CHARACTERIZING EARTHQUAKES FROM THEIR GNSS-TEC RESPONSE MULTIPLETS

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01 INTRODUCTION

Large earthquakes excite acoustic waves that propagate into the ionosphere, creating Coseismic Ionospheric Disturbances (CIDs). While typically observed as single N-waves, complex ruptures can generate multiplets, multiple Total Electron Content (TEC) peaks. Building on the Noto 2024 case described by Heki (2024) [2], we investigate whether the time delay between peaks encodes fault geometry. We analyze four events where doublet signatures carry spatial information about seismic source complexity.

02 OBJECTIVE

We propose a 2D geometric inversion scheme to retrieve the inter-source distance (L) and rupture orientation from GNSS-TEC multiplets. We evaluate the ionosphere as a remote sensor for earthquake source complexity, particularly for offshore events where terrestrial geodetic networks provide limited coverage.

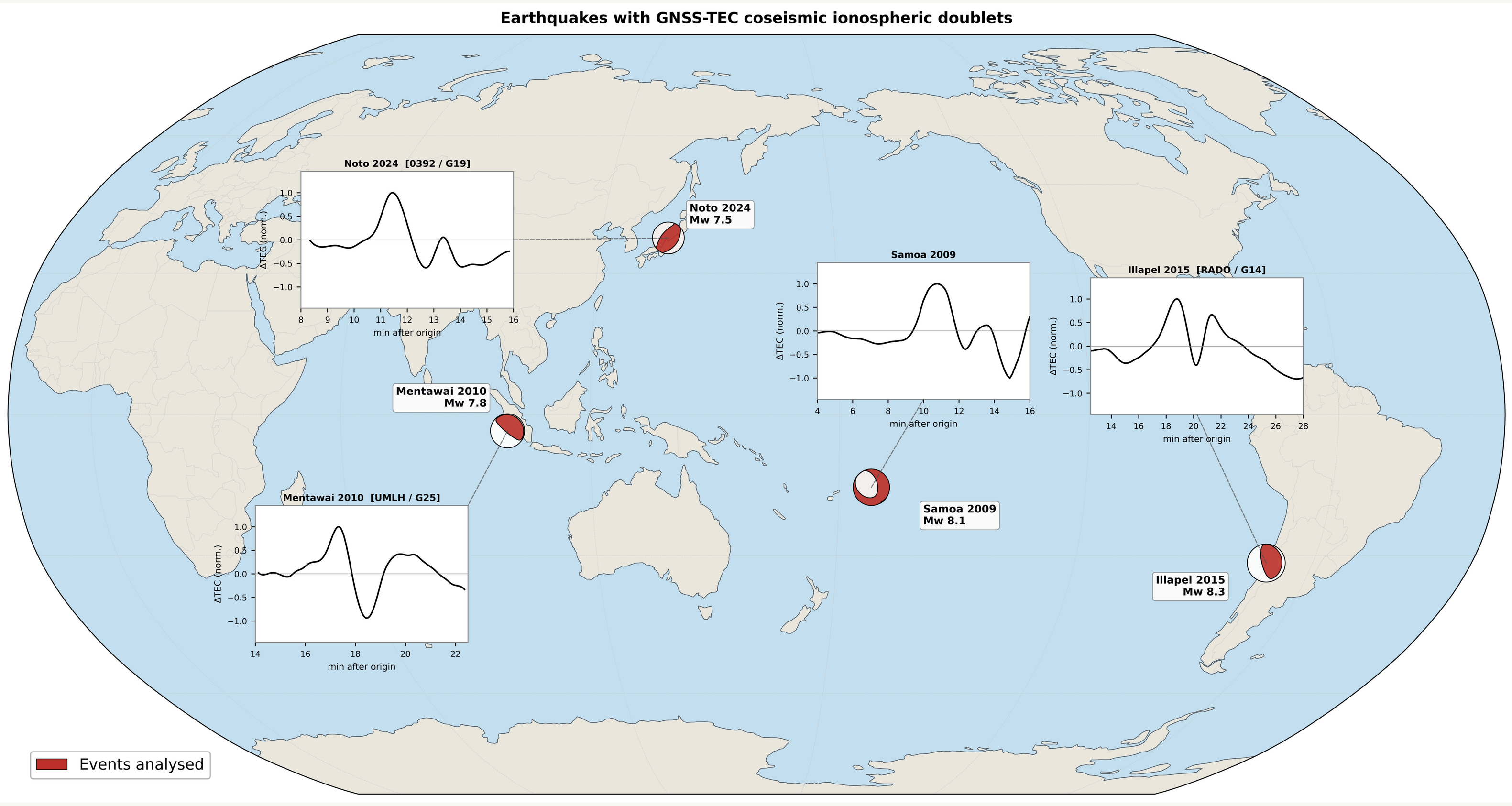

Fig. 1 Global distribution of the analysed earthquakes (red), each with its best-observed GNSS-TEC doublet waveform. Focal mechanisms from GCMT [8].

The ionosphere as a remote sensor for earthquake rupture geometry

03 METHODS

The inversion assumes two spatially separated seismic sources (S_1, S_2) placed symmetrically and equidistant from the catalog epicenter, which serves as the geometric midpoint. The inversion is initialized independently from both USGS and GCMT catalog locations to assess robustness to the choice of reference epicenter. Input data are differential arrival times (Δt) extracted by manual picking of detrended TEC time series [4]. A constant acoustic propagation velocity c = 0.75 km/s converts time delays into path differences. A grid search (0–180°) identifies the optimal rupture azimuth minimizing the location residual across the GNSS network.

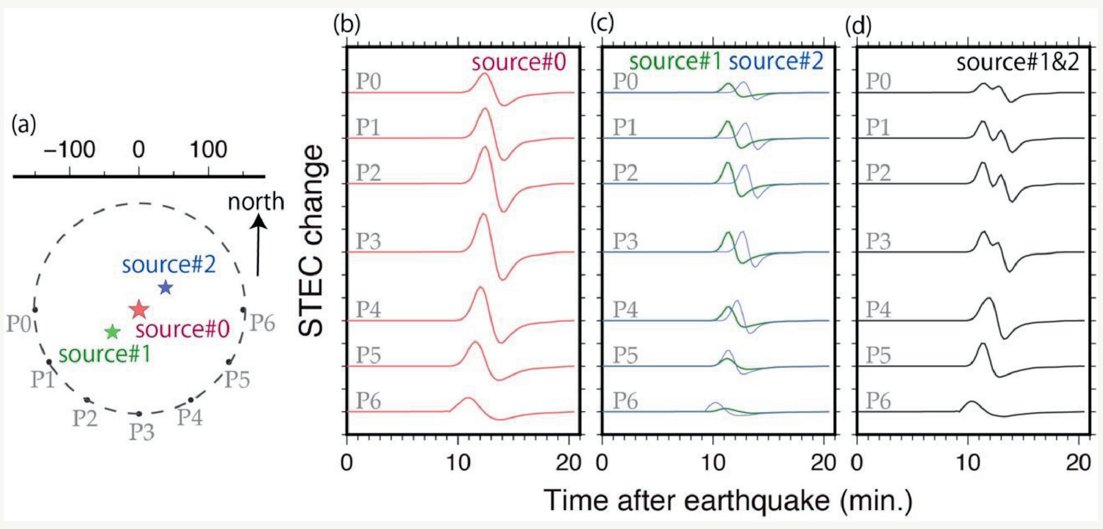

Fig. 2 Synthetic STEC response. A single source (red, b) yields one N-wave; two offset sources (green and blue, c) superpose into a doublet (d) whose peak separation depends on viewing azimuth . Figure from Heki (2024) [2] (Fig. 7).

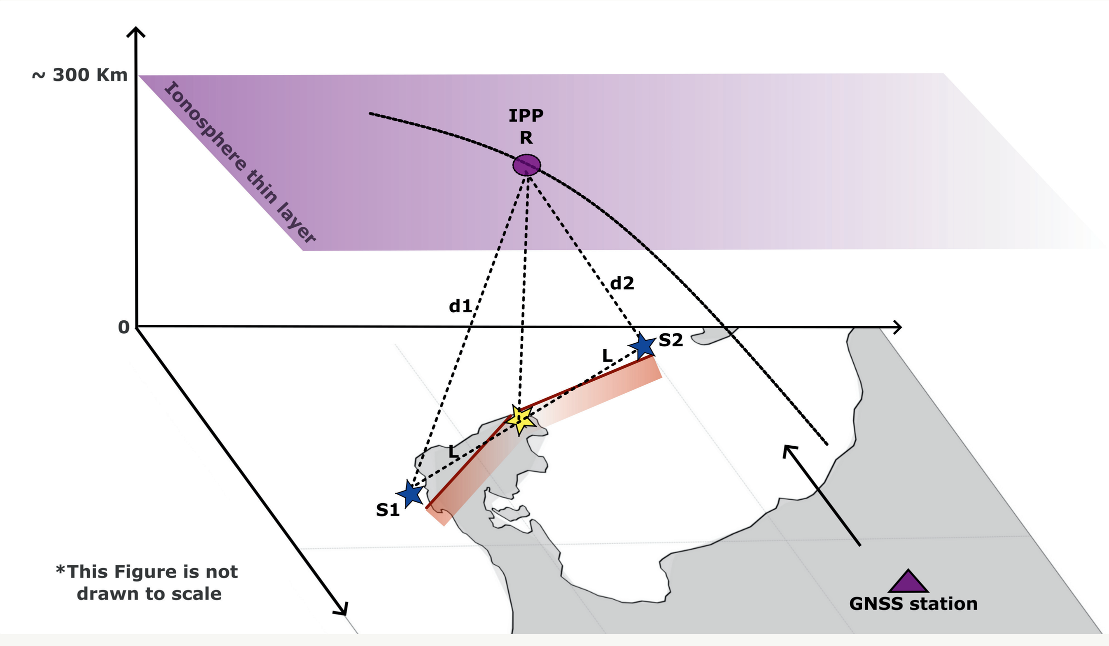

Fig. 3 Inversion geometry. Differential paths (d1, d2) from sources S1, S2 to the Ionospheric Pierce Point (IPP) at H=300 km constrain the inter-source distance L.

04 RESULTS

Doublet signatures were inverted for Samoa Mw 8.1, Mentawai Mw 7.8, Noto Mw 7.5, and Illapel Mw 8.3 earthquakes. Inverted distances and azimuths show good agreement with seismological literature for Noto [2,5] and Samoa [1]; partial agreement is found for Mentawai [7] and Illapel [3,6].

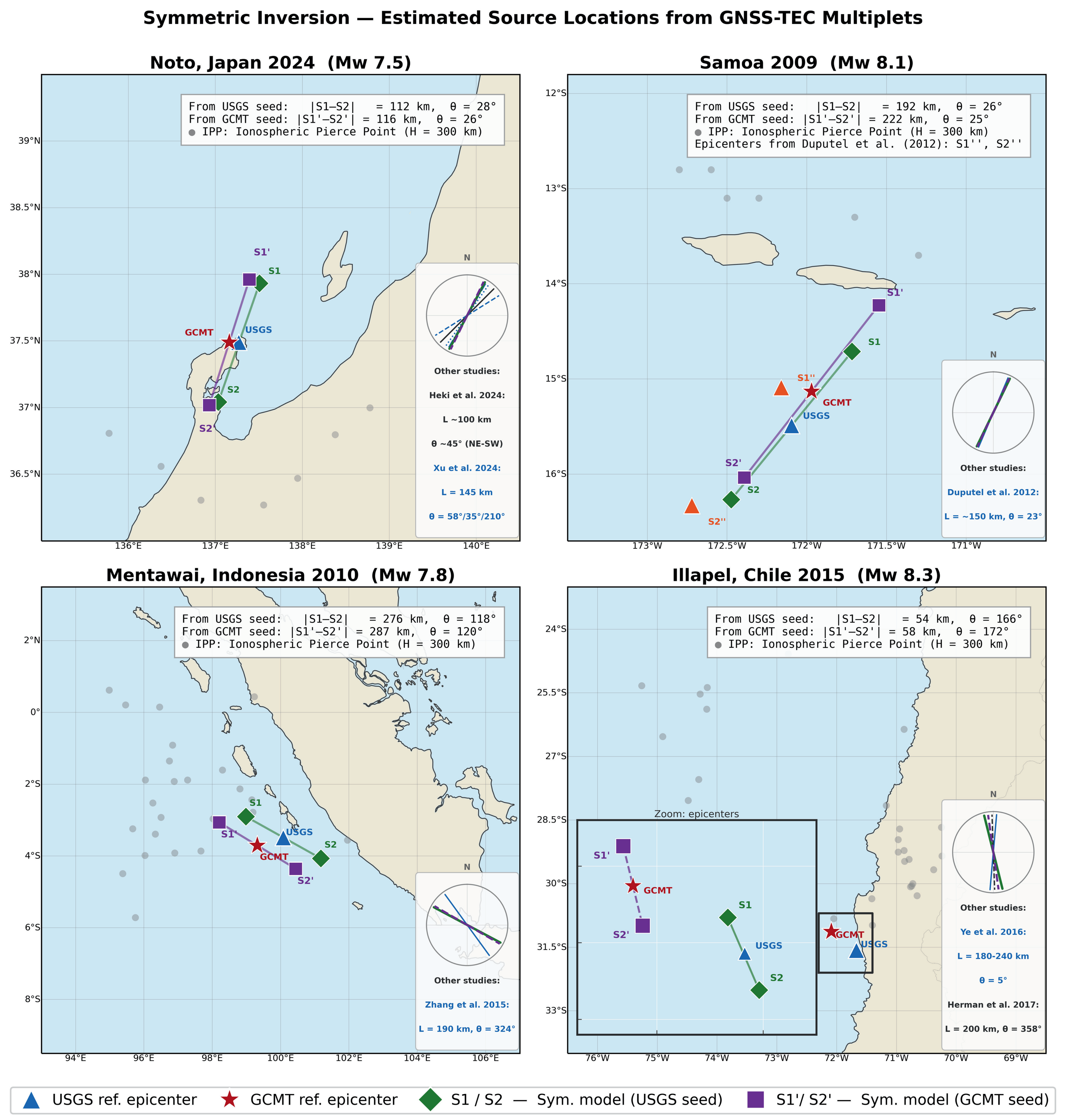

Fig. 4 Symmetric inversion. Estimated source locations from GNSS-TEC multiplets, seeded from USGS and GCMT reported epicenters, with diagrams comparing recovered azimuths (in purple and green) to published models (in blue and black) in the inset panels [1,2,3,5,6,7]. Measurement points are shown with grey dots.

05 CONCLUSIONS

- GNSS-TEC multiplets are **direct ionospheric manifestations** of seismic rupture complexity and spatially distributed slip.
- Results are **robust to the choice of reference catalog** (USGS vs. GCMT), with differences < 30 km and < 6° across all events.
- Visibility of differential arrival times depends critically on the **azimuthal distribution** of the GNSS network relative to fault orientation.
- The symmetric geometric inversion recovers inter-source distances and orientations **consistent with seismological models** (Noto and Samoa) ; partial agreement for Mentawai and Illapel motivates the asymmetric case.
- Ionospheric monitoring is a **complementary tool** for characterization of offshore earthquake geometry.
- **Future work**: incorporate asymmetric bilateral ruptures and explore a model with variable rupture initiation times.

06 REFERENCES

[1] Duputel, Z. et al. (2012). Geophys. J. Int., 189(2), 1125–1147. https://doi.org/10.1111/j.1365-246X.2012.05419.x
[2] Heki, K. (2024). Earth Planet. Sci. Lett., 640, 118796. https://doi.org/10.1016/j.epsl.2024.118796
[3] Herman, M. W. et al. (2017). J. Geophys. Res. Solid Earth, 122(6), 4691–4711. https://doi.org/10.1002/2016JB013617
[4] Twardzik, C. et al. (2025). EGUsphere [Preprint]. https://doi.org/10.5194/egusphere-2025-5088
[5] Xu, L. et al. (2024). Science, 385(6711). https://doi.org/10.1126/science.adp0493
[6] Ye, L. et al. (2016). Pure Appl. Geophys., 173(2), 321–332. https://doi.org/10.1007/s00024-015-1202-y
[7] Zhang, L. et al. (2015). Geod. Geodyn., 6(3). https://doi.org/10.1016/j.geog.2015.03.005
[8] Ekström, G. et al. (2012). Phys. Earth Planet. Inter., 200–201, 1–9. https://doi.org/10.1016/j.pepi.2012.04.002

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