Improved Detection of Ionospheric Disturbances using Optimal Line-of-sight Geometries of TEC Measurements

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Scope: This study examines how line-of-sight (LOS) geometry affects GNSS Total Electron Content (TEC) observations of ionospheric disturbances over the continental US, aiming to identify the most effective LOSs which can vary for disturbances of different nature. Results are presented for traveling ionospheric disturbances (TIDs) driven by different natural phenomena, but focus will be on TEC signatures of ULF waves during a sudden commencement.
Problem: Conventionally, when using TEC measurements to observe ionospheric disturbances, all measurements are treated as equivalent, overlooking geometry differences (elevation and azimuth angles of LOSs). **However, while only some LOSs are aligned with the plasma fluctuations and can effectively measure them, others may fail due to cancellation effects.**
Significance: Using only TEC measurements that effectively capture ionospheric disturbances driven by a given phenomenon allows for a more accurate representation and characterization of the disturbances. Understanding which LOS geometries are sensitive to different types of ionospheric disturbances can, in turn, improve a range of applications that utilize TEC measurements.

TEC Measurements and Cancellation Effects

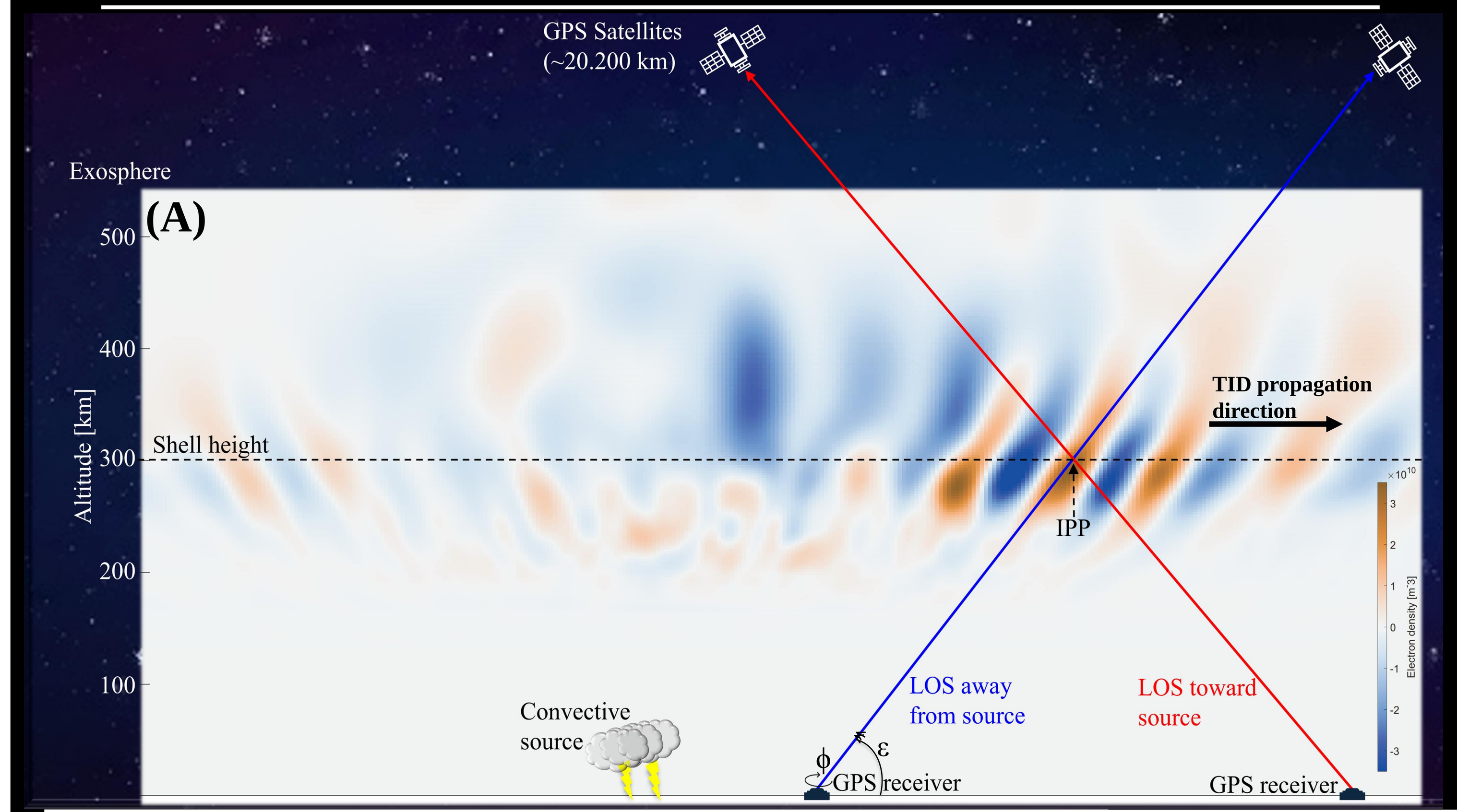
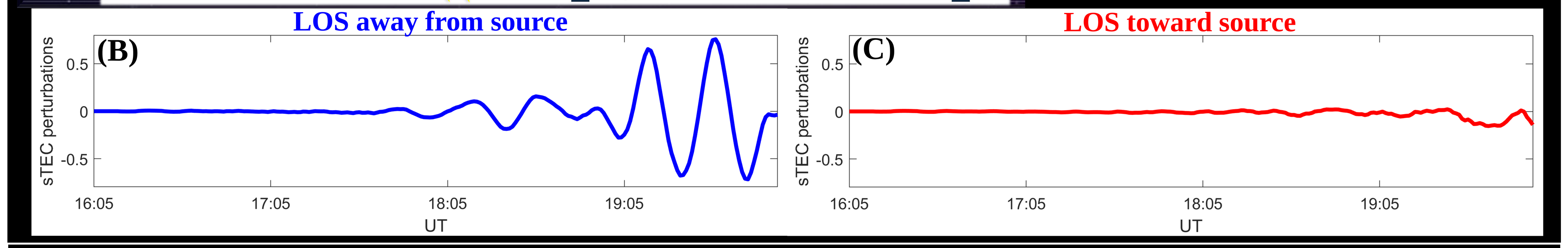


Figure 1 – (A) Illustration showing an altitude-longitude slice from a simulation of TIDs driven by convectively-generated gravity waves (GWs). It further exhibits two LOSs having the same elevation angle and share the same IPP. However, **when it comes to observing the TIDs, their azimuth orientation is critical.** The one **oriented toward the convective source (red) gets integrated to near-zero value (suffers cancellation effects)**, rendering it ineffective for observing the TIDs as shown in panel (C), but the one **oriented away from the source (blue) is more aligned with the phase fronts and can observe the TIDs effectively,** as shown in panel (B).



Observational Results – Effects of LOS Orientation on TID Observations

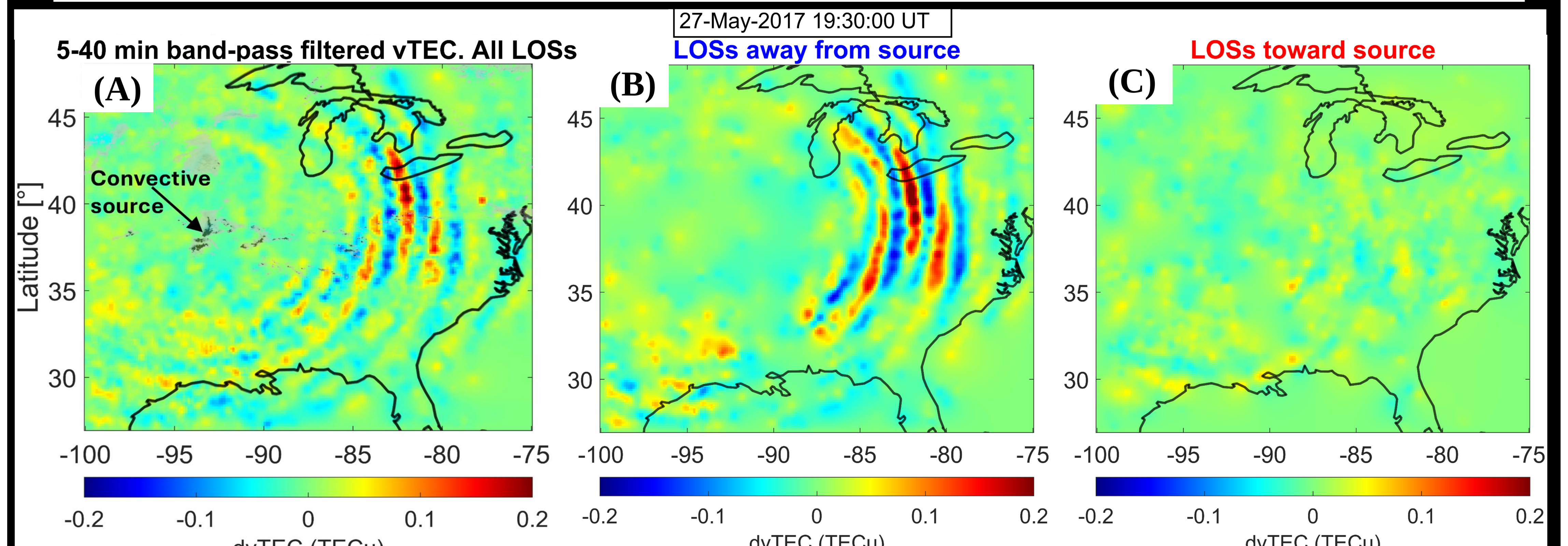


Figure 2 – Three vTEC maps of GW-driven TIDs, constructed using: (A) all LOSs, (B) only LOSs oriented away from the source, (C) only LOSs toward the source. **LOSs in (C) fail to observe the TIDs due to cancellation effects. Including all LOSs (A) degrades the visualization compared to (B).**

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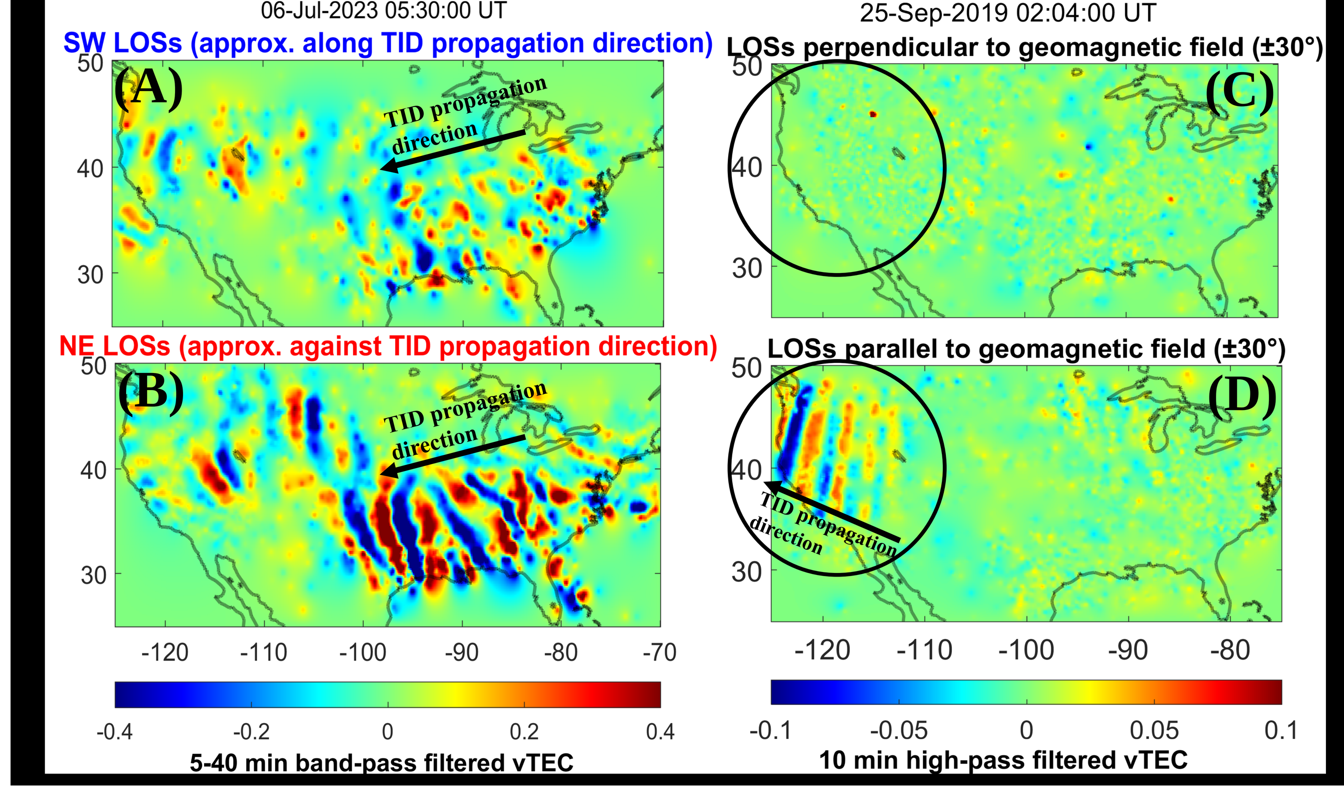

Figure 3 – Preliminary results **illustrating LOS effects for TIDs driven by different processes.** (A) and (B) show TEC maps of electrified MSTIDs, where (A) is constructed from LOSs oriented along their propagation direction and (B) from LOSs oriented against it. The latter appear more effective. (C) and (D) show TEC maps of TIDs presumably originating from magnetospheric sources constructed from LOSs perpendicular (C) and parallel (D) to the geomagnetic field. Only the parallel LOSs can capture these signatures. These results demonstrate that **TIDs of different origins have distinct optimal LOS orientations, which depends on their underlying physical mechanisms.**

Event Overview: Sudden Commencement Following an Interplanetary Shock

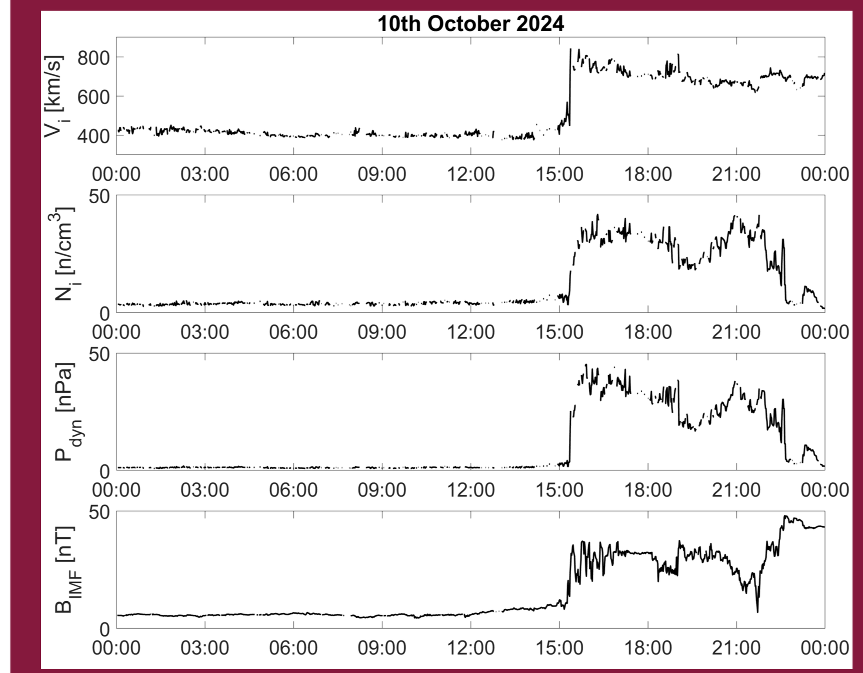

Figure 4 – Time-shifted solar wind and IMF data indicating an **interplanetary shock arrival at ~15:15 UTC.** Data from NASA OMNI database (King and Papitashvili, 2005).

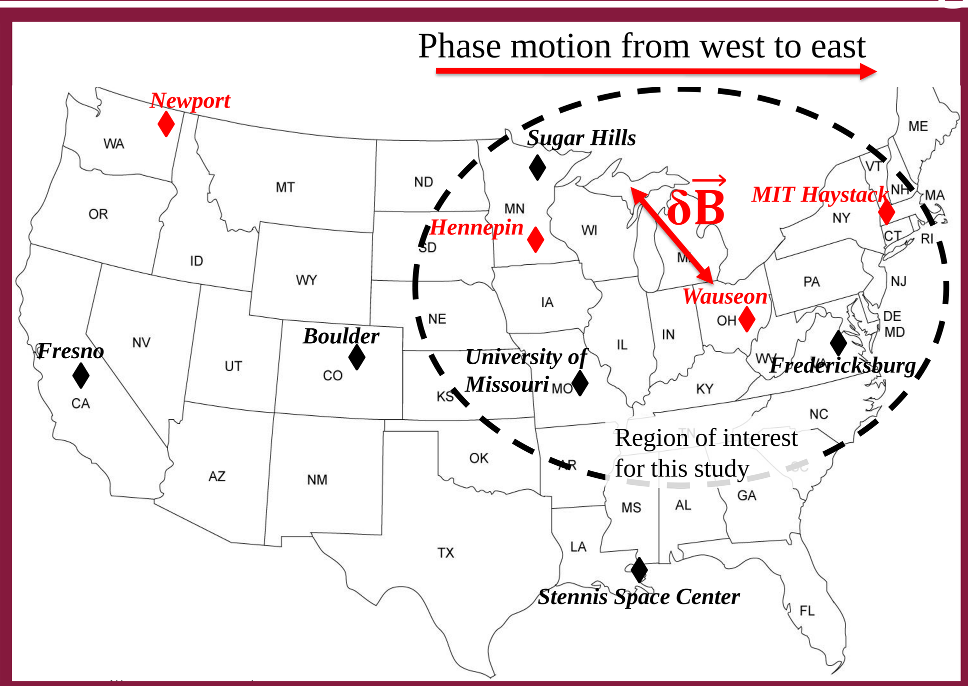

Figure 5 – Locations of ground magnetometers used in the study. The symbol **$\delta\vec{B}$ denotes the direction of geomagnetic pulsations** observed within the dotted region, approximately oriented northwest–southeast (NW–SE) based on magnetometer data.

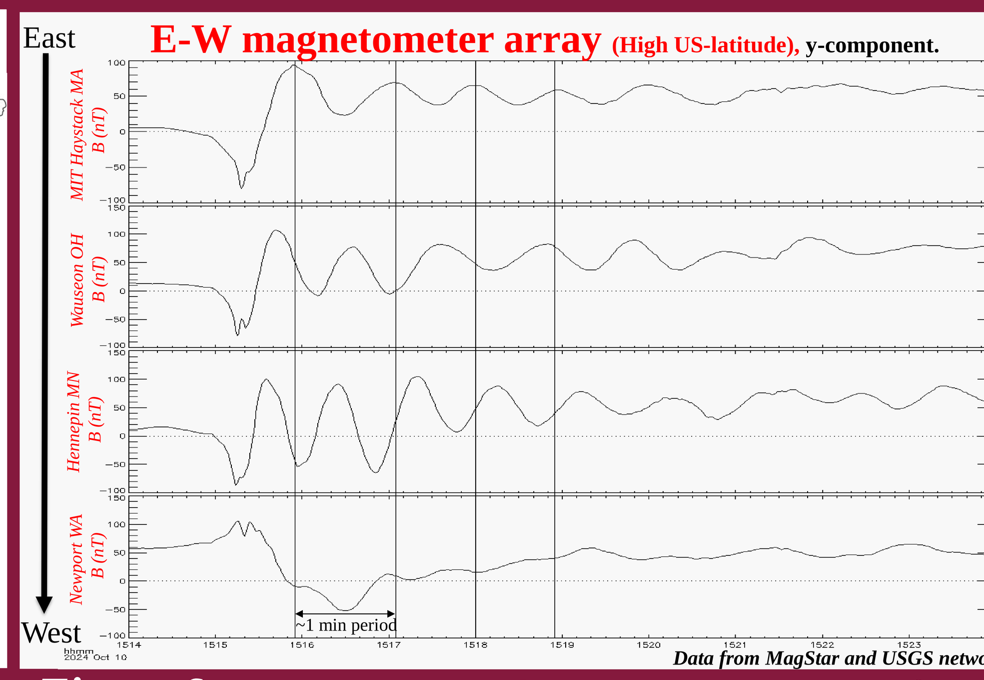

Figure 6 – Geomagnetic pulsations (y-component) from an E-W magnetometer array, showing the occurrence of a single pulse in the western US but a **longer transient period in the eastern US**, which is the region of interest for this study.

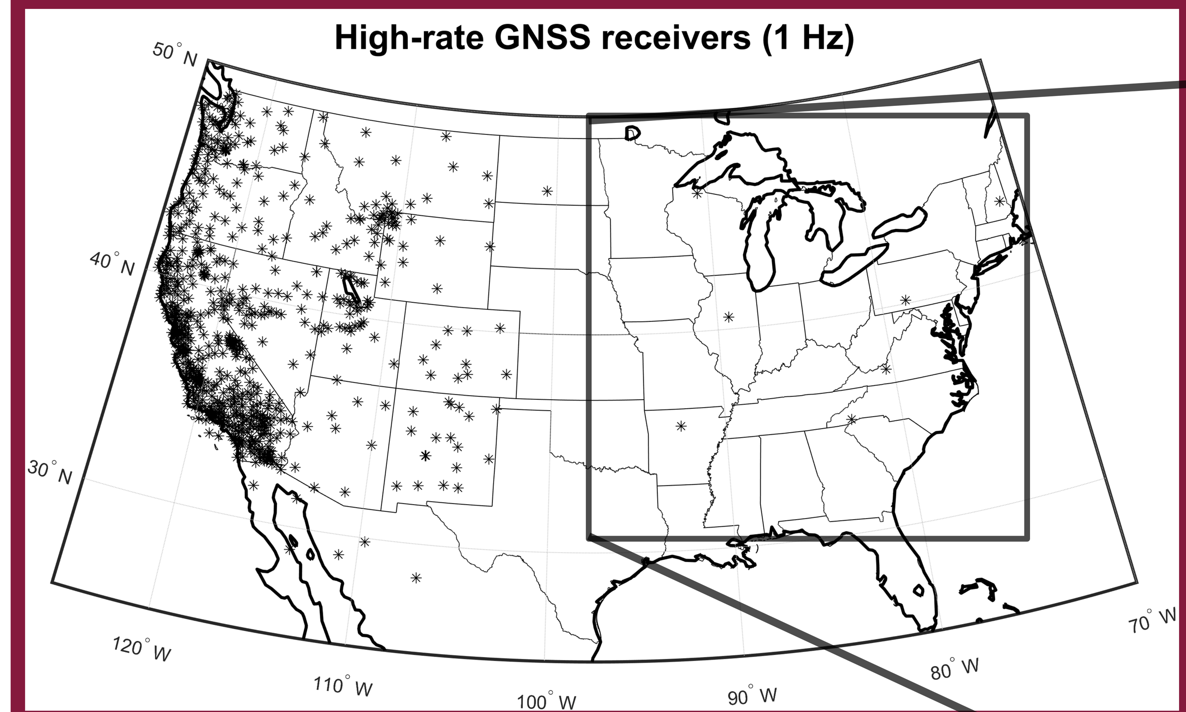

Figure 7 – High-rate GNSS receiver network over the continental US. **In order to observe the ULF waves under study here (period ~ 1 min), high-rate measurements (1 Hz) are required.**

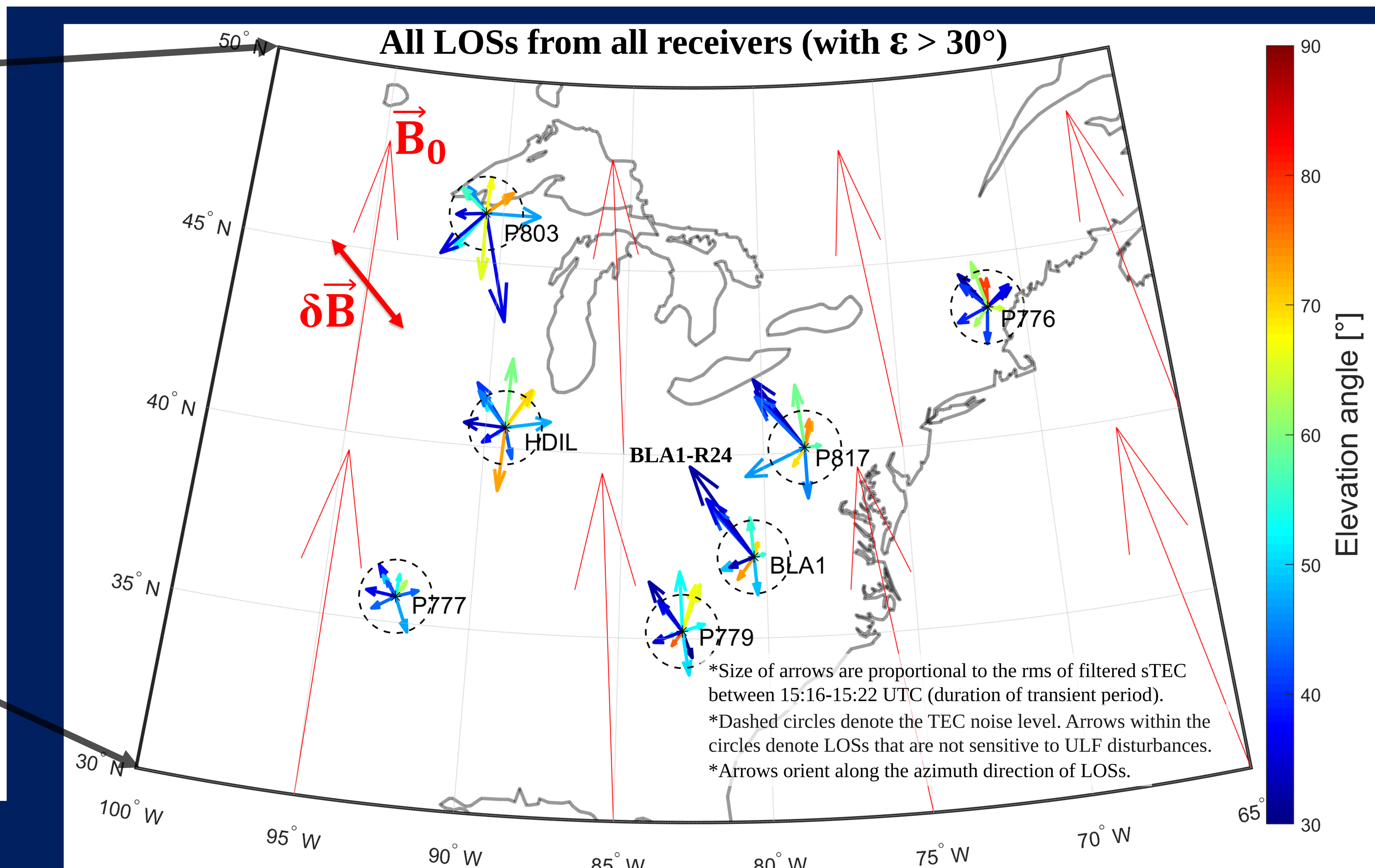

Figure 8 –LOSs orient in their azimuth direction, colored with their elevation angle. Their size reflects how effective they are at sensing ULF-driven ionospheric disturbances. **Lower elevation-angle LOSs aligned with the direction of geomagnetic pulsations ($\delta\vec{B}$) seem most sensitive.**

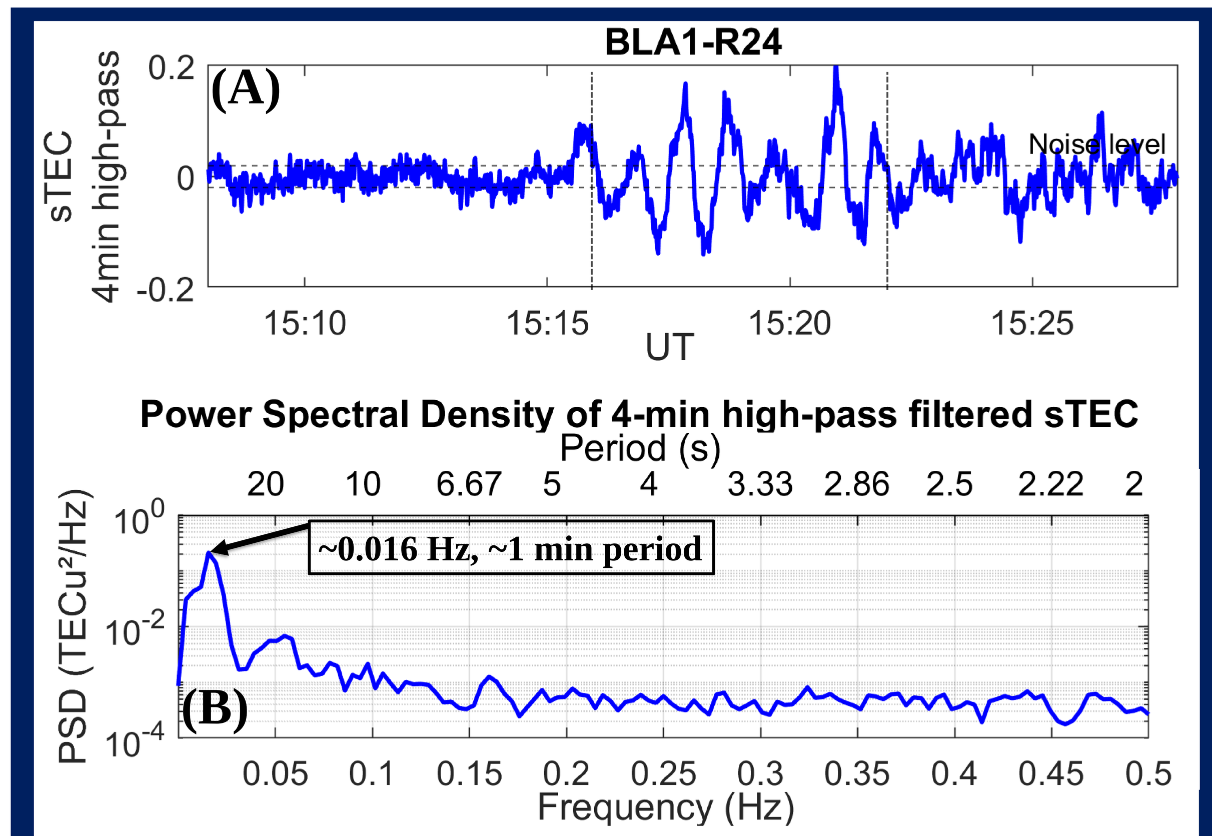

Figure 9 – (A) 4-minute high-pass filtered sTEC from receiver-satellite pair BLA1-R24, as an example of **a LOS that effectively sensed the ULF wave-driven ionospheric disturbances.** (B) Power spectral density for the receiver-satellite pair BLA1-R24 showing a dominant frequency corresponding to ~1 minute period (Pc4 range), **matching the period of the ULF waves observed in magnetometer data.**

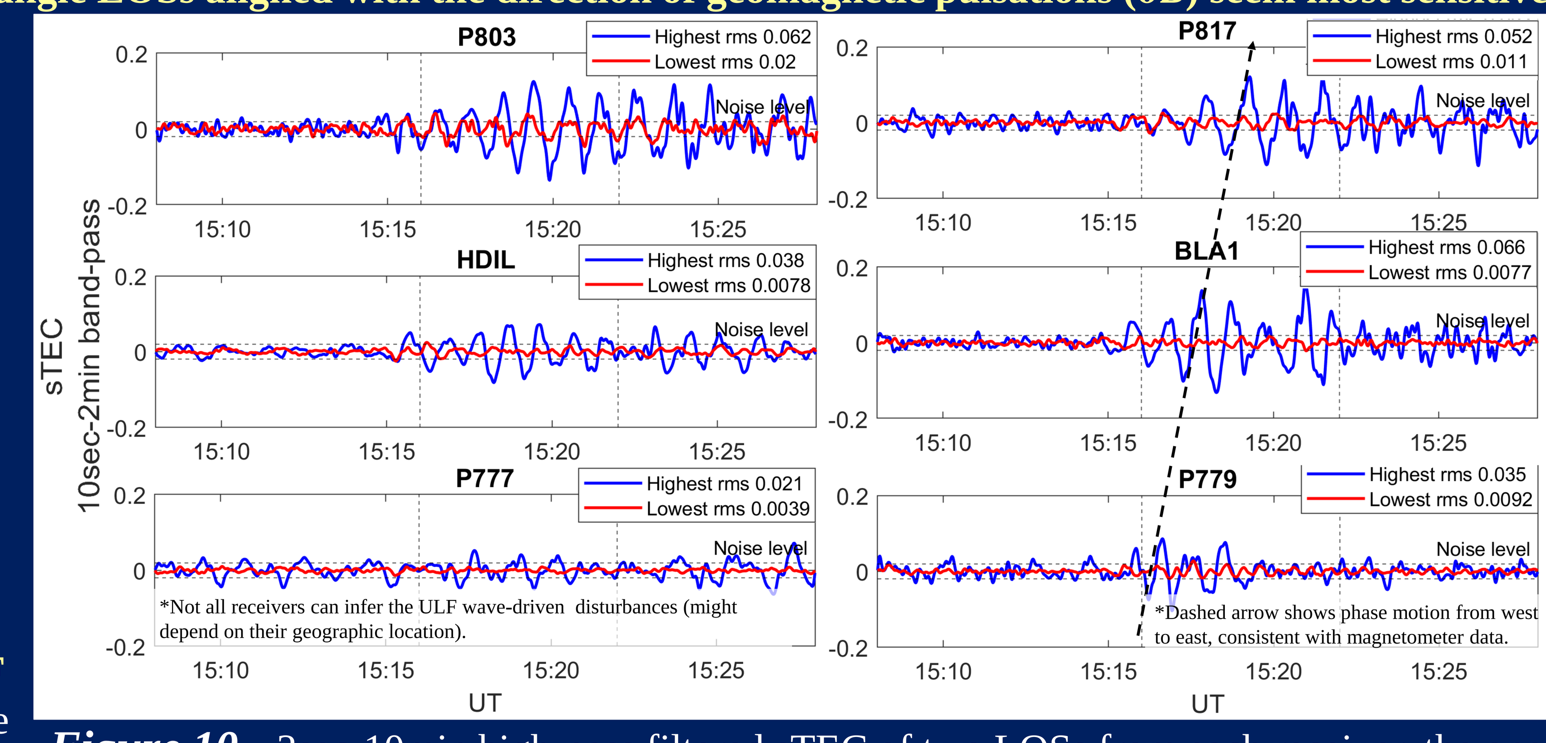

Figure 10 – 2sec-10min high-pass filtered sTEC of two LOSs from each receiver, the ones with the highest and lowest rms over the time interval of the transient period 15:16-15:22 UTC. **For each receiver, some LOSs can sense the disturbances well, while others can not.**

Conclusions and Discussions

- Understanding which LOS geometries are sensitive to different types of ionospheric disturbances **allows for a more accurate characterization of the disturbances.**
- For ULF wave-driven ionospheric disturbances, **TEC appears most sensitive along the direction of geomagnetic pulsations** (which could differ between geographic locations).
- **Analyzing different geometries of TEC measurements can offer valuable insights into ULF wave characteristics**, such as phase motion or direction of geomagnetic pulsations.

Future work

- Further analyze magnetometer data to **determine the difference (if any) in the direction of geomagnetic pulsations between geographic regions**, to enable a more detailed study of the relationship between their direction and effective LOS geometries.
- Study ULF wave-driven ionospheric disturbances during other sudden commencements, **especially over the west US to utilize the dense receiver network.**
- Investigate the use of GNSS signals from geostationary satellites (SBAS) to incorporate LOSs with stationary ionospheric pierce points.

Acknowledgements

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