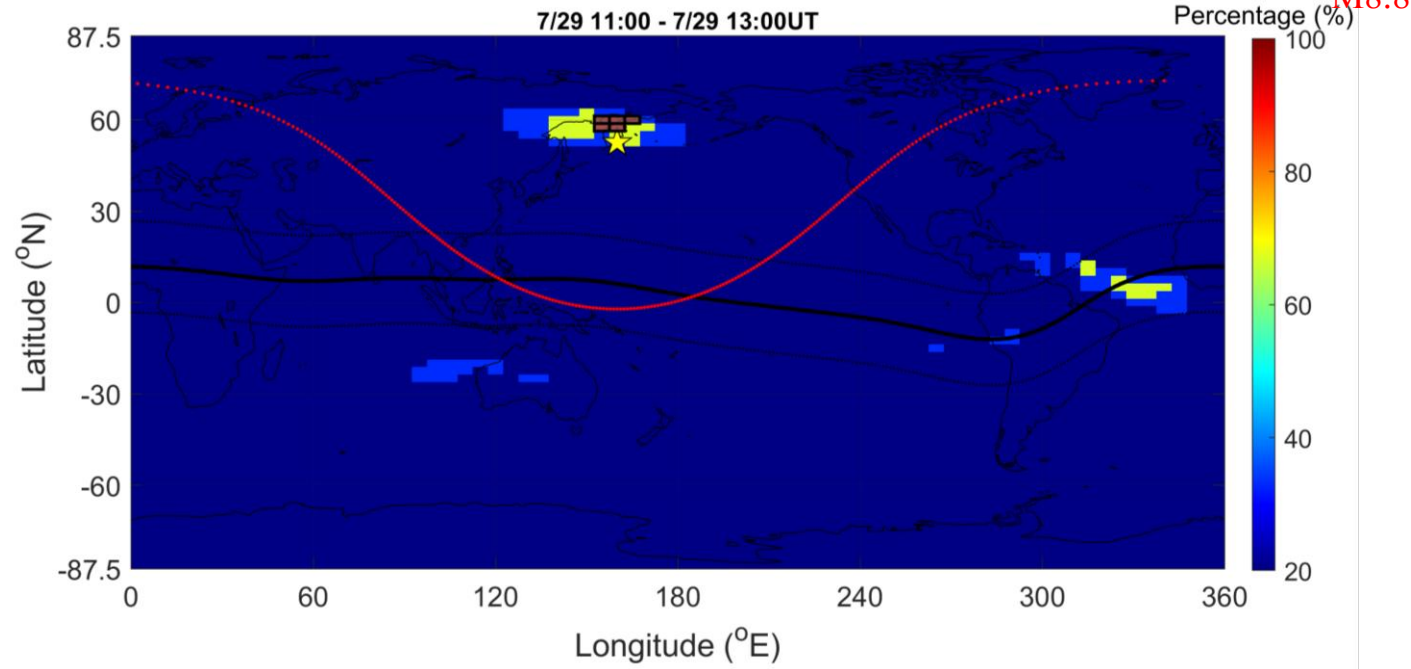
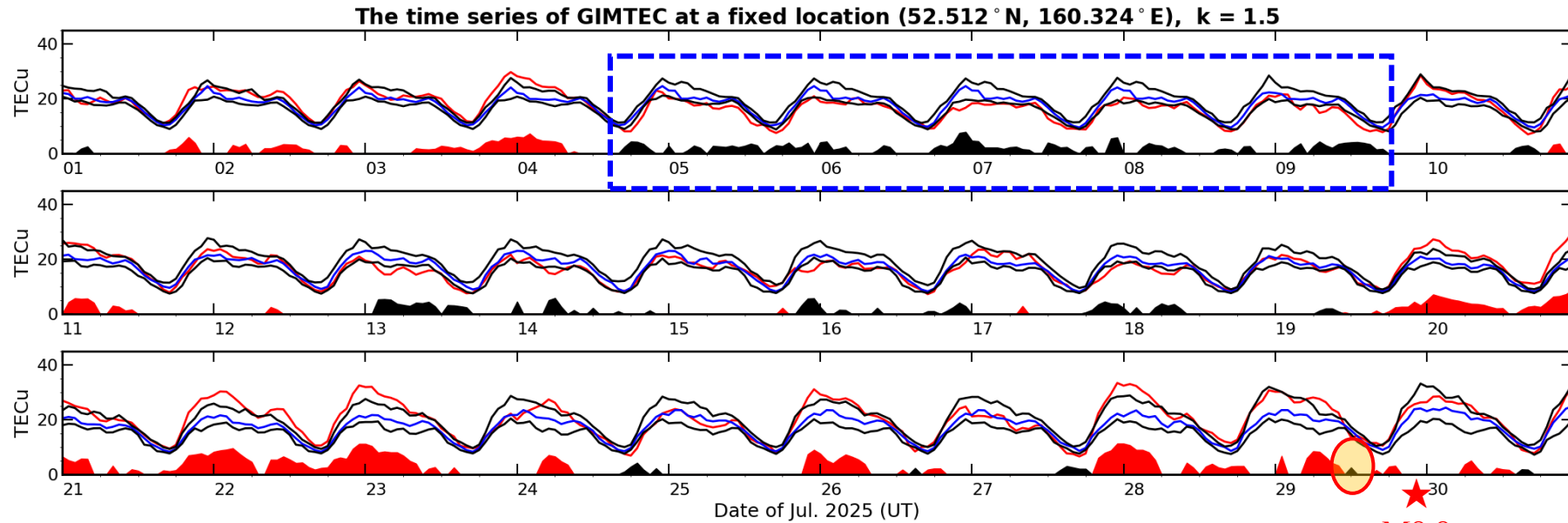
$$LB = M - k (M - LQ)$$

$$UB = M + k (UQ - M)$$



* 0.02-0.04% (1 and/or 2 out of 5183)

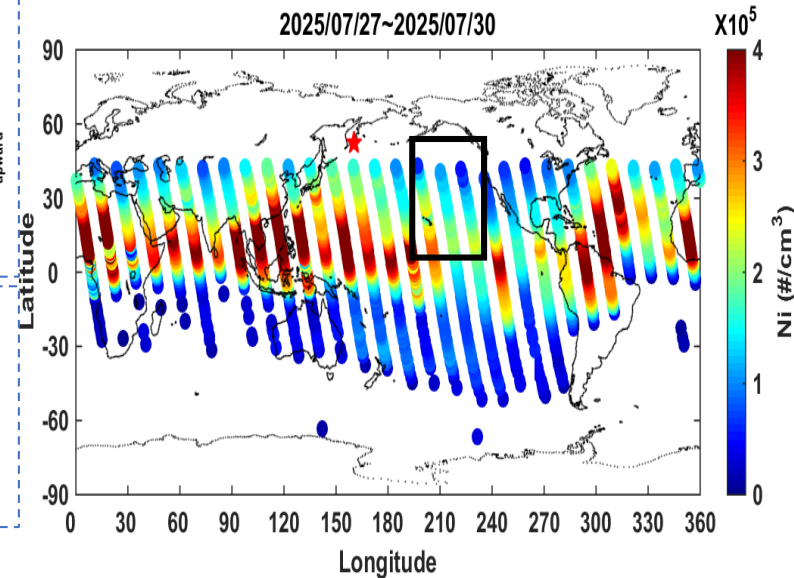
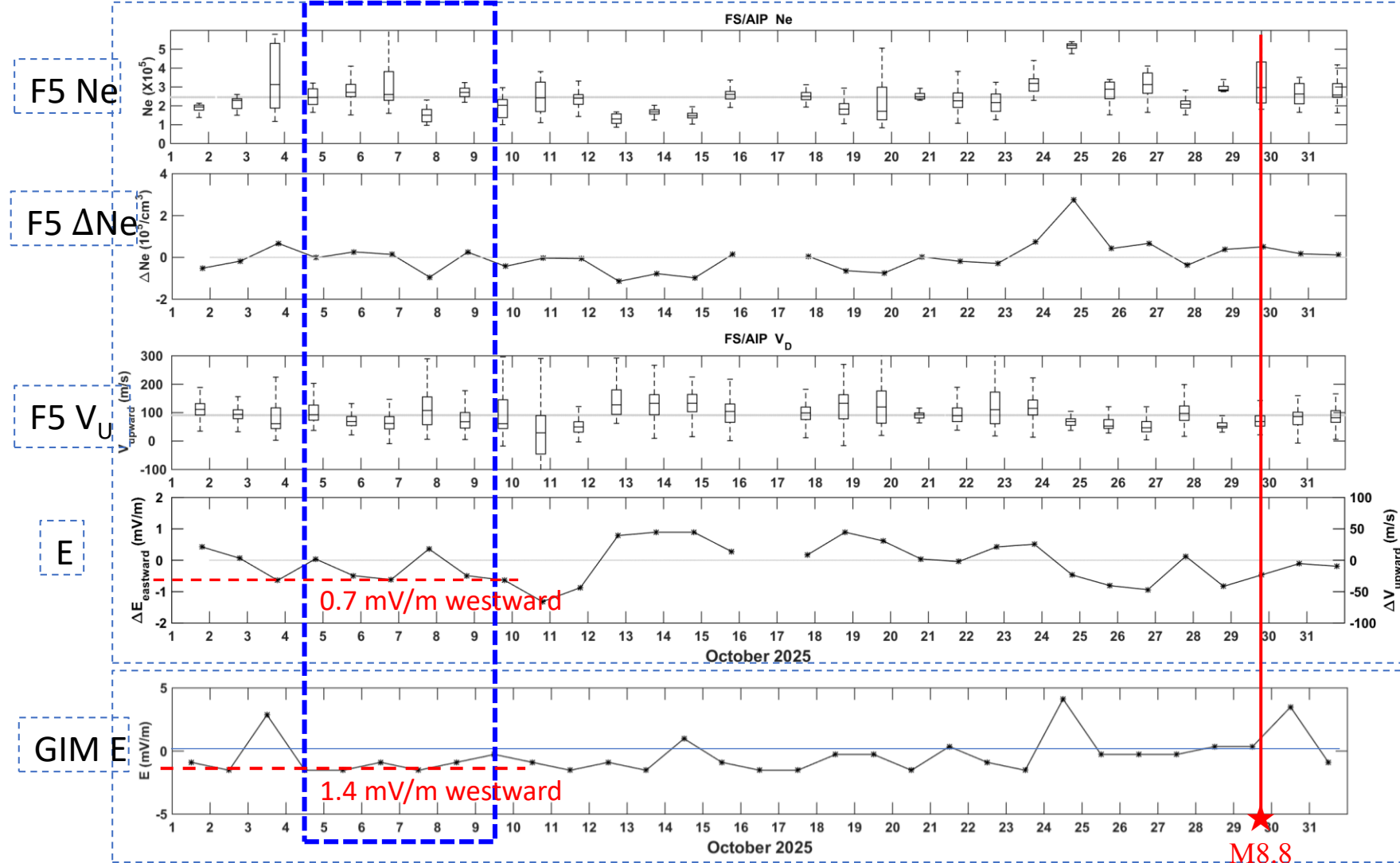
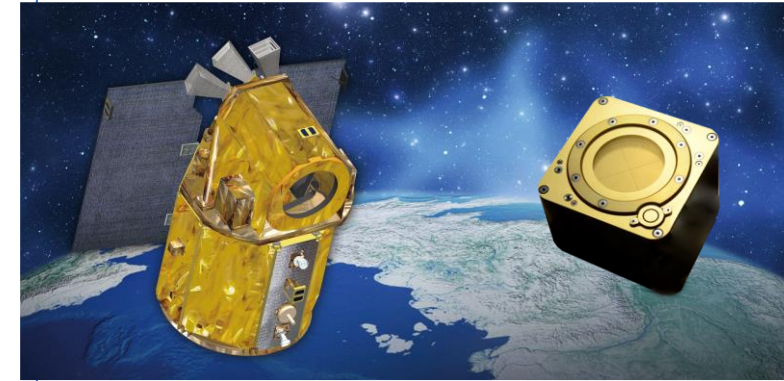
Decreases of GIMTEC anomalies at 11-12 hours before the earthquake



Seismo-electric fields day 20-25 before the earthquake

Dynamo processes

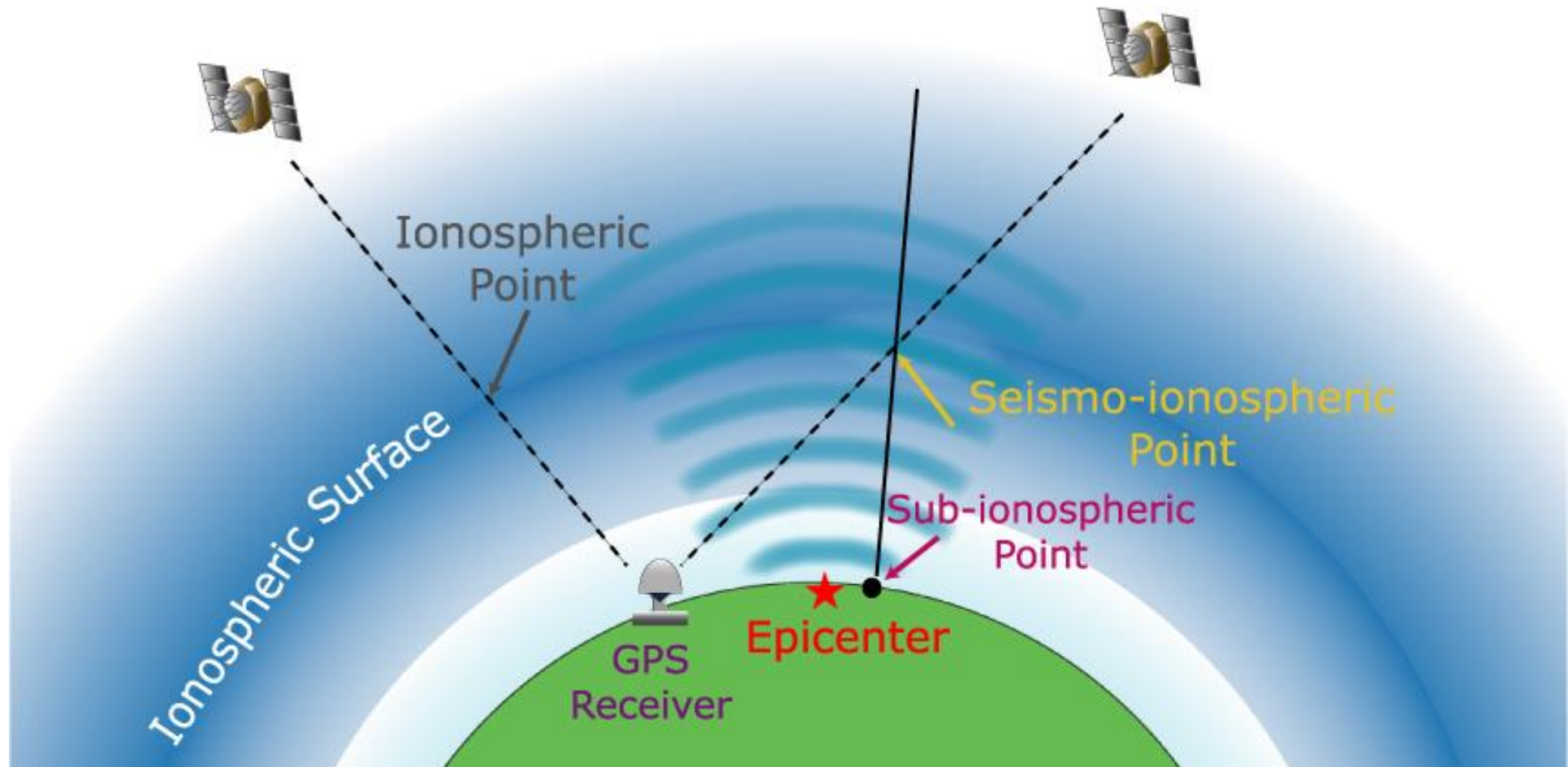
$$\mathbf{E} = (\mathbf{E}_0 + \mathbf{E}_s) - \mathbf{V} \times \mathbf{B}$$



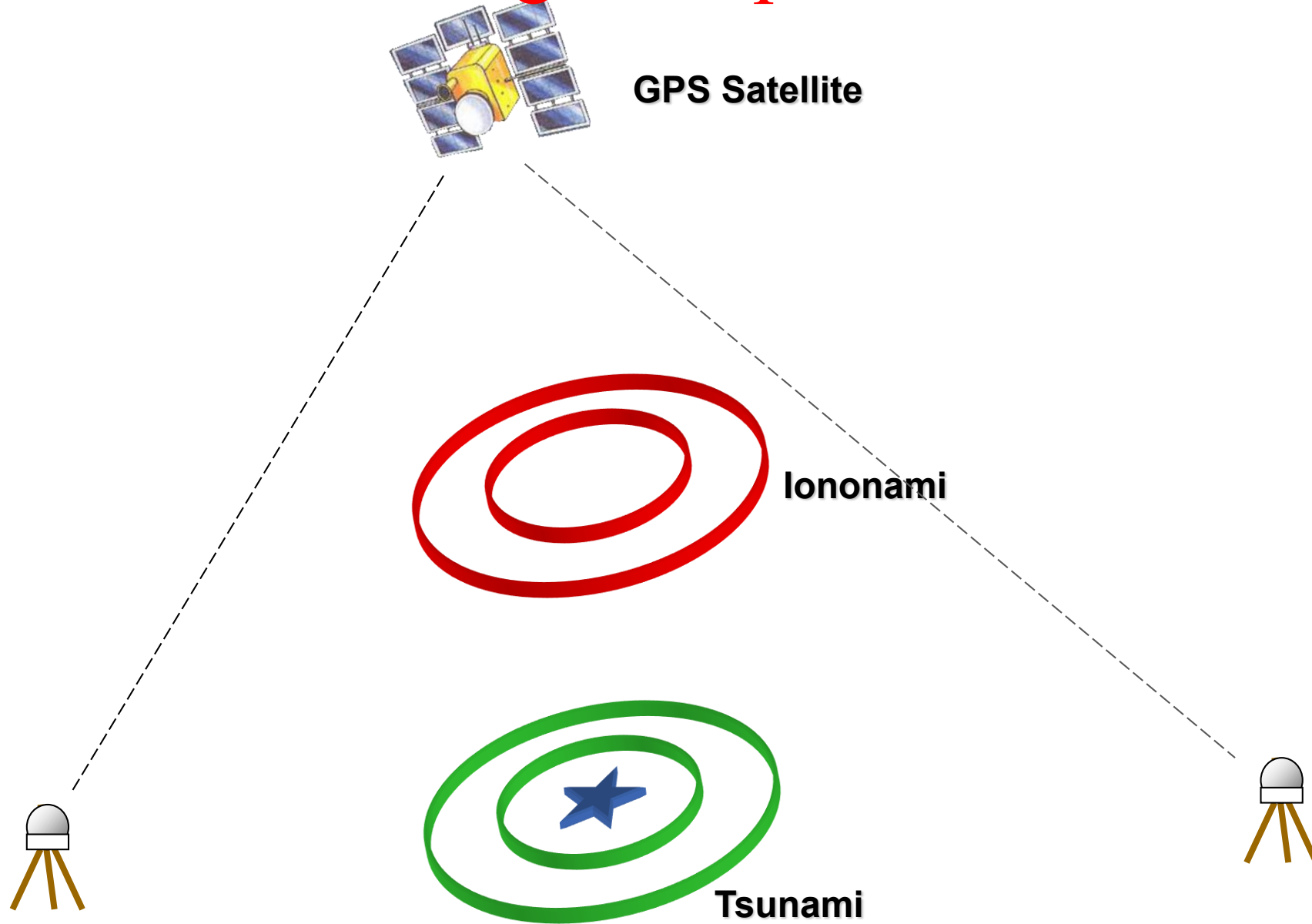
Remark 1

- The spatial analyses of GIM TEC show that negative seismo-ionospheric anomalies (SIPs) appear around the epicenter 10-11 hours and 20-25 days with the duration of 2 and 147 hours, respectively, before the the 2025 Mw 8.8 Kamchatka earthquake.
- The chances of observing the negative anomalies frequently occur pacifically near the epicenter is 0.01-0.02%.
- The seismo-electric fields related to the SIPs before 20-25 days estimated by the EIA crest distance in GIM TEC and F5/AIP ion velocity are about 0.7-1.4 mV/m westward.

GNSS TEC observations of traveling ionospheric disturbances triggered by seismic waves and tsunami

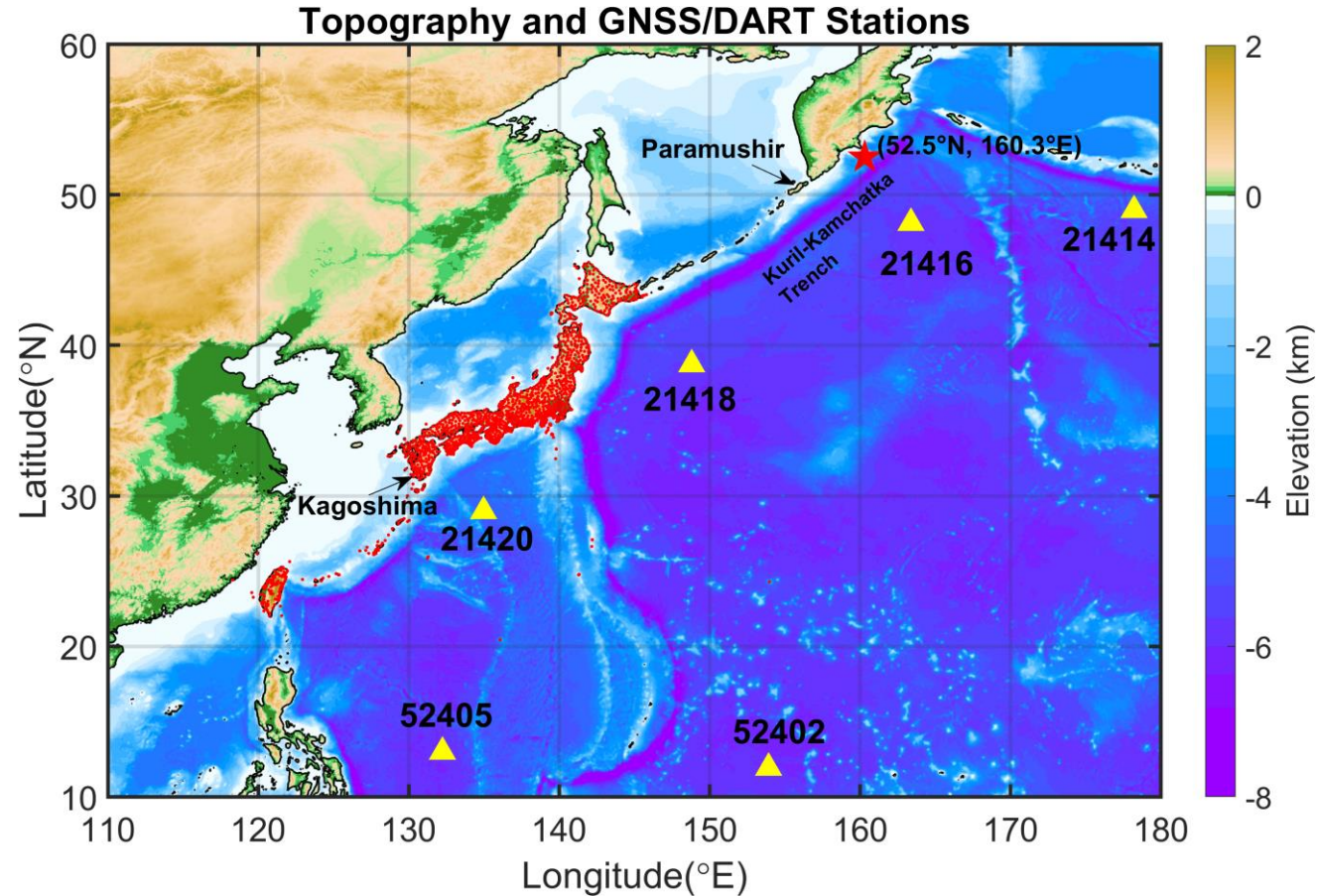


Tsunami traveling ionospheric disturbances



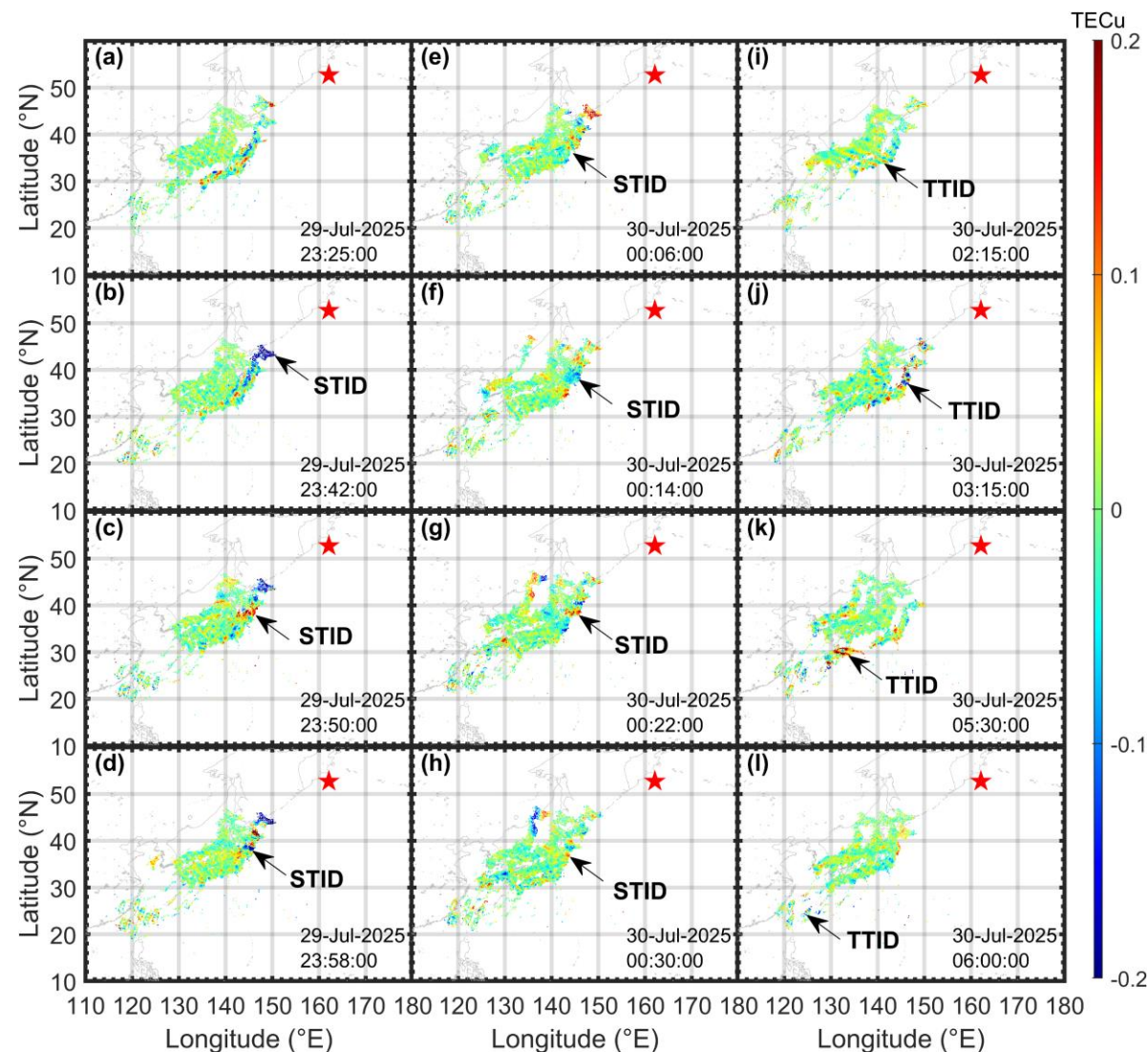
STIDs and TTIDs in GNSS TECs during the M8.8 Kamchatka Earthquake

Ground-based GPS receivers and DART stations during the earthquake



Regional topography and bathymetry. Red dots and yellow triangles denote ground-based GPS receivers and DART stations, respectively. The red star marks the epicenter (52.5°N, 160.3°E).

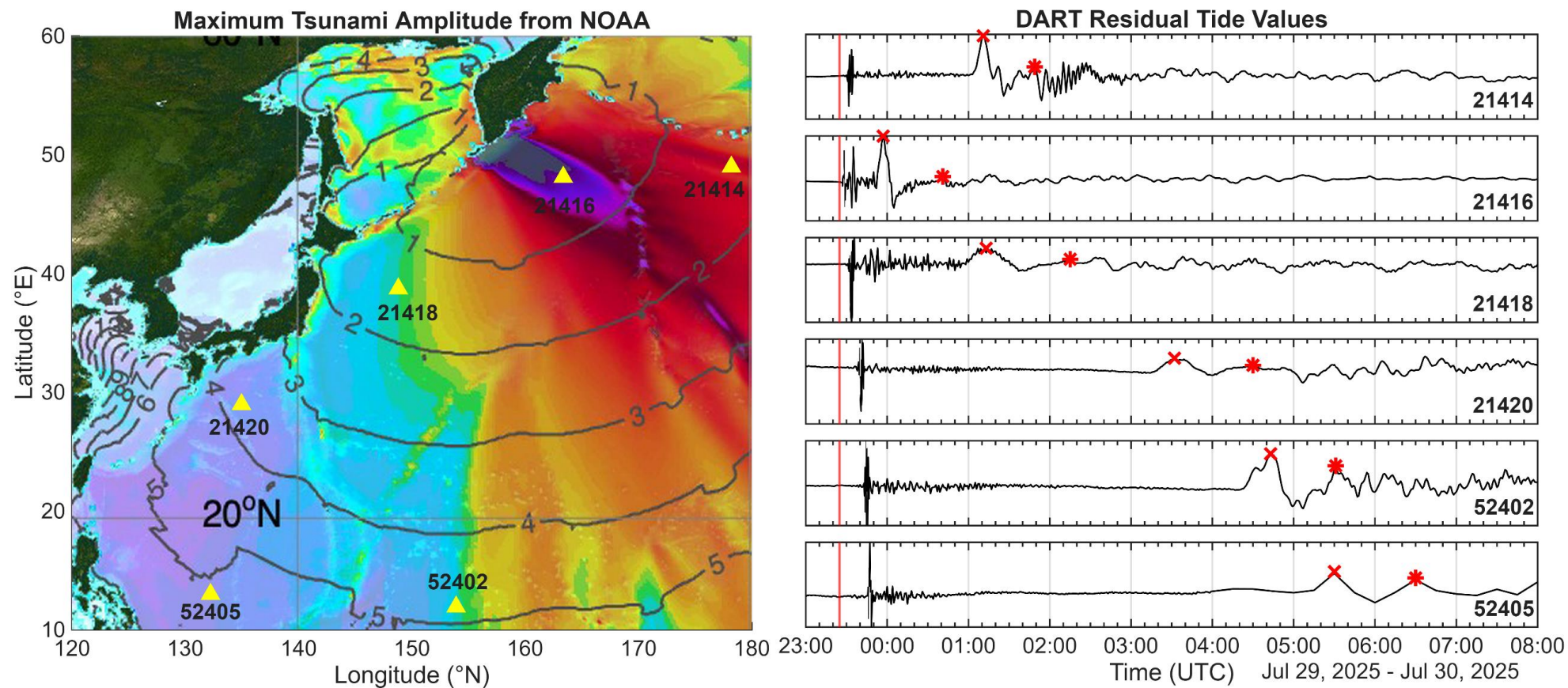
Temporal evolution of the filtered TEC perturbations after the earthquake



Huang et al. (GRL 2026)

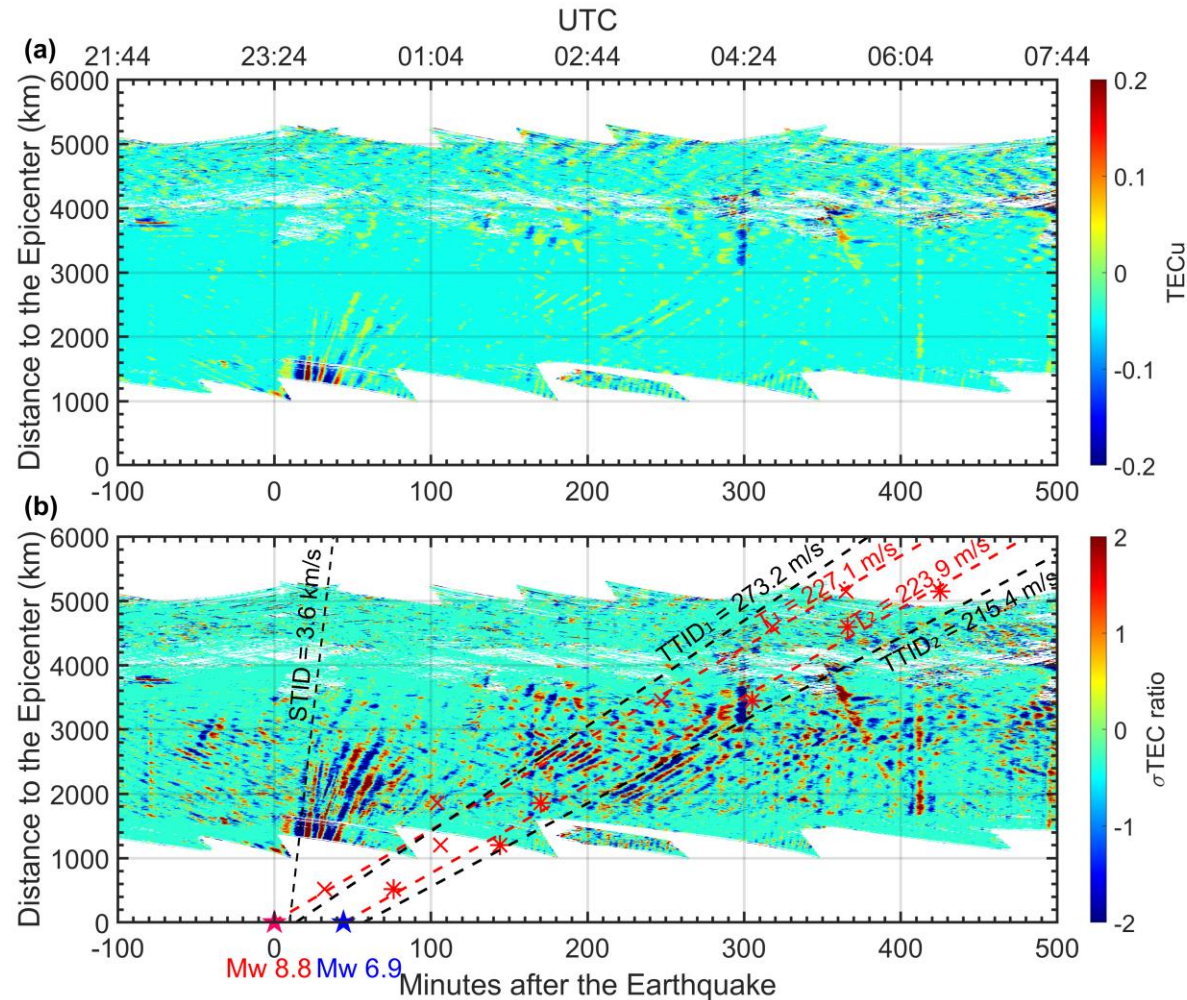
Temporal evolution of the filtered TEC perturbations after the earthquake. Panels (a)–(l) show sequential maps from 23:25 UT on 29 July to 06:00 UT on 30 July 2025. The red star denotes the epicenter, and the black arrows indicate the disturbance.

Maximum tsunami amplitude and DART station and corresponding residual tide records



Maximum tsunami amplitude and DART station locations (left; adapted from the NOAA Center for Tsunami Research) and corresponding residual tide records (right) for July 29–30, 2025. The black contour lines in the left panel represent the arrival time. Red vertical lines mark the earthquake onset, while crosses and asterisks indicate the primary and secondary tsunami arrivals, respectively. The amplitude is omitted to emphasize the timing and relative waveform characteristics.

Spatiotemporal distribution of filtered TEC and normalized TEC



The z-score normalization

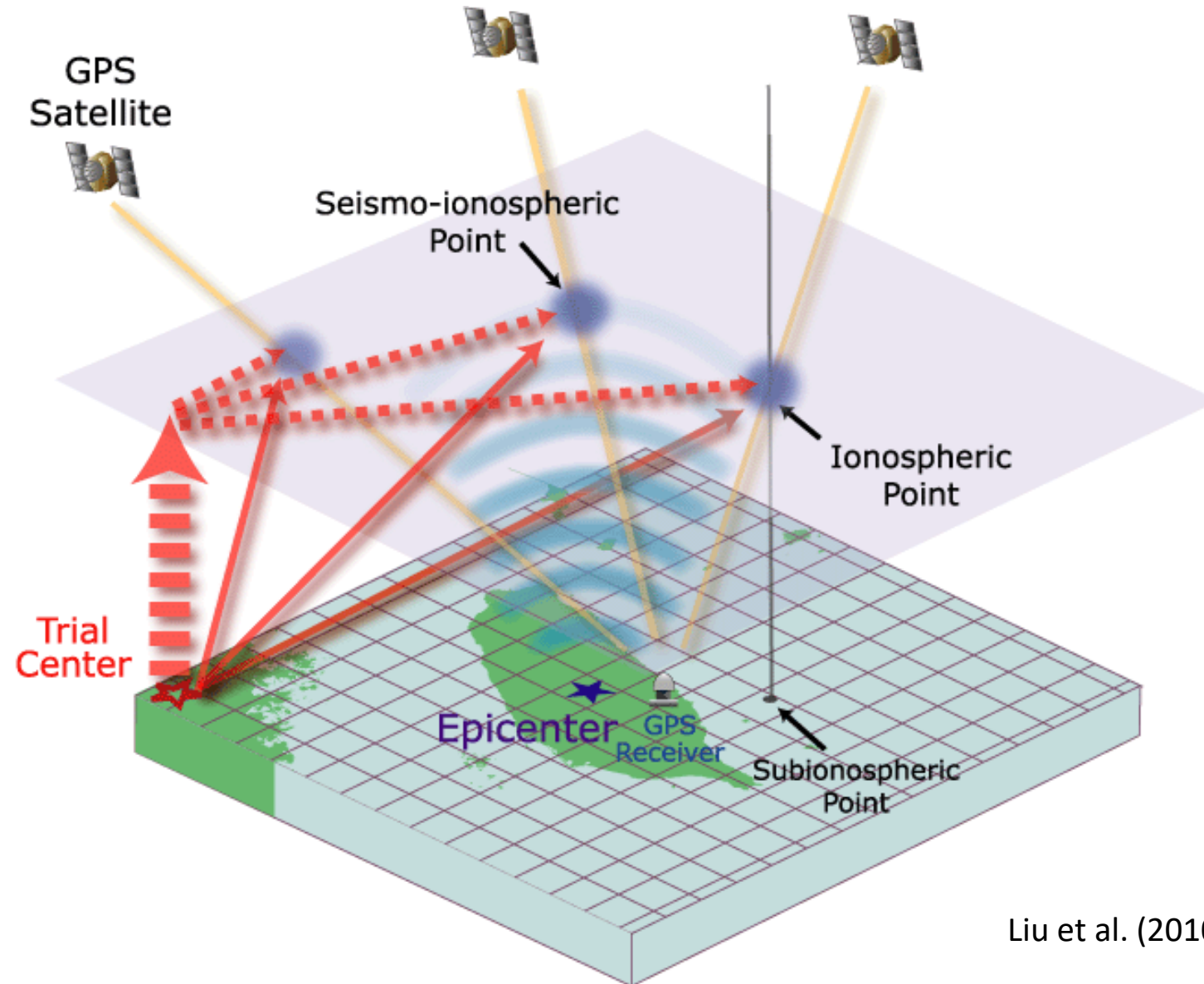
The time–distance diagram is normalized by subtracting the mean and dividing by the standard deviation (σ) at each distance, where the statistics are computed using all time points at each distance bin. A distance-dependent scaling factor proportional to $\sqrt{r}$, where r is the distance to the epicenter in kilometers, is also applied to compensate for geometric signal attenuation with increasing range.

STIDs: 3.6 km; TTIDs: 216-273 m/s

Spatiotemporal distribution of (a) filtered TEC and (b) normalized TEC as functions of time and epicentral distance, from 21:44 UT on 29 July 2025 to 07:44 UT on 30 July 2025. The red and blue stars mark the main shock (Mw 8.8 at 23:24 UT) and the aftershock (Mw 6.9 at 00:09 UT), respectively. The black dashed lines indicate the wavefront propagation with estimated horizontal velocities. The red crosses and asterisks denote DART buoy observations and their linear fits. [Huang et al. \(GRL 2026\)](#)

Ray-Tracing Technique

Assume the average speed and find the origin



Liu et al. (2010)

Ray-Tracing Technique

Assume the average speeds in the vertical and horizontal direction to be V_Z and V_H , respectively.

$$\Delta t_{i,j} = \Delta Z_{i,j}/V_Z + \Delta S_{i,j}/V_H$$

where the STID at the ionospheric point altitude $\Delta Z_{i,j} = 350$ km and the horizontal distance from the STID to the trial epicenter $\Delta S_{i,j}$. Since the arrival time t_i at a STID is recorded, the onset time t_{Gi} at the trial epicenter “j” can be computed,

$$t_{Gi,j} = t_i - \Delta t_{i,j}$$

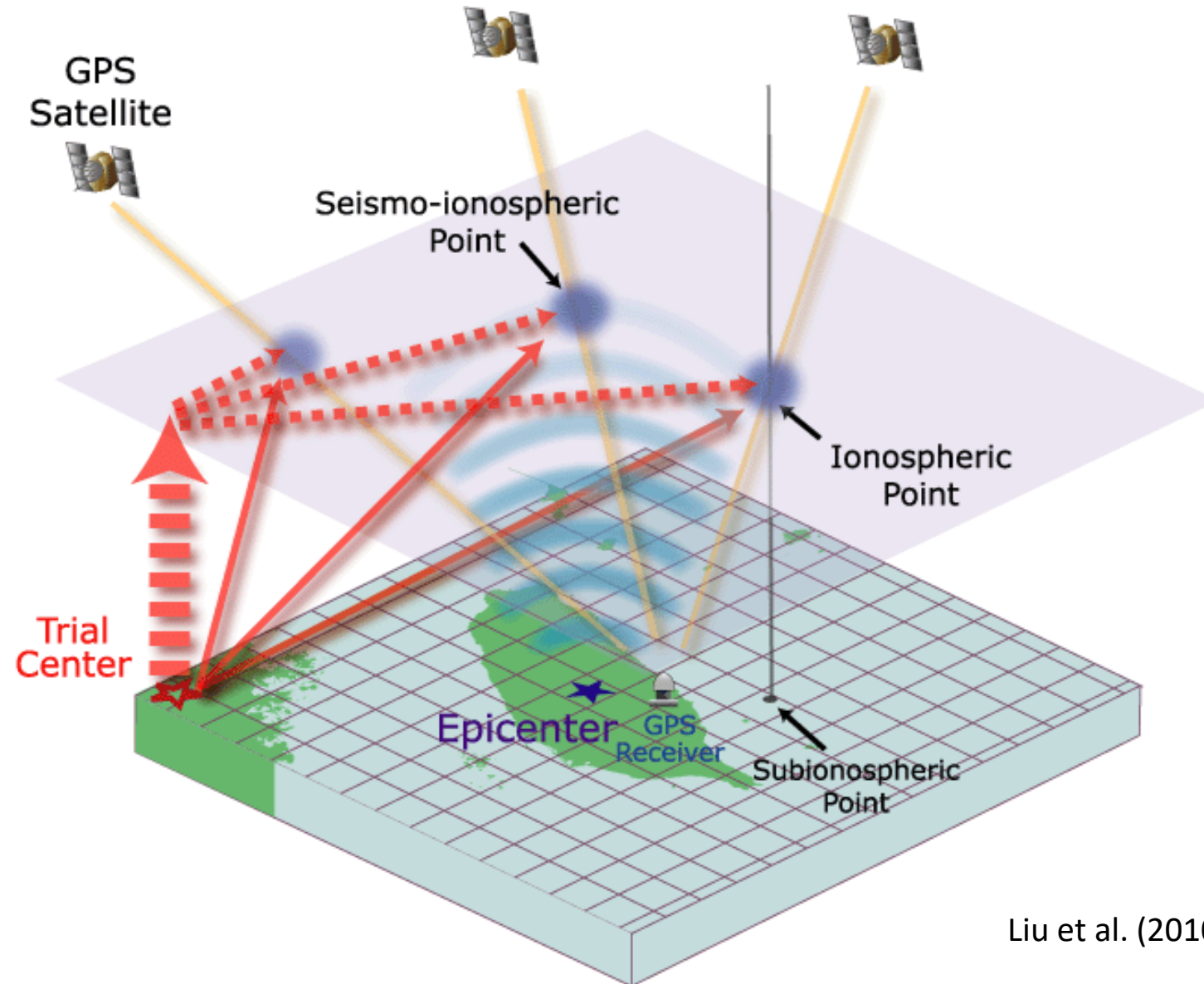
If N points of STIDs are detected, the standard deviation of the computed onset times at the trial center can be written as

$$\sigma_j = [\sum (t_{Gi,j} - \mu_j)^2 / N]^{1/2}$$

where μ_j is the associated mean value.

Beam-Forming Technique

Assume the earthquake onset time and find the origin



Liu et al. (2010)

Beam-Forming Technique

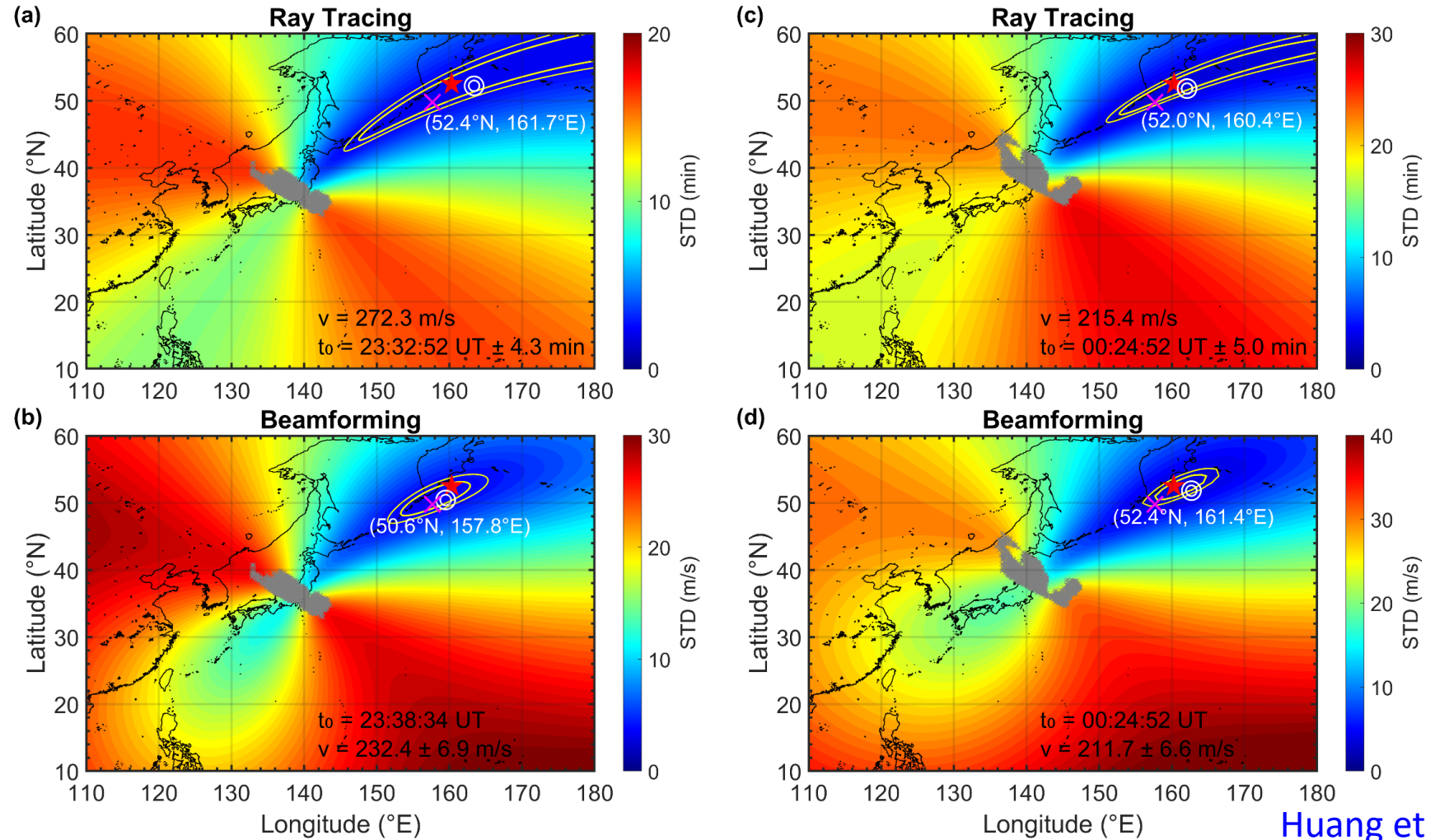
Here we simply **guess a onset time t_o** and compute the velocity $V_{i,j}$ by dividing the distance from the STID point to the trial epicenter $\Delta S_{i,j}$ by a given traveling time $\Delta t_i (= t_i - t_o)$ at each STID point,

$$V_{i,j} = \Delta S_{i,j} / \Delta t_i$$

Similarly, for N points of the detected STIDs, the standard deviation of the computed velocities (speeds) at the trial center can be written as

$$\sigma_j = [\Sigma(V_{i,j} - \mu_j)^2 / N]^{1/2}$$

Computed TTID₁ and TTID₂ sources inferred from ray tracing and beamforming



Huang et al. (GRL2026)

Computed TTID₁ and TTID₂ sources inferred from ray tracing (a, c) and beamforming (b, d). The red star marks the earthquake epicenter, and the white concentric circles denote the estimated TTID sources, and the magenta cross indicates the maximum-slip location from Fujii and Satake (2025). Grey crosses represent space buoys. v and t_0 are the estimated horizontal velocity and the TTID onset time, respectively. Yellow contours show regions within 10% (inner) and 20% (outer) of the minimum std.

Remark 2

- The z-score normalization enhances the detection of two tsunami-induced ionospheric disturbances of the 2025 Mw 8.8 Kamchatka earthquake.
- The origin of tsunami-induced ionospheric disturbances matches the tsunami source inverted from deep-ocean pressure data.
- Even with single-region GNSS coverage, ray tracing and beamforming successfully resolve tsunami sources over 2,000 km away.

STIDs and TTIDs in ionograms and CW-HF Doppler Frequency Shifts during the M8.8 Kamchatka Earthquake

29 July 2025

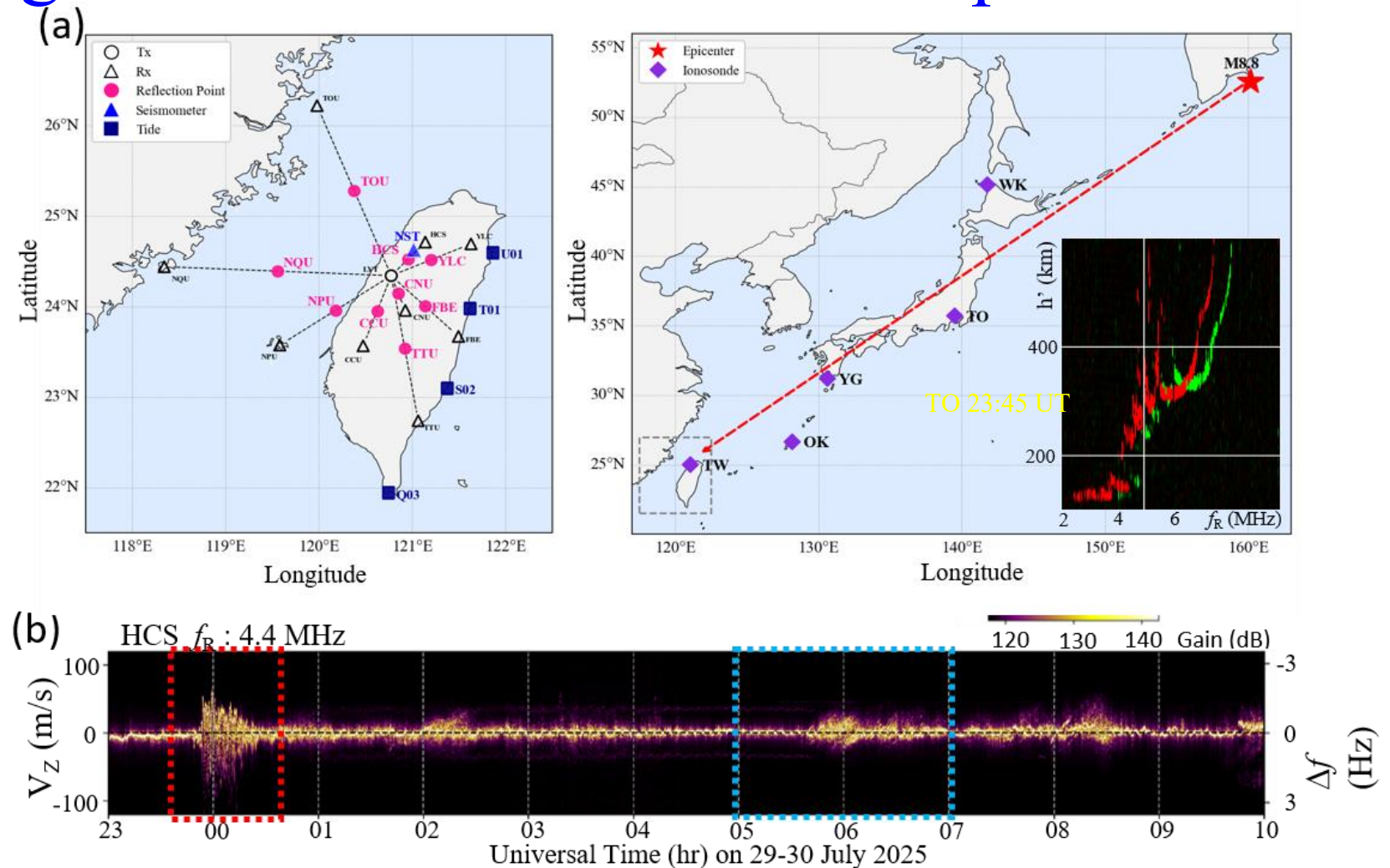
23:24:52 UT

Mw8.8 earthquake

5 sounding frequencies

9 receiving stations

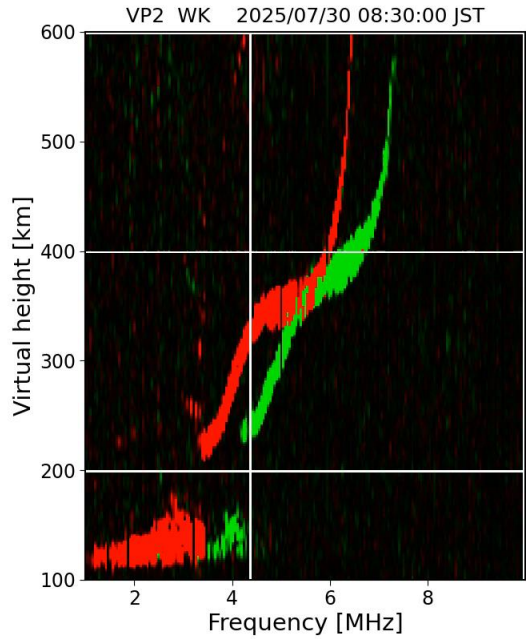
45 (=5x9) reflection point



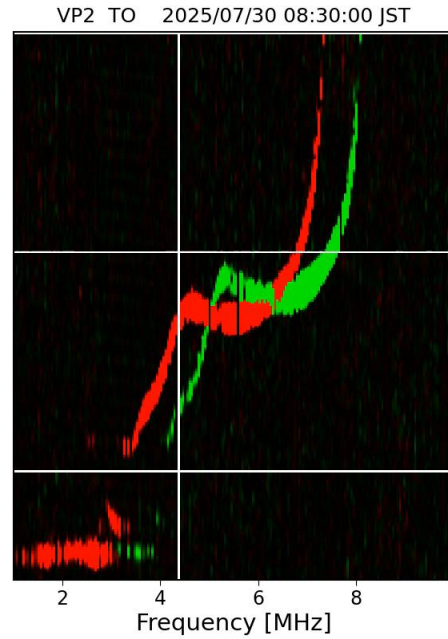
Locations of Doppler sounding systems, ionosondes, seismometers, and tide gauges as well as DFS observations and sketches of STIDs and TTIDs.

Seismo-TIDs in ionograms triggered by the M8.8 Kamchatka Earthquake

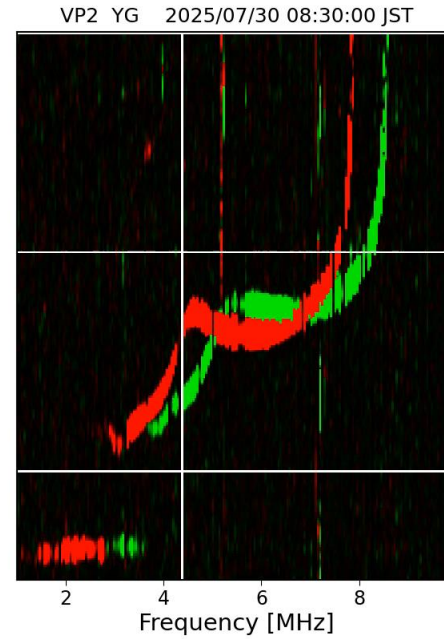
WK



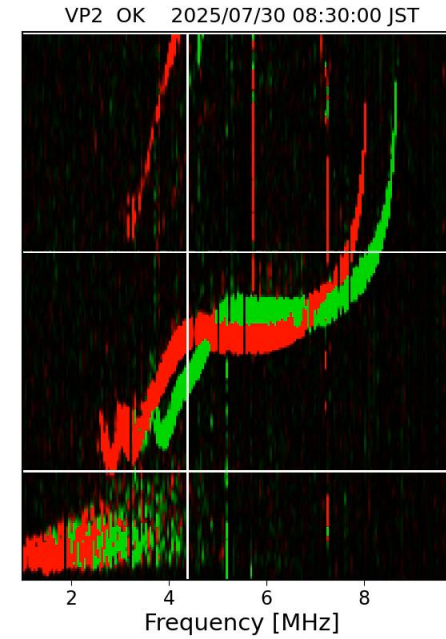
TO



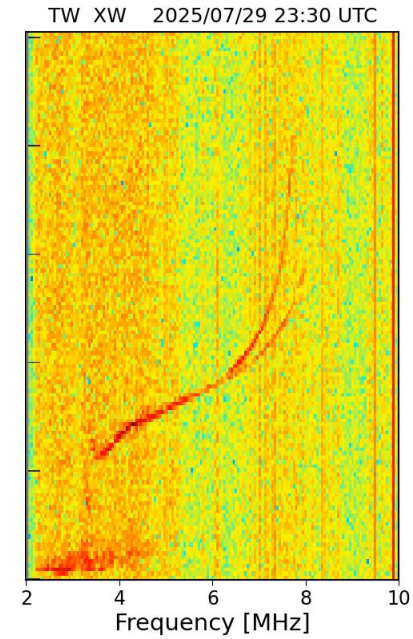
YA



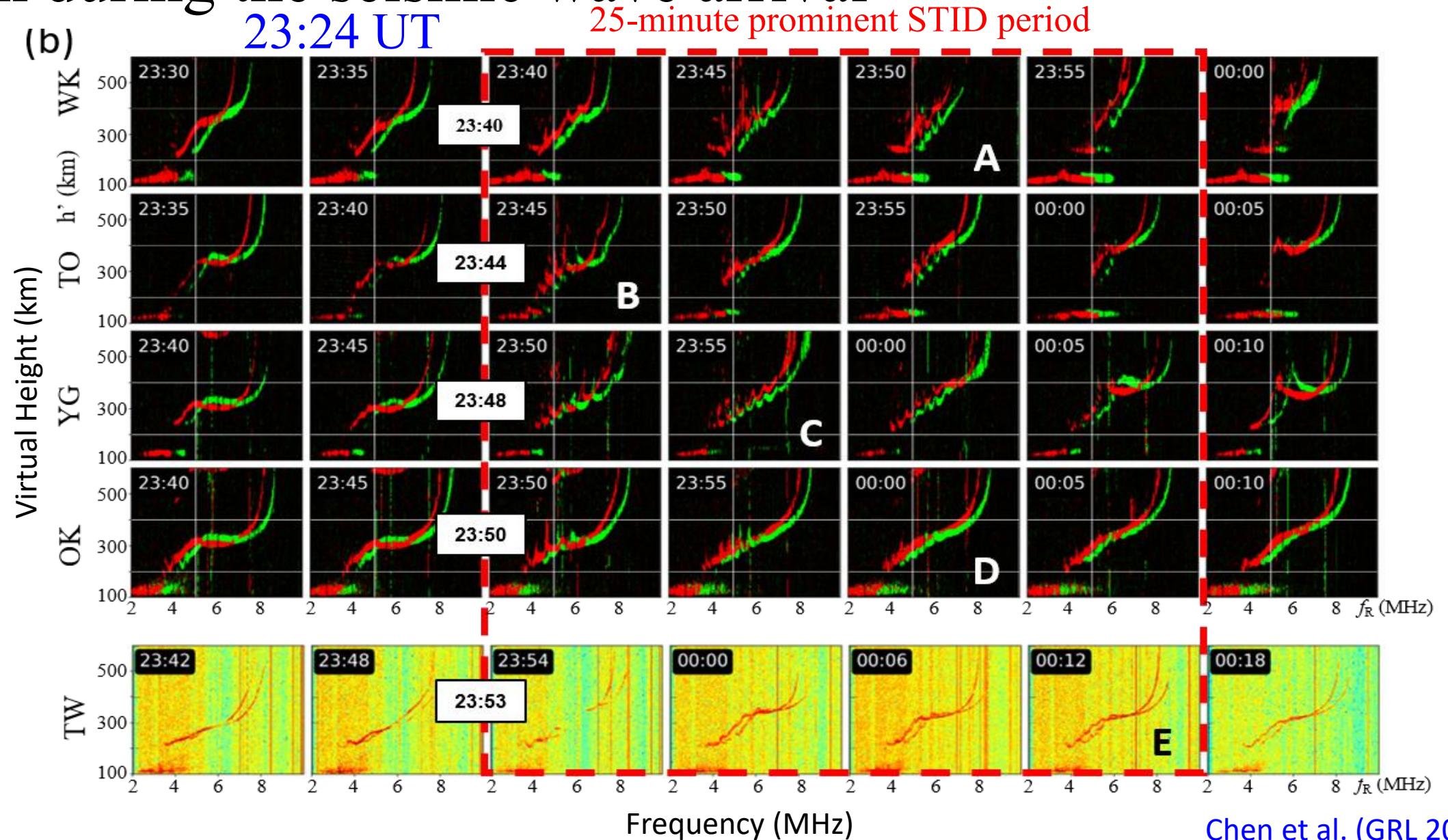
OK



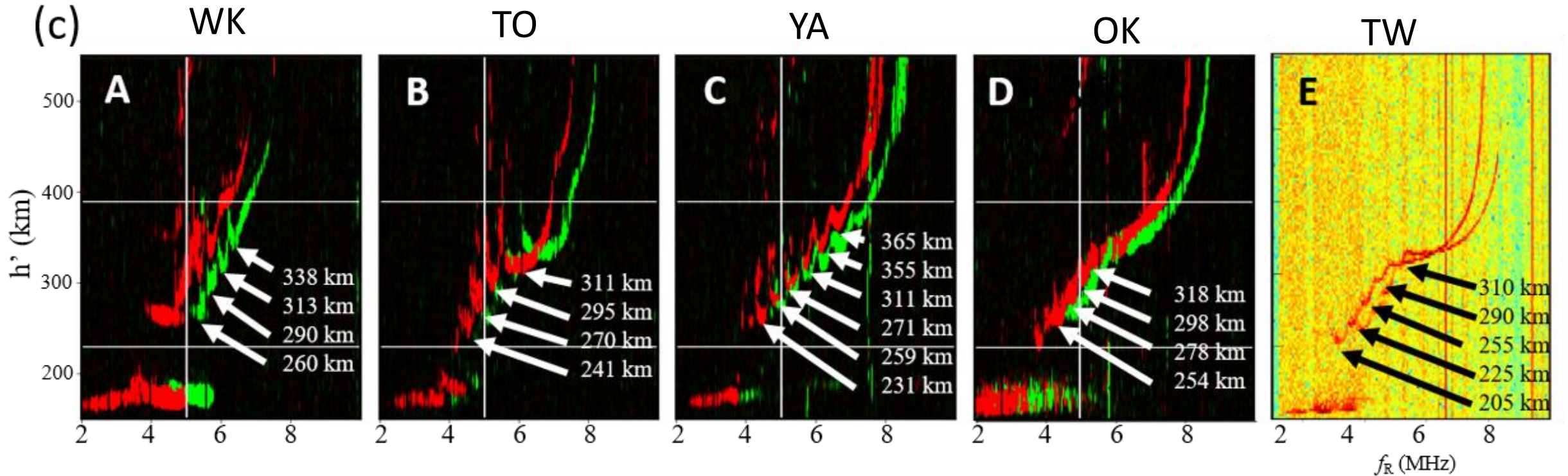
TW



Sequences of ionograms recorded by the five ionosondes in Taiwan during the seismic wave arrival



The vertical wavelength of Seismo-TIDs



The representative examples shown in Figure 2c give the following separations: Panel A (WK): separations of 25, 23, and 30 km (range: 23–30 km). Panel B (TO): separations of 16, 25, and 29 km (range: 16–29 km). Panel C (YG): separations of 10, 44, 40, 12, and 28 km (range: 10–44 km). Panel D (OK): 318, 298, 278, separations of 20, 20, and 24 km (range: 20–24 km). Panel E (TW): separations of 20, 35, 30, and 20 km (range: 20–35 km). The vertical wavelengths at TW and over all five ionosonde stations are 26.5 ± 3.5 and 26.6 ± 2.5 km in virtual height, respectively. **The vertical wavelength is about 16.2 ($=26.5 \times 0.61$) km in true range.**

Amplification Factor

Based on the concept of energy (potential and kinetic energy density) conservation, the energy density of STIDs can be expressed as,

$$1/2\rho_G v_G^2 = 1/2\rho_I v_I^2$$

where G and I denote the ground and the ionosphere, respectively. Thus, ρ_G and v_G (ρ_I and v_I) stand for the mass density of the atmosphere and maximum oscillation speed on the ground (in the ionosphere), respectively. For a simple harmonic motion, the oscillation speed can be written $v=A\omega$, where A is the oscillation amplitude and ω is the angular frequency. $\rho_G(A_G\omega_G)^2 = \rho_I(A_I\omega_I)^2$. Assume the angular frequency of the long-period waves remains unchanged, $\omega=\omega_G=\omega_I$,

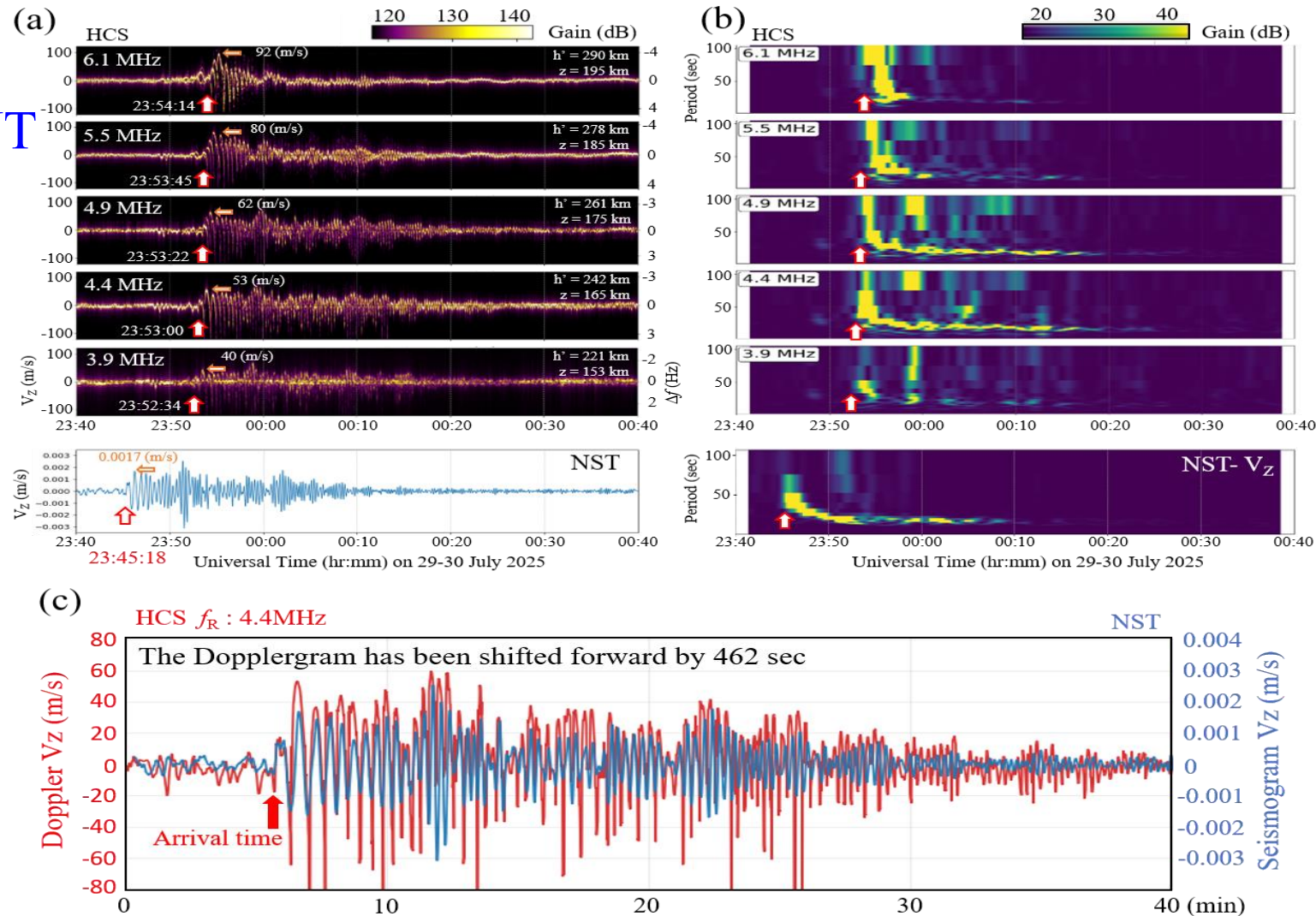
Liu et al. (TAO 2012)

$$A_I/A_G = (\rho_G/\rho_I)^{1/2}$$

$A_G = 1$ meter on the ground
-- $> A_I = 100$ km at 200 km altitude

DFSs and seismic waves upon the STID arrival observed in Taiwan

23:24:52 UT



The period of 20 sec

$$F = \frac{v_I}{v_G} = \sqrt{\frac{\rho_G}{\rho_I}}$$

The ratio of the amplitude of STIDs in DFSs at the sounding frequency of 4.9 MHz (175 km altitude) to that of seismic waves is 3.6×10^4 ($=62/0.0017$).

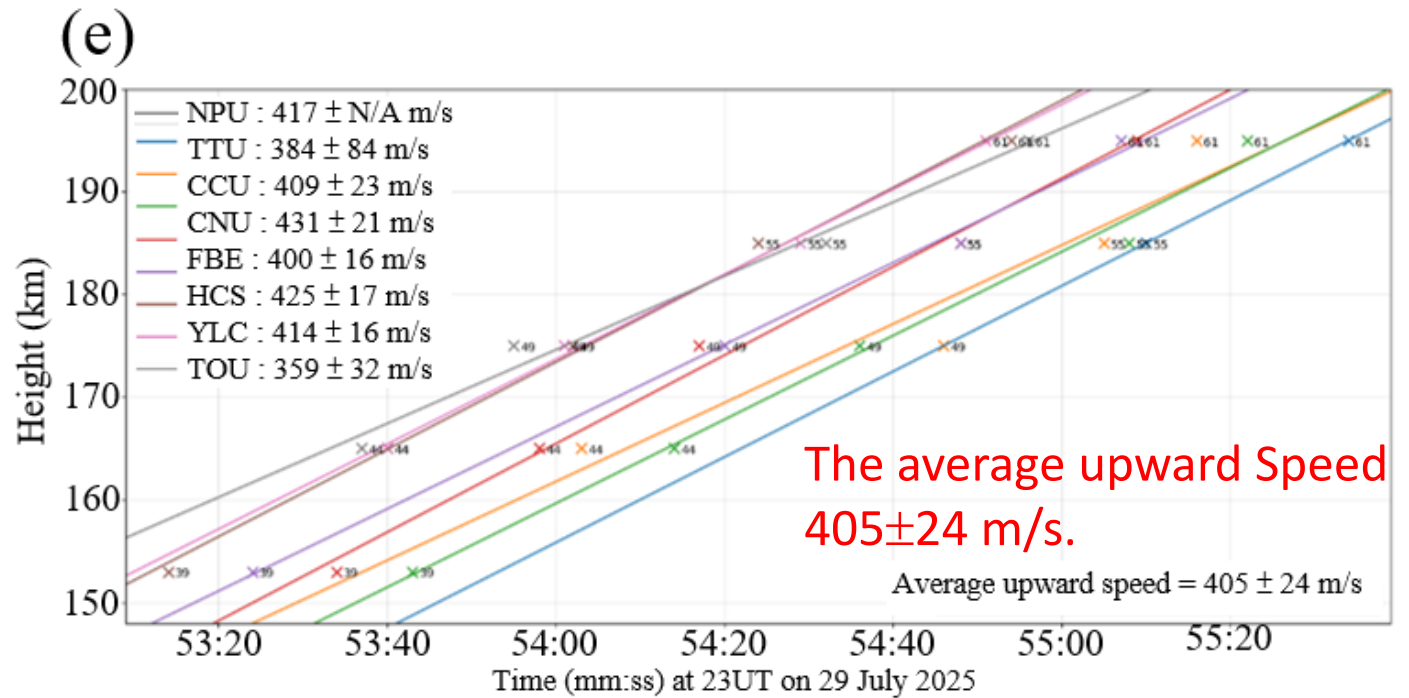
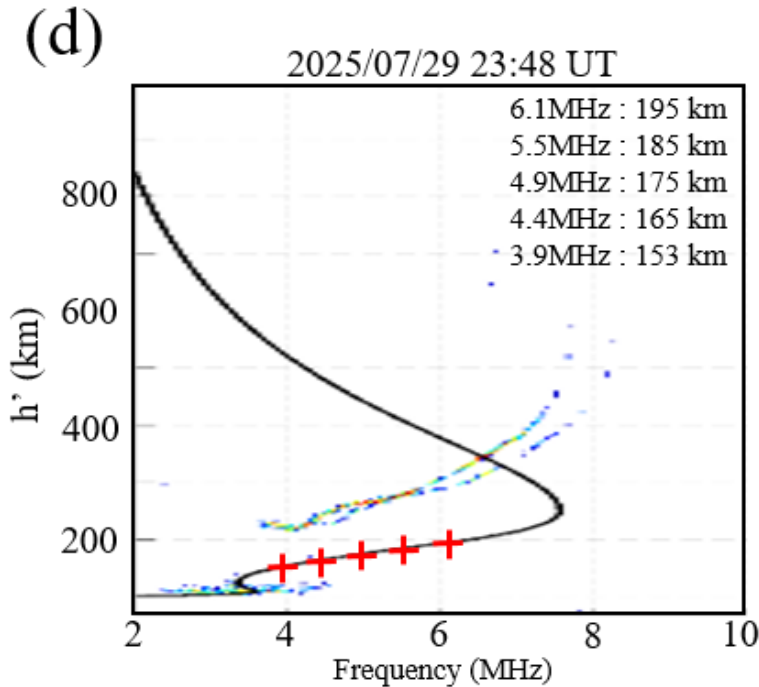
Chen et al. (GRL 2026)

(a) DFSs of five sounding frequencies at HCS and a seismogram recorded at NST, and (b) their associated periodograms. (c) Upward velocity in the seismogram and Dopplergram.

The Vertical Propagation in STIDs of DFSs

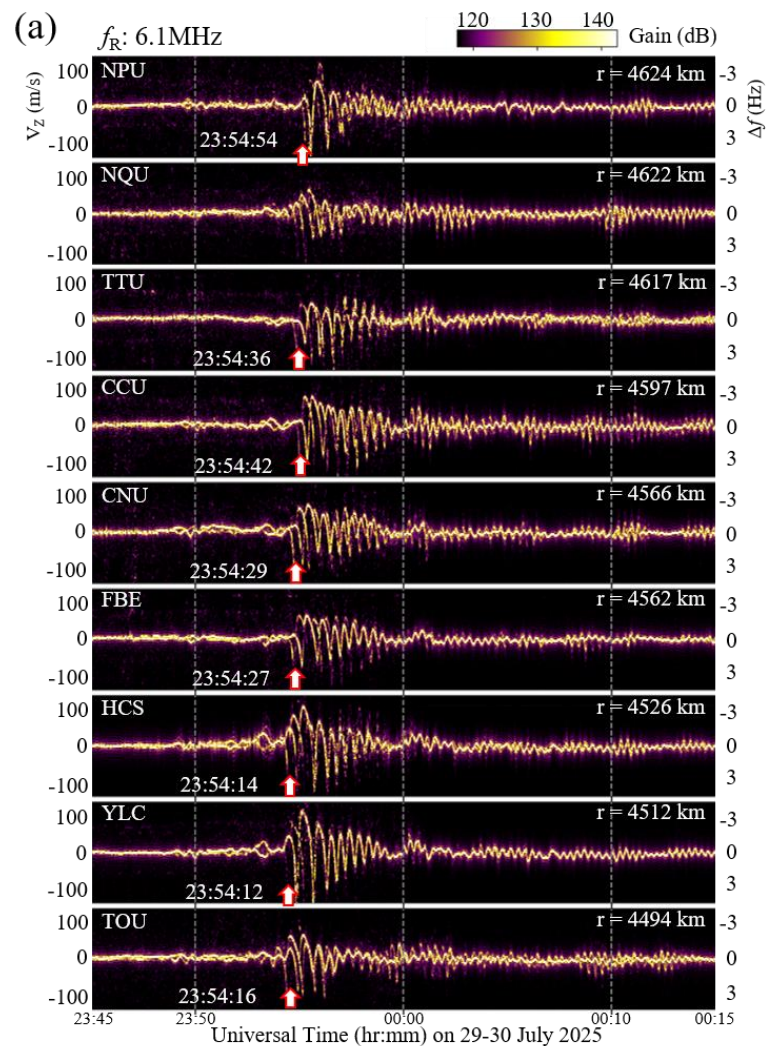
$$V = v\lambda = \frac{1}{T} \lambda$$

$$\text{Period: } T = \frac{\lambda}{V} = \frac{16200 \text{ (m/s)}}{405 \text{ (m)}} \approx 40 \text{ (sec)}$$



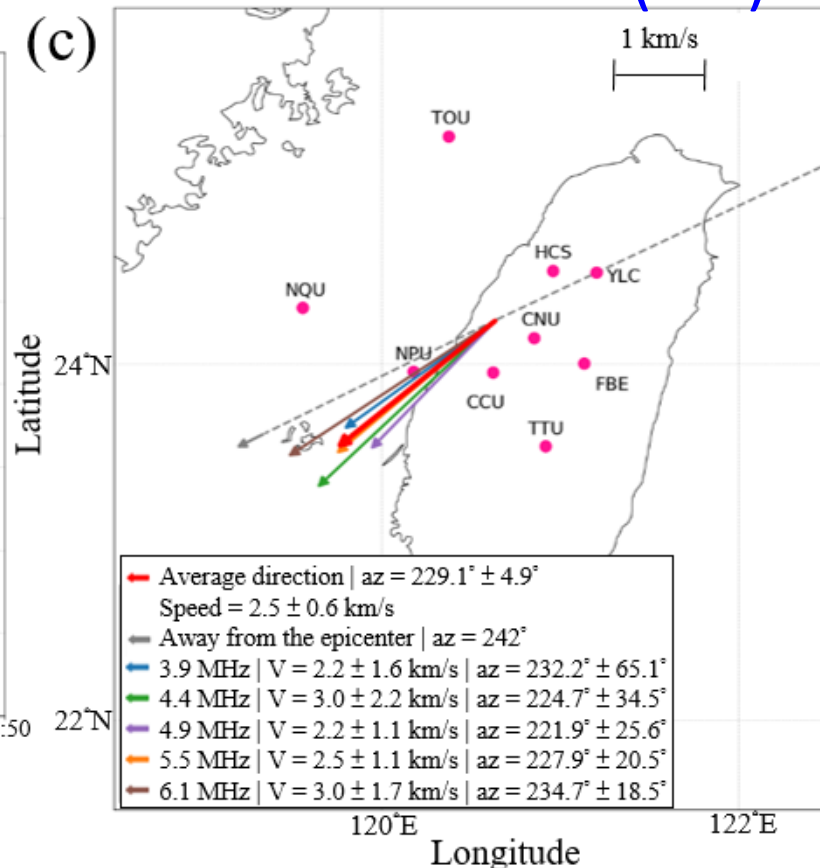
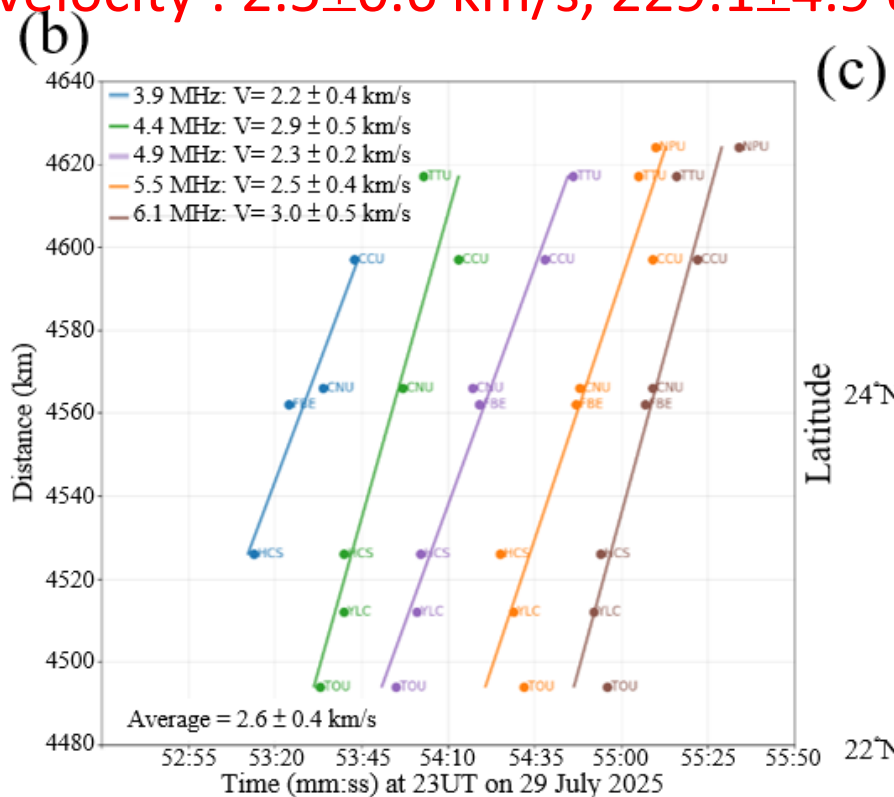
(d) A local ionogram together with its true height profile. (e) The upward speed over the nine receiving stations. Red arrows denote the arrival time of STIDs in DFSs and seismic waves.

The Horizontal Propagation of Seismo-TIDs in DFSs



The great circle horizontal speed in STIDs of 3.7 km/s .

The average horizontal Speed $2.6 \pm 0.4\text{ km/s}$ $\lambda = 2.5 \sim 3.7 \times 20$
(velocity : $2.5 \pm 0.6\text{ km/s}$, $229.1 \pm 4.9\text{ deg.}$). $= 50 \sim 74\text{ (km)}$

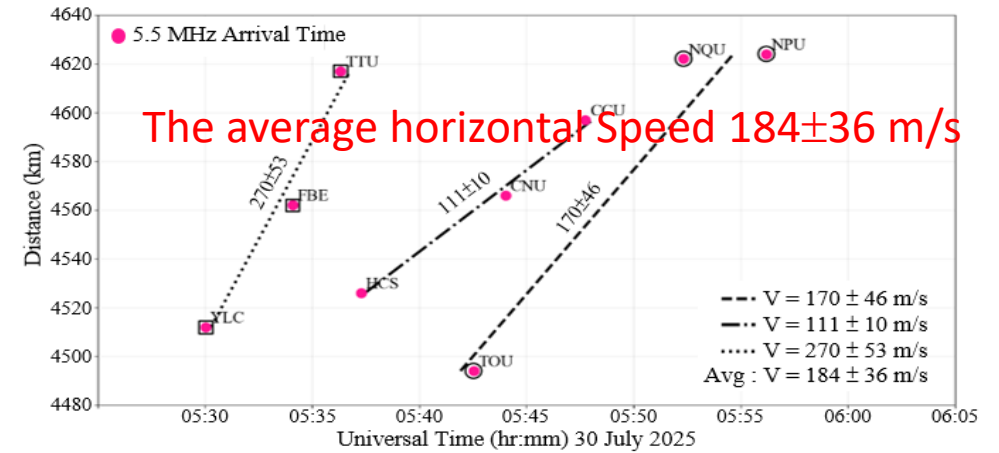
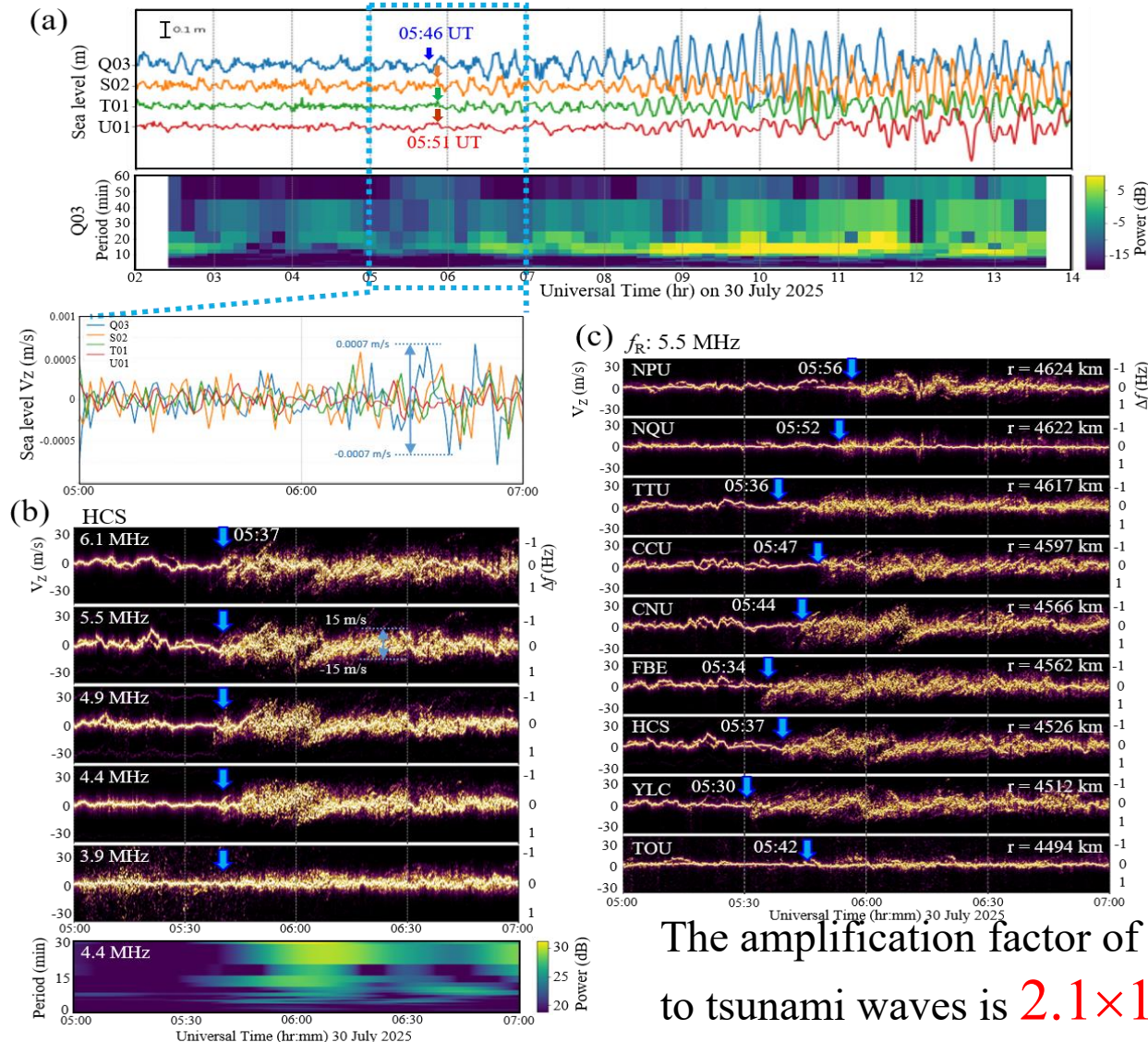


(a) DFSs at 6.1 MHz sounding frequency recorded by the nine receiving stations. The horizontal speeds obtained by (b) the plane wave assumption and (c) TDOA at the height of five sounding frequencies. Red dots denote latitude-longitude locations of the nine reflection points.

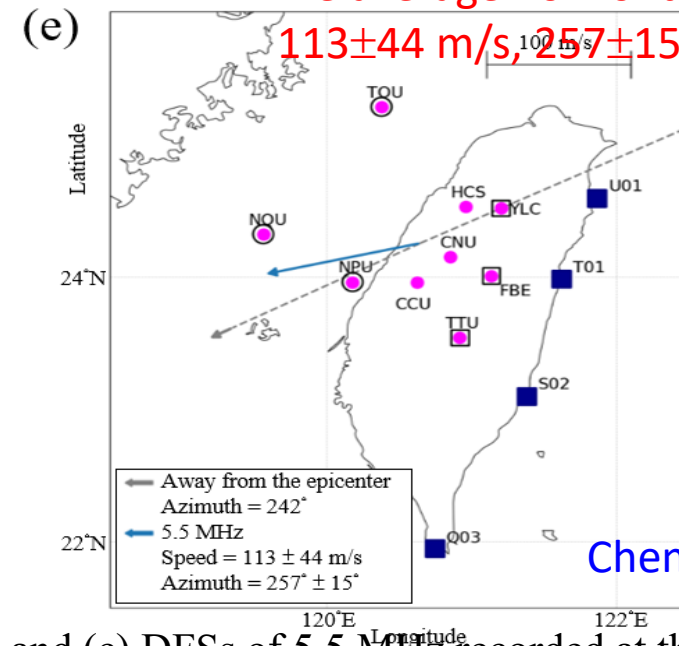
Chen et al. (GRL 2026)

The Horizontal Propagations in Tsunami-TIDs of DFSs

The great circle horizontal speed of tsunami waves, 207 m/s



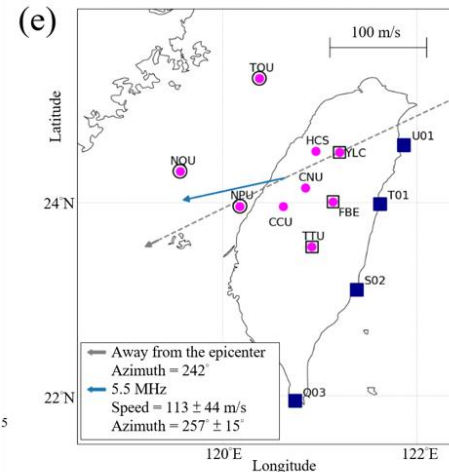
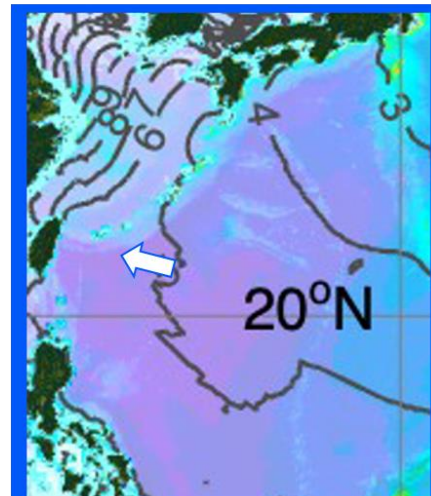
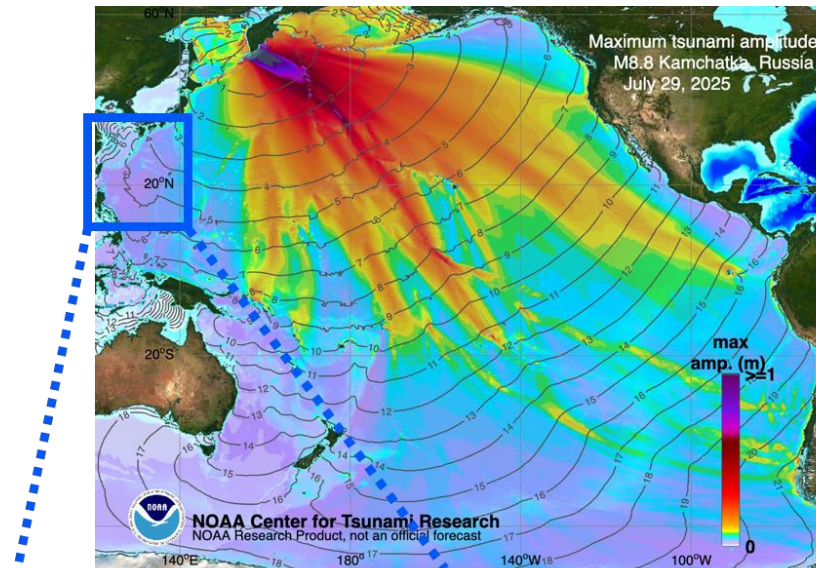
The average horizontal Velocity:
 113 ± 44 m/s, 257 ± 15 deg



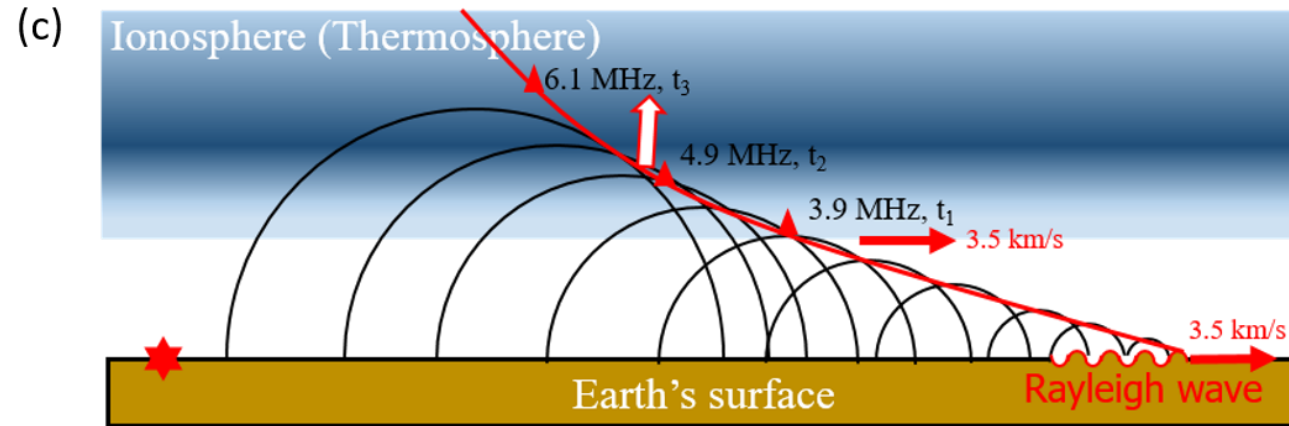
Chen et al. (GRL 2026)

(a) Sea level fluctuations, (b) TTIDs in DFSs of the five frequencies recorded at HCS, and (c) DFSs of 5.5 MHz recorded at the nine receiving stations. (d) Speeds derived by the plane wave approach and (e) the velocity computed by TDOA. Light-blue arrows denote the arrival times.

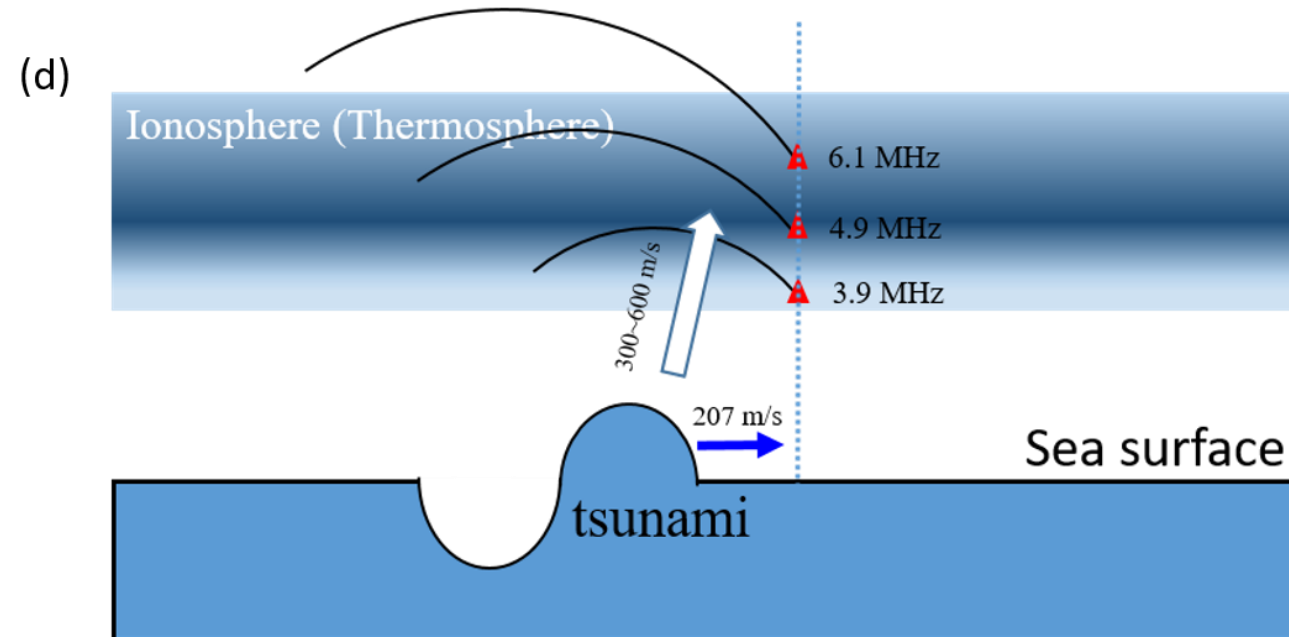
The Horizontal Propagations of Tsunami and TTIDs of DFSs



Sketches of (c) STID and (d) TTID Propagations



The amplification factor of STIDs to seismic waves is 3.6×10^4 .



The amplification factor of TTIDs to tsunami waves is 2.1×10^4 .

Remark 3

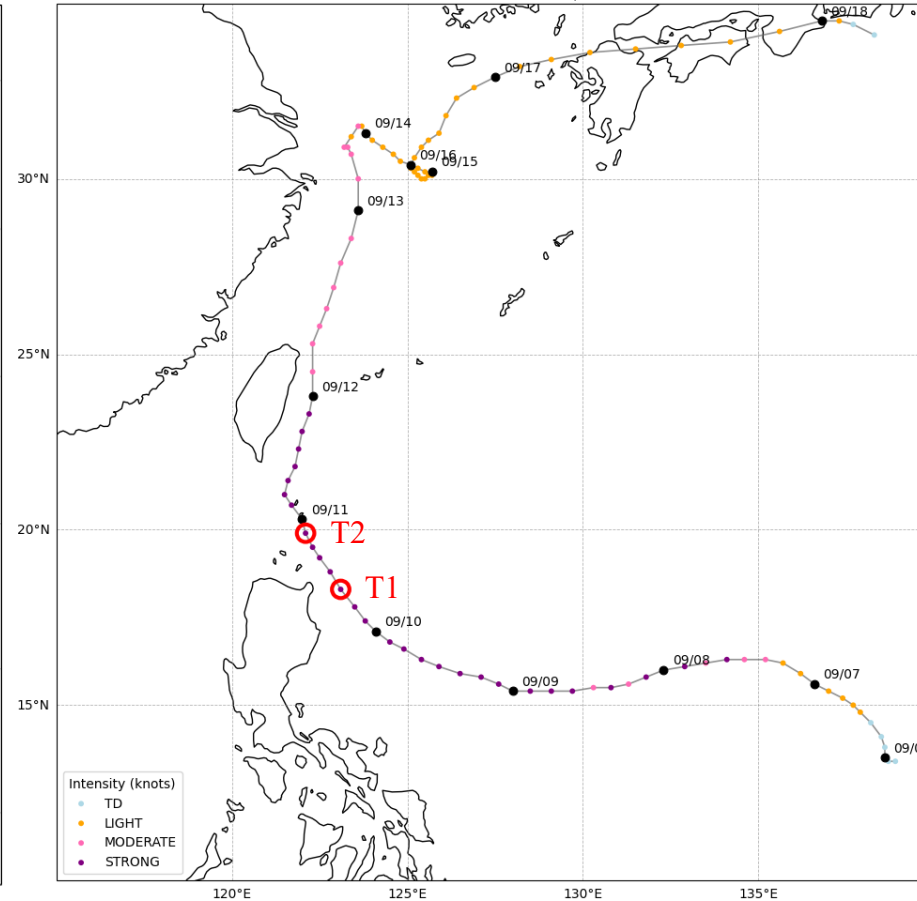
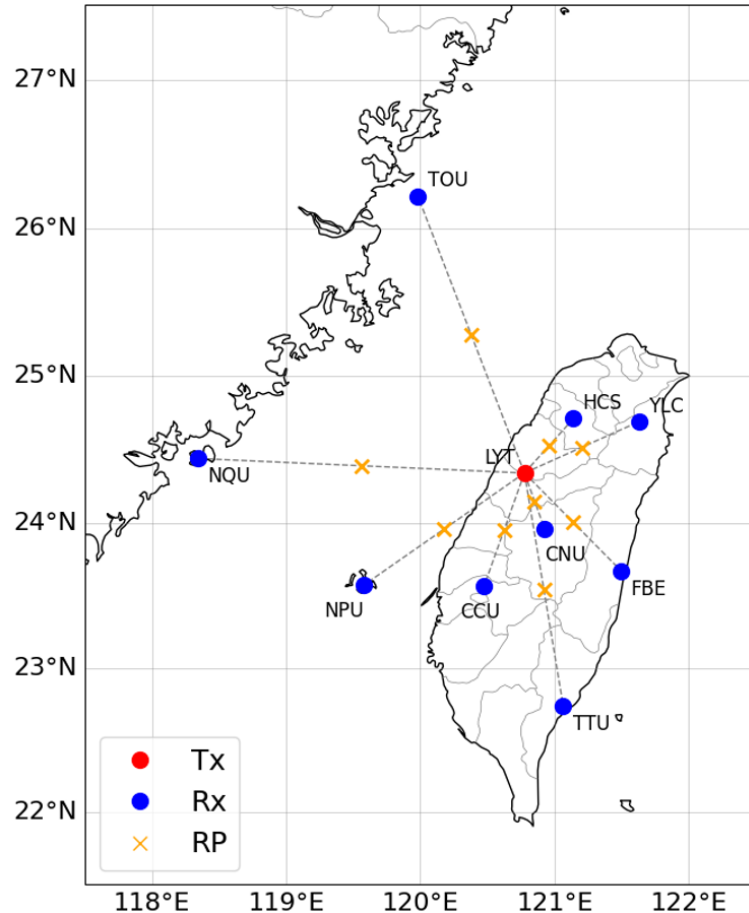
- The origin of tsunami-induced ionospheric disturbances matches the tsunami source inverted from deep-ocean pressure data.
- The supersonic front induced by seismic waves causes STIDs, while acoustic/infrasonic and acoustic-gravity waves triggered by tsunami waves result in TTIDs.
- The STIDs horizontally (upward) travel with the speed of 3.7 or 2.2~3.0 km/s (405 m/s), the wavelength of 74 (16) km, and the period of 20 (40) sec.
- The amplification factor of STIDs (TTIDs) to seismic (tsunami) waves is 3.6×10^4 (2.1×10^4).

Conclusion

- Seismo-ionospheric precursors (SIPs) are often associated with electromagnetic processes of seismo-generated electric fields.
- Seismo and tsunami travel ionospheric disturbances (STIDs and TTIDs) are caused by mechanical processes of the earth's vertical fluctuations.
- The supersonic (shock) front induced by surface seismic (Rayleigh) waves can efficiently trigger TTIDs.

2021.09 Chanthu Typhoon

2021 CHANTHU

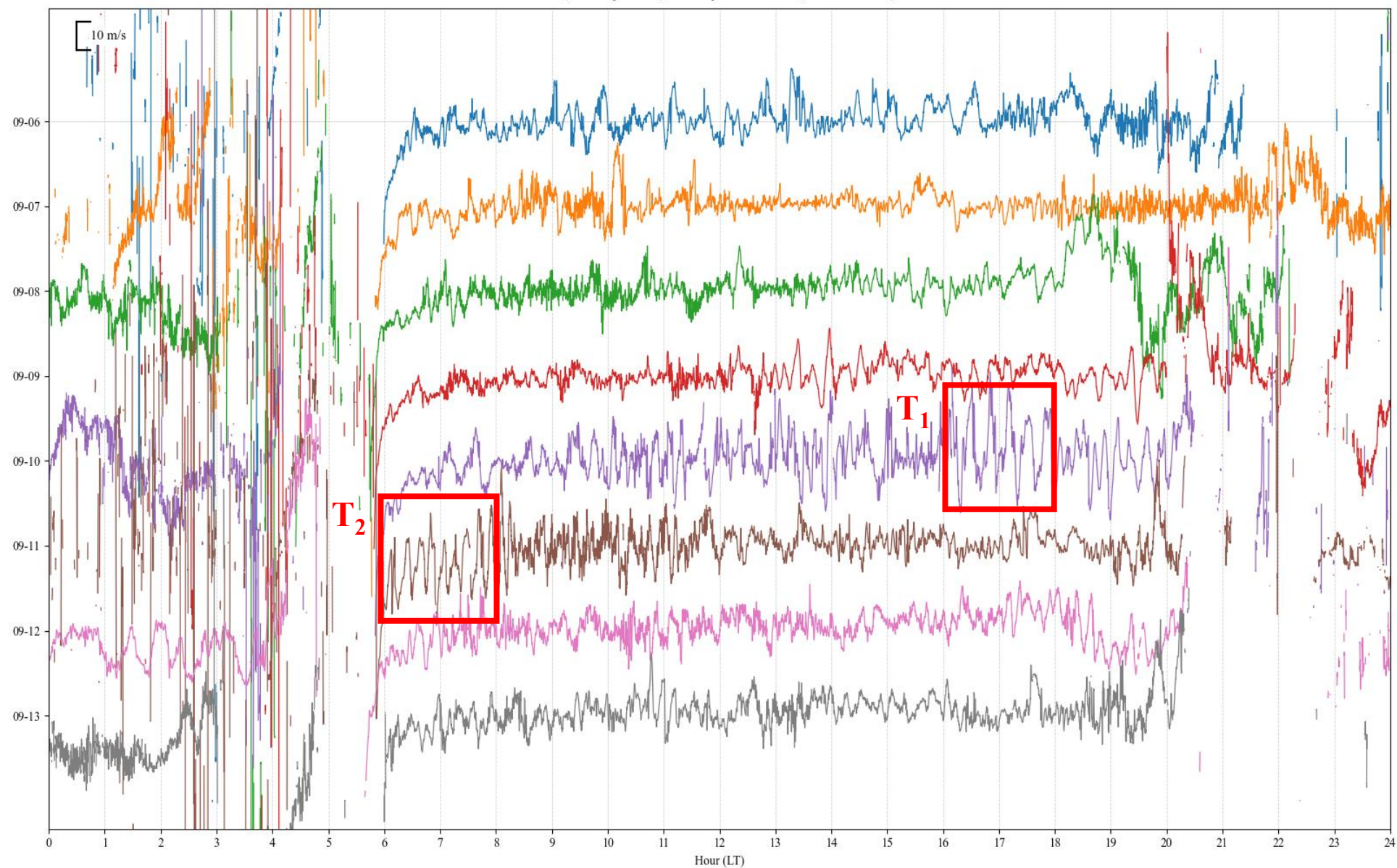


T_1 : 09/10 08:00-10:00 UT 18.3°N 123.1°E

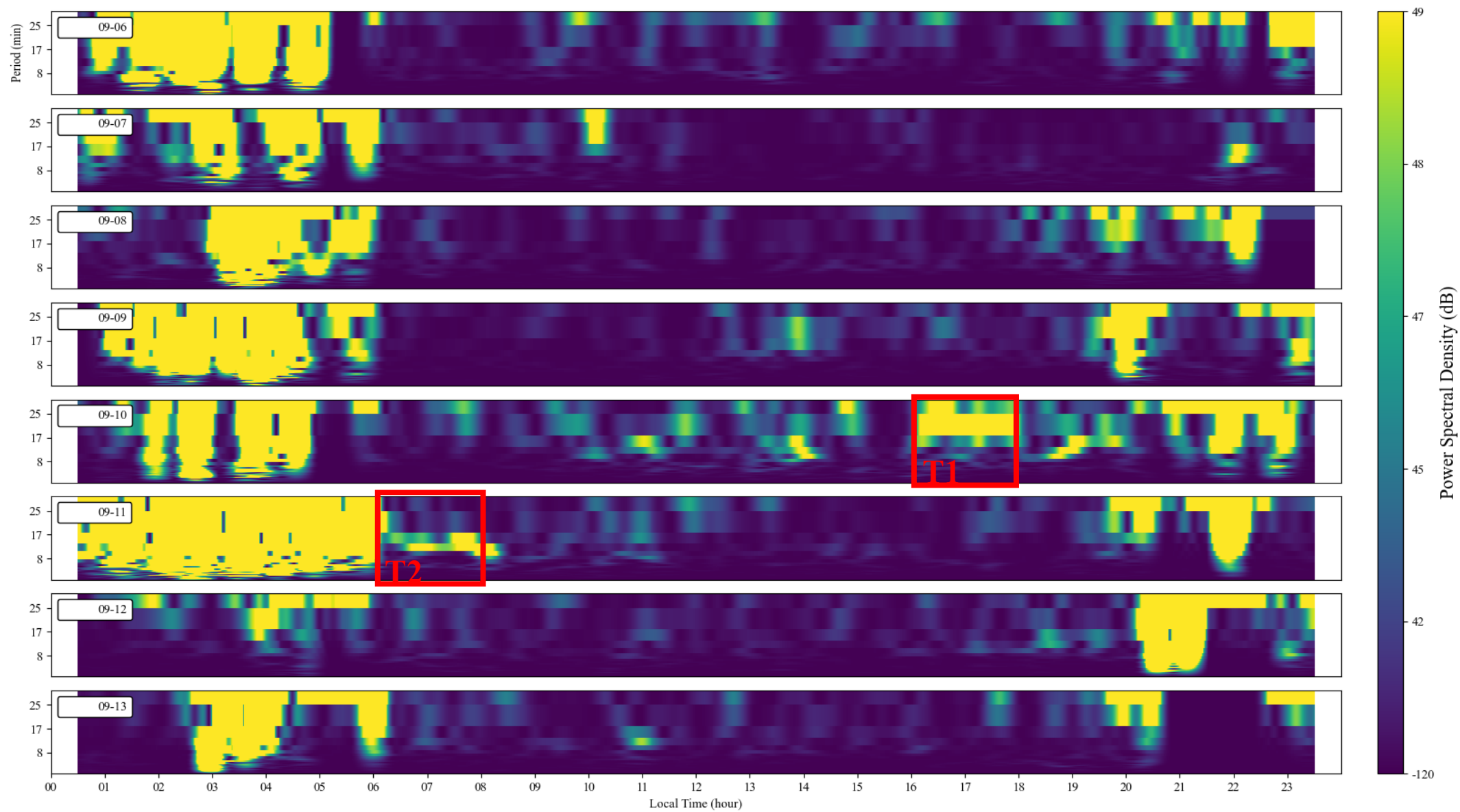
T_2 : 09/10 22:00-24:00 UT 19.9°N 122.1°E

Typhoon Chanthu (2021) was a powerful Category 5-equivalent super typhoon that rapidly intensified and heavily impacted the Philippines, Taiwan, China, and Japan in September 2021.

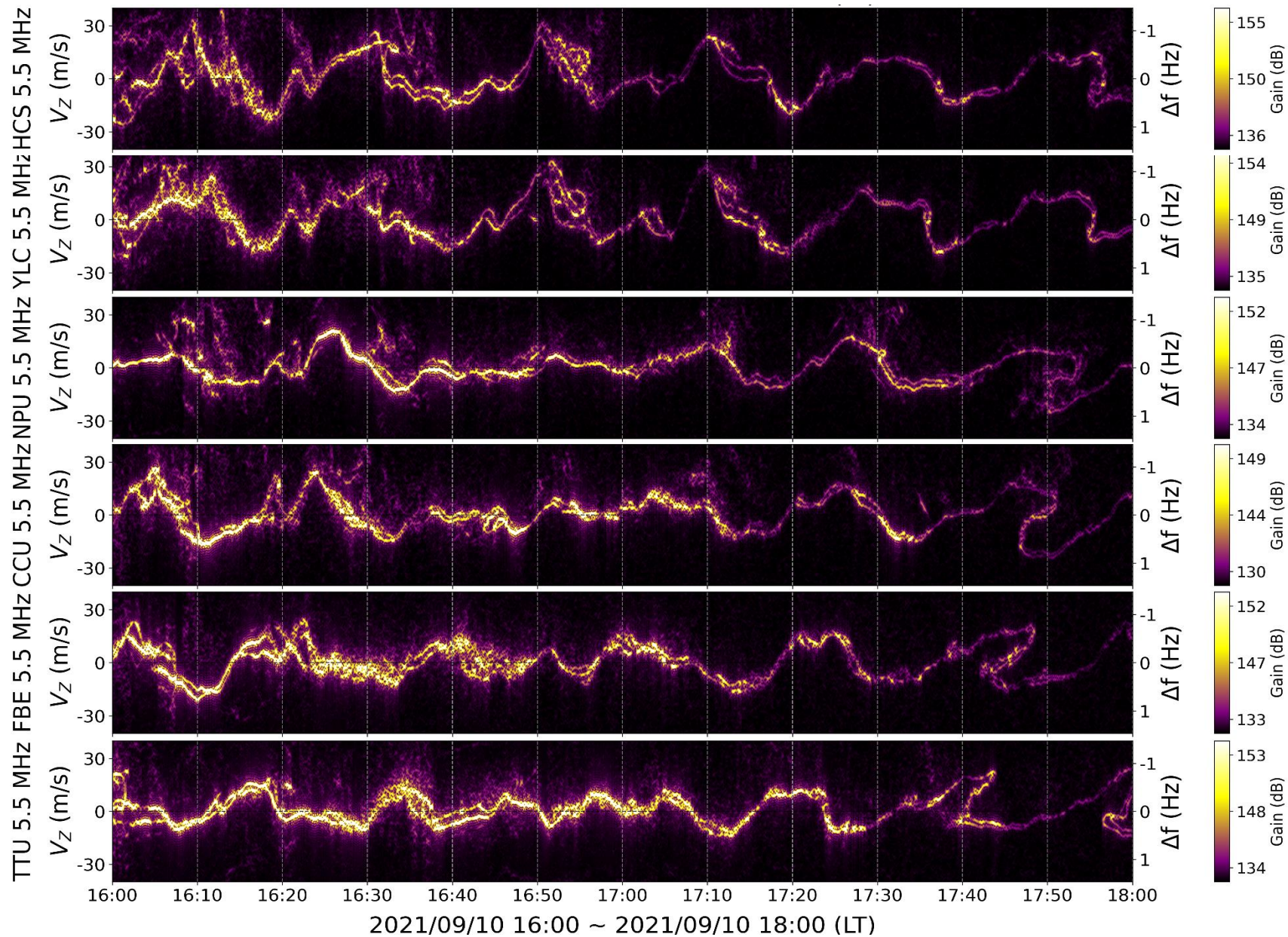
Raw Vz (no interpolation) — 8 days on one axes (Y ticks = dates)



Vz Periodogram — baseline color scale (win=3600 s, step=60 s)

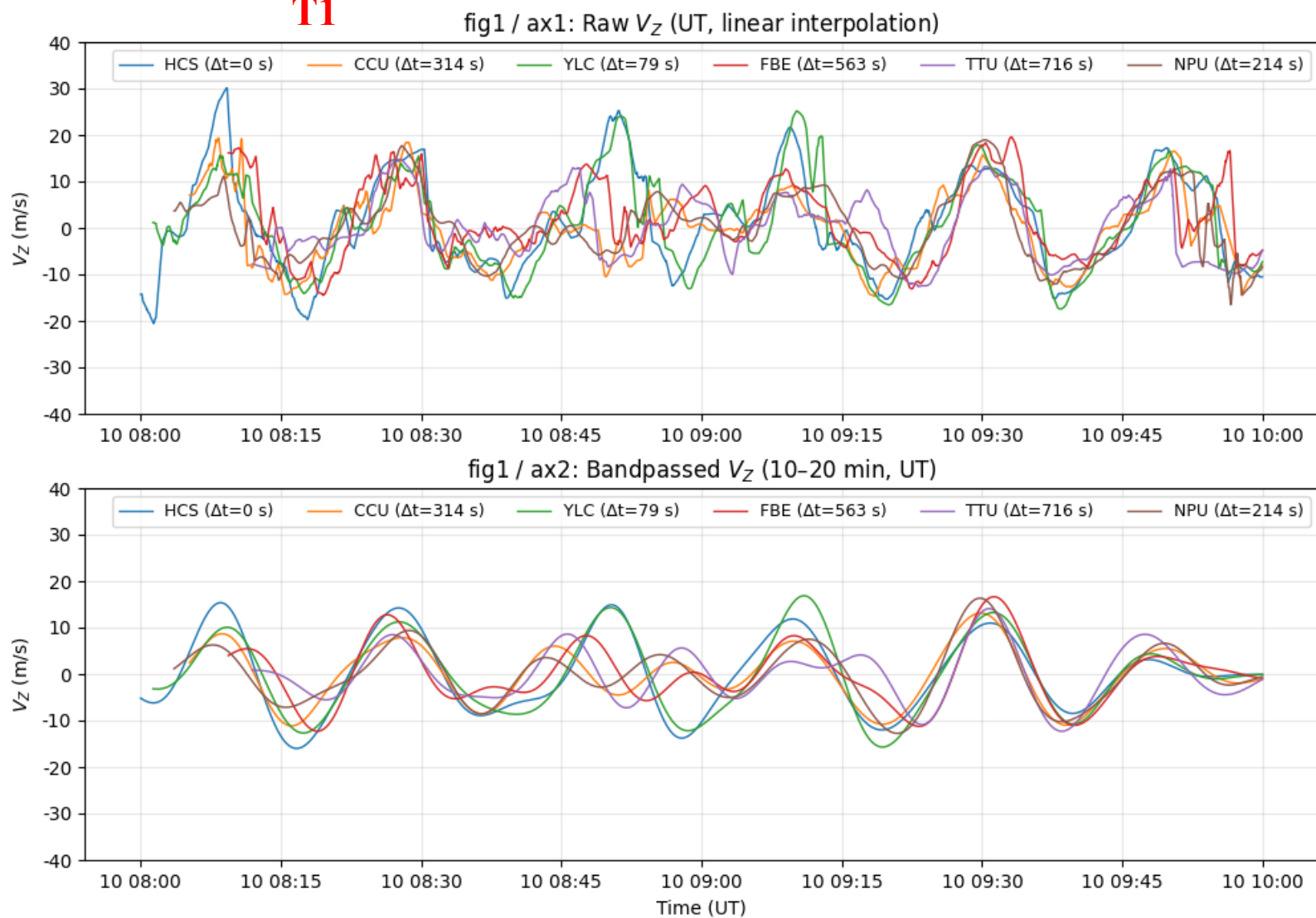


T1



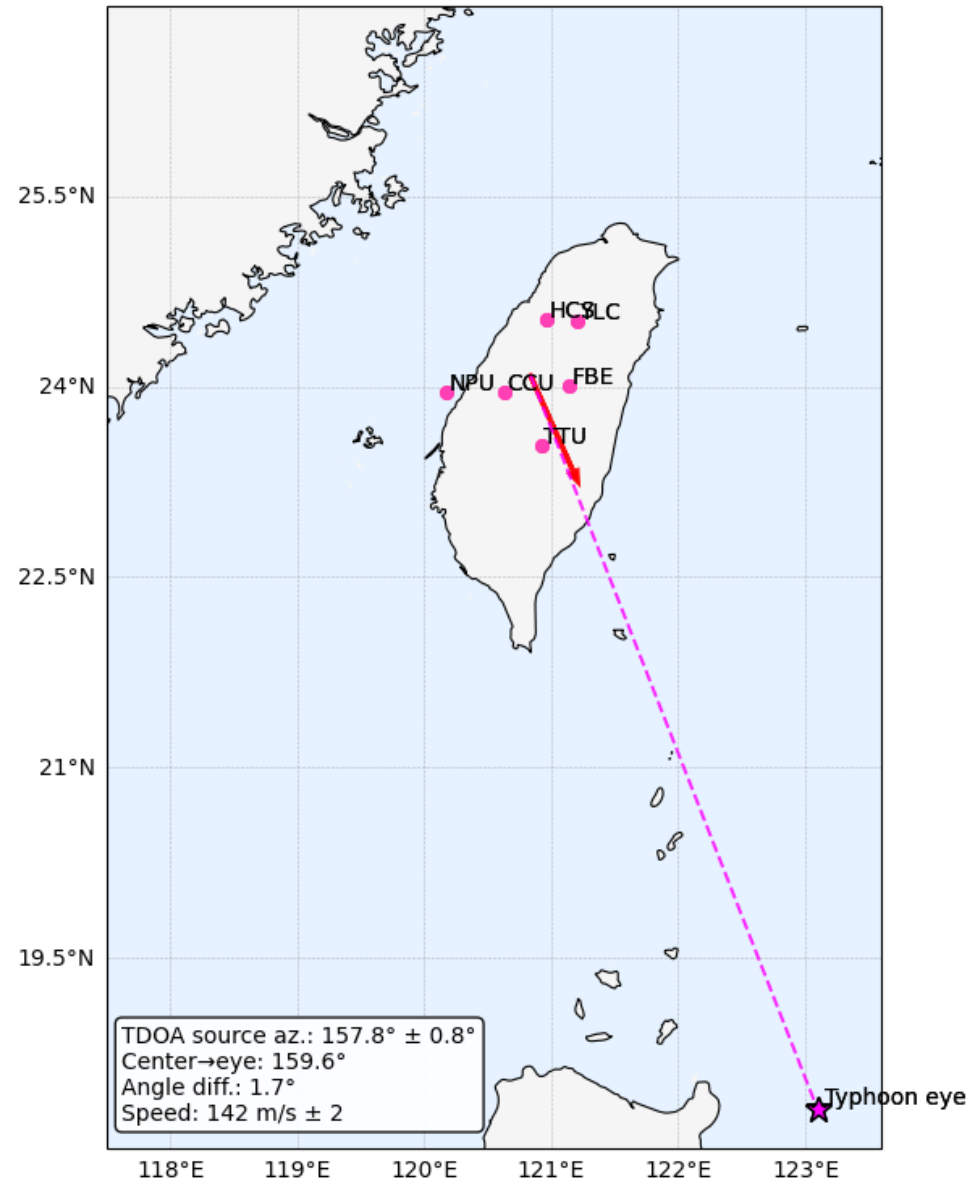
09/10 16-18

T1

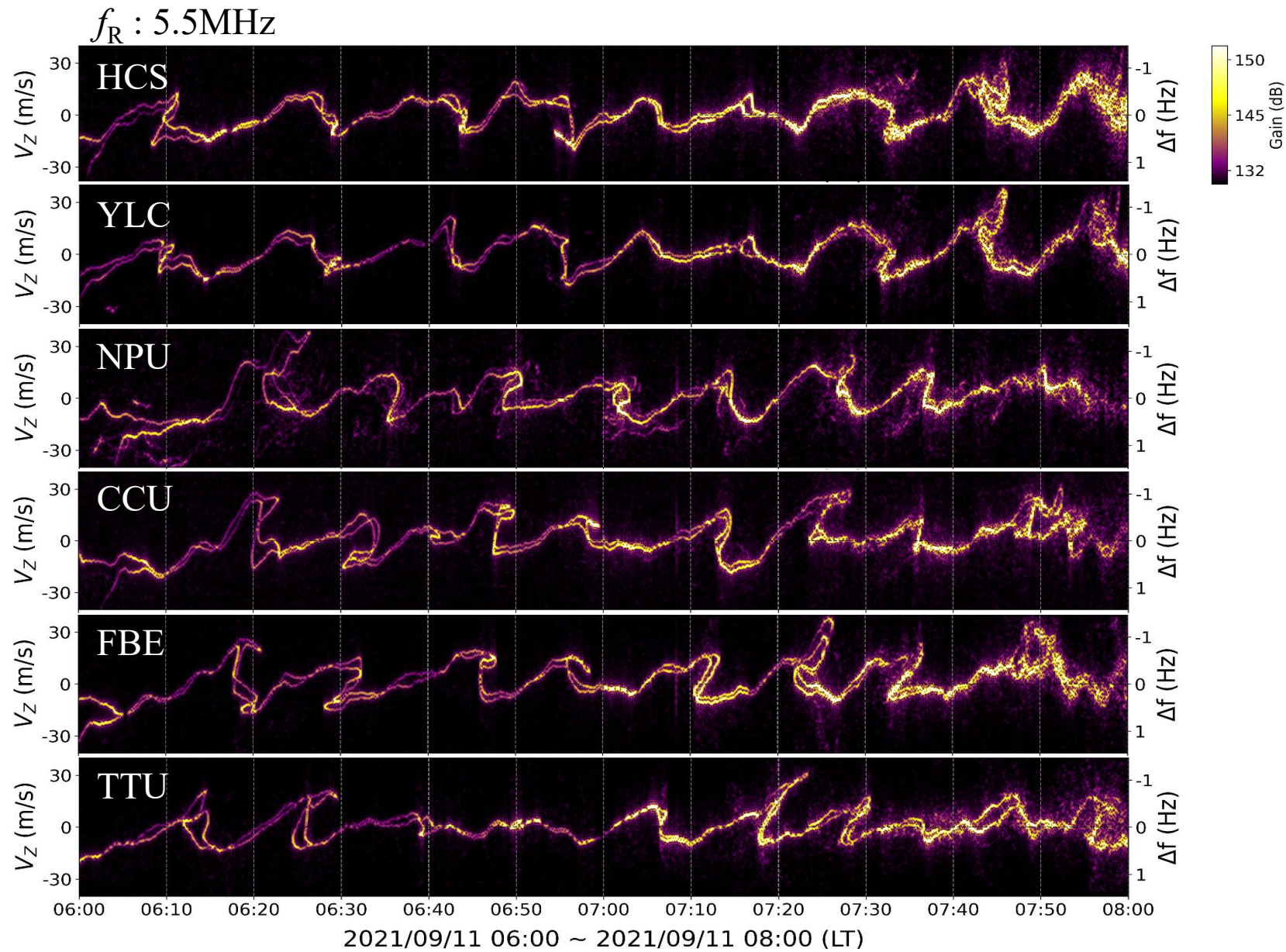


T₁

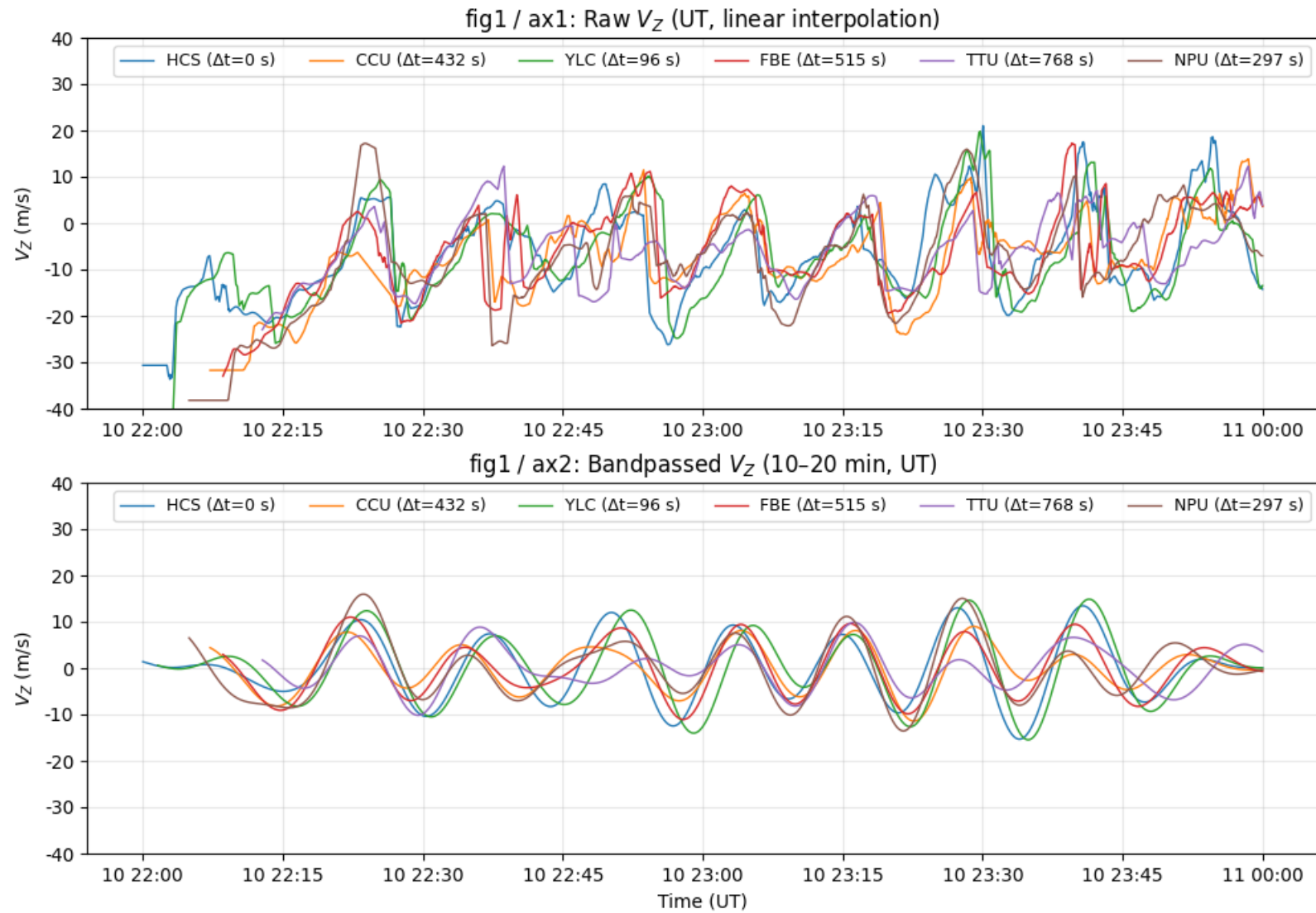
週期 20 min
速度 142 m/s
波長 170 km



T2

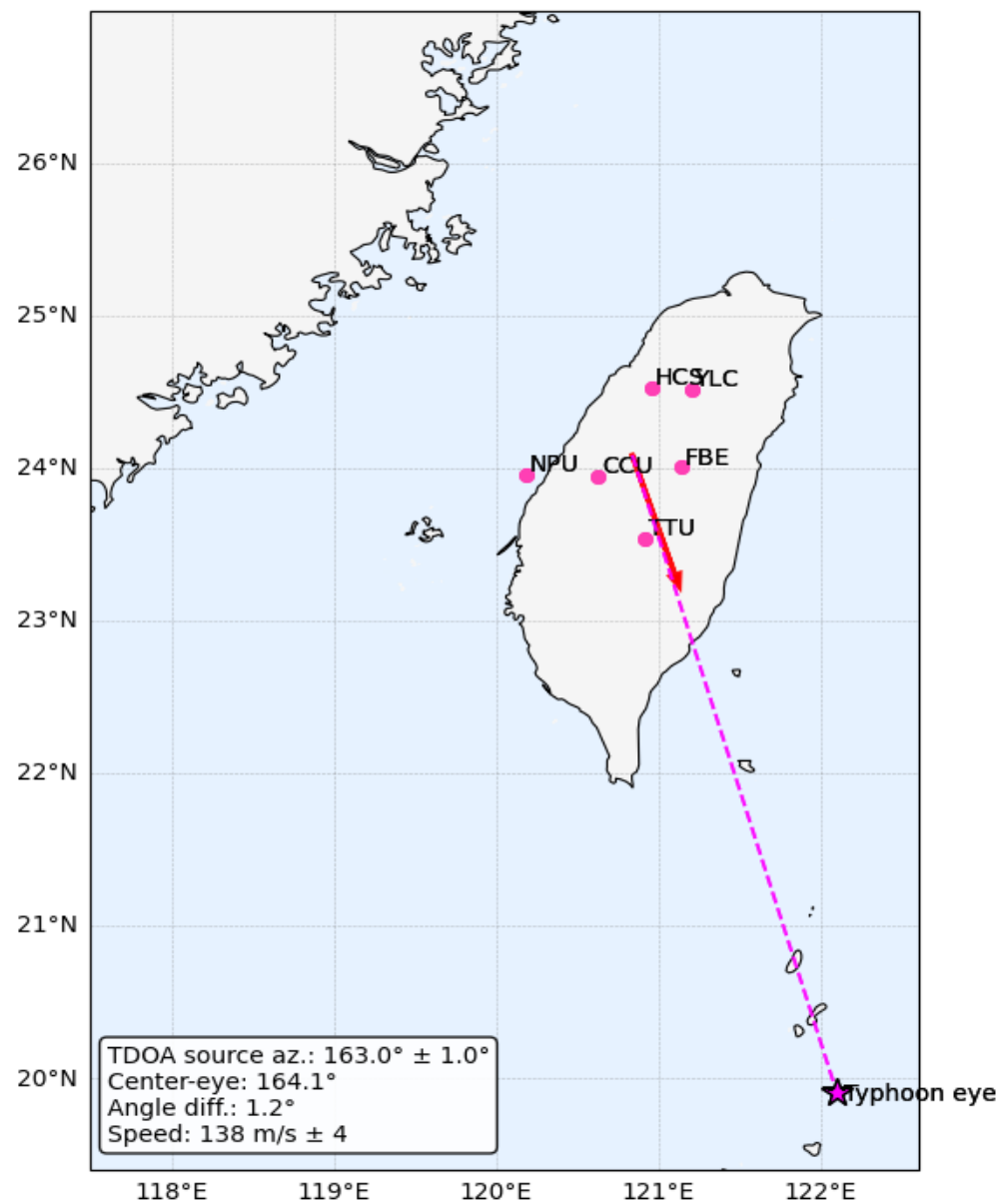


T2



T_2

週期 15 min
速度 138 m/s
波長 124 km



Summary

- Prominent traveling ionospheric disturbances with Doppler shifts greater than 1 Hz and periods of 15-20 minutes induced by the 2021 Chanthu Typhoon observed when the typhoon approaching the Taiwan island.
- The typhoon traveling ionospheric disturbances of T1 and T2 travel with the horizontal speeds of 142 and 138 m/s, and wavelength of 170 and 124 km, respectively.
- Results show the typhoon eye acts a source of gravity waves.