Observing Interplanetary Shock-Driven ULF Disturbances Beyond the Ionosphere with GNSS TEC

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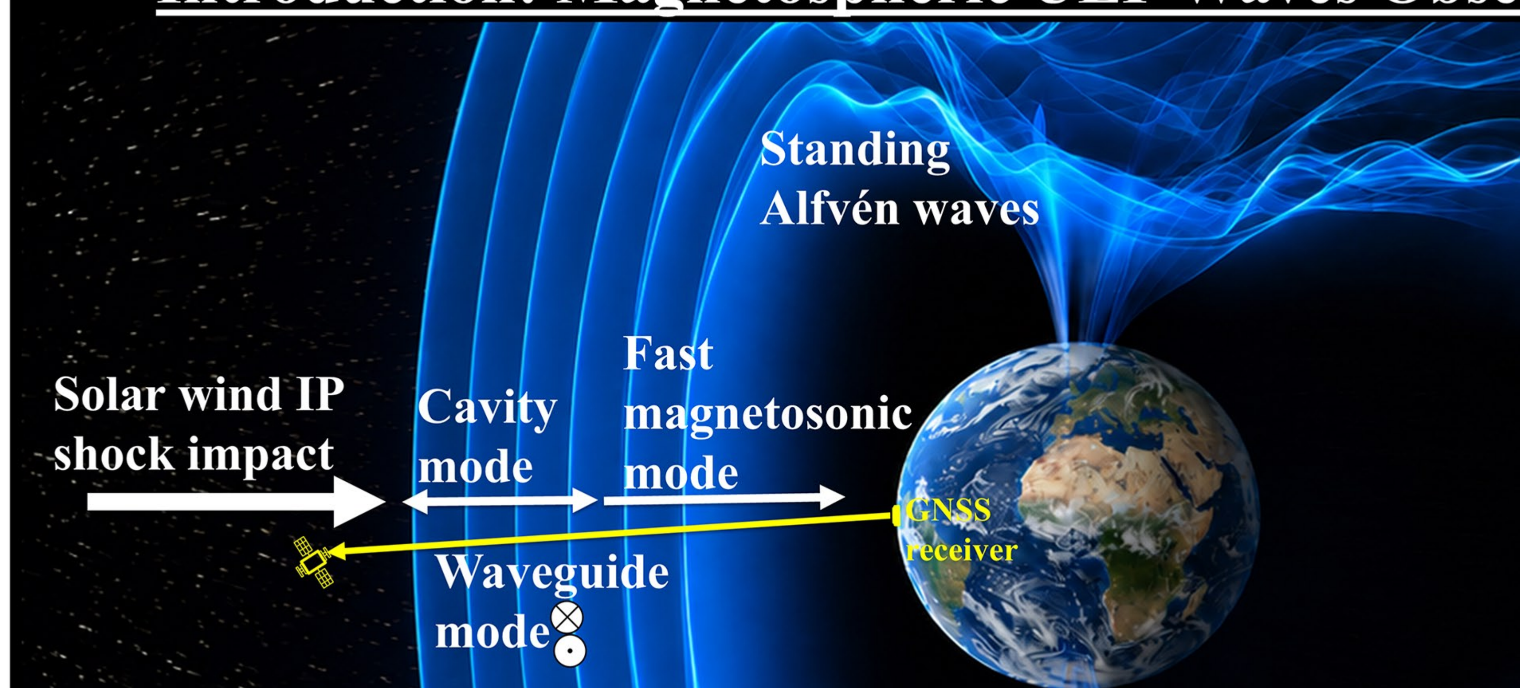
CEDAR 2026
Des Moines, IA.
IRRI-12

Introduction: Magnetospheric ULF Waves Observed with TEC



Problem:

- Although ultra-low-frequency (ULF) wave-driven total electron content (TEC) disturbances have been reported in previous studies, they often appear only along some receiver-satellite line-of-sights (LOSs), while neighboring ionospheric pierce points (IPPs) show weak or no response.
- **This strong LOS-geometry dependence remains poorly understood** and limits how reliably TEC can characterize ULF waves.
- ULF-TEC disturbances are usually assumed to occur in the ionosphere, but **no clear magnetosphere-ionosphere coupling mechanism has been established.**

Objective: While most of the integrated electron density is expected to be from the F-region ionosphere, perturbations at higher altitudes may possibly leave a signature in TEC.

- **This study investigates whether TEC can sense higher-altitude perturbations and be used to characterize different magnetospheric ULF wave modes.**

Significance: Satellite and ground magnetometer spatial coverage is limited, and it is often challenging to constrain propagation speeds and other parameters related to ULF wave activity.

- **Establishing a link between LOS geometries and different ULF wave modes would enable the far more numerous GNSS receivers to be used as a distributed sensor network for magnetospheric ULF waves.**

TEC Response to Interplanetary Shock on Jan 19, 2026 ~19:18 UT

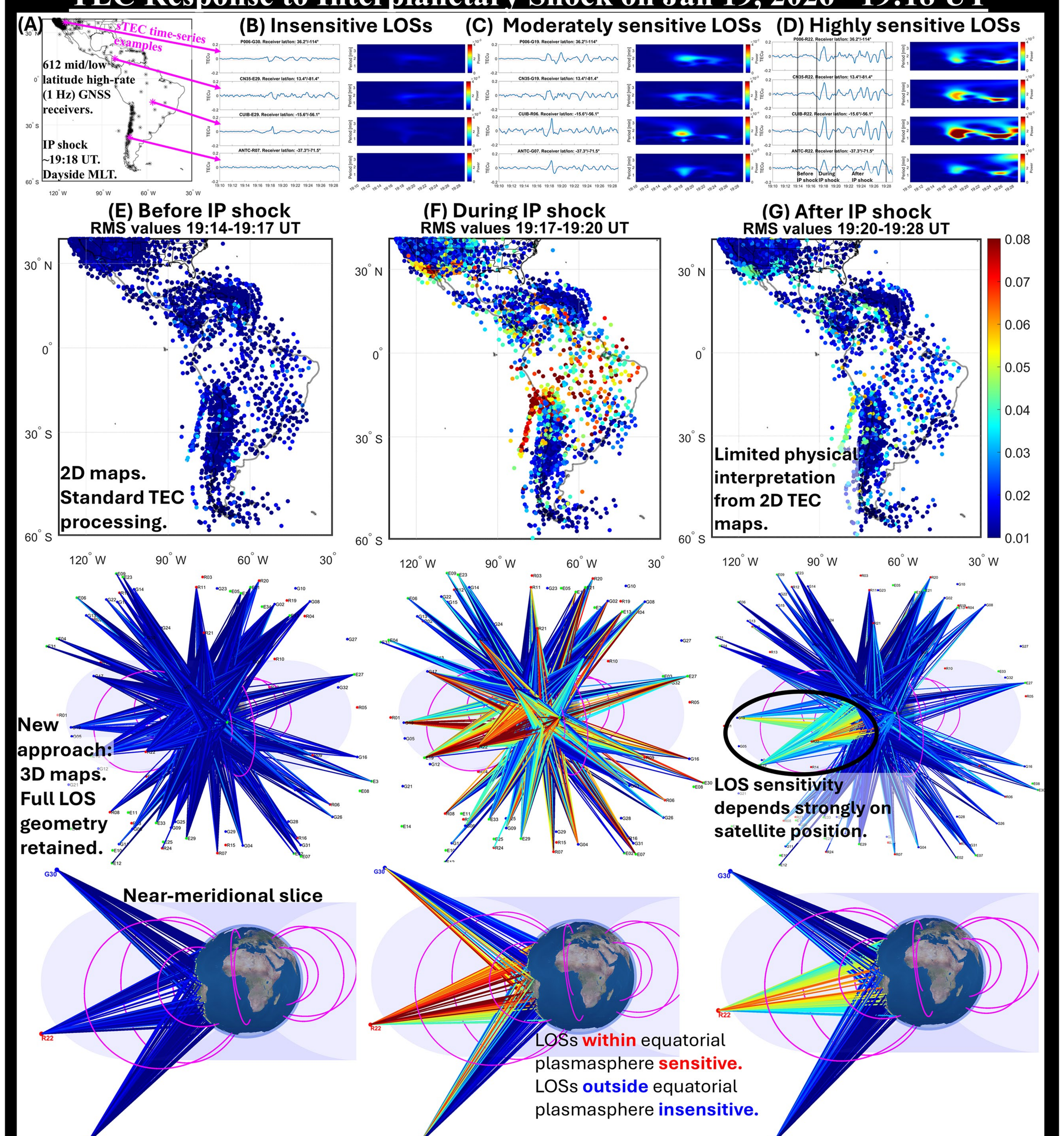


Figure 1 – **(A)** shows the location of the 612 high-rate GNSS receivers (black stars), along with four arbitrary receivers at different latitudes (pink stars). **(B-D)** show examples of LOSs from each of the pink-labeled receivers, that are insensitive, moderately sensitive, and highly sensitive to the ULF disturbances, respectively. **(E-G)** compare the TEC response before, during, and after the IP shock using standard 2D TEC maps (top), 3D TEC maps with the full LOS geometry retained (middle), and 3D TEC maps for selected satellites (bottom). **The 3D TEC mapping is a new approach that avoids standard TEC processing steps such as shell-height assumptions, IPP projection, and vTEC conversion, and instead plots filtered sTEC along the full receiver-satellite LOS, providing a less processed and more fundamental representation of the measurements that are capable of highlighting disturbances occurring at altitudes much higher than the F-region ionosphere.**

Results - ULF Fast Magnetosonic Mode During IP Shock

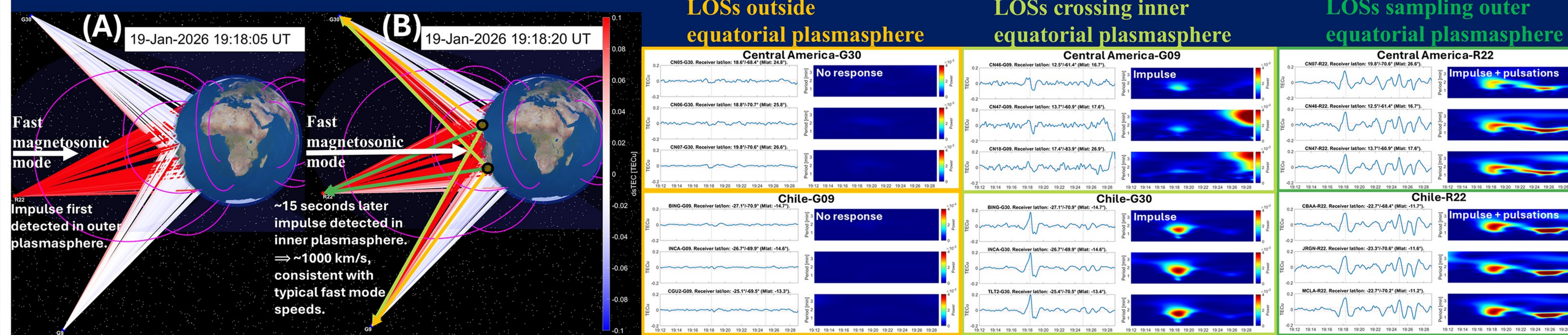


Figure 2 – A near-meridional slice of 3D TEC maps at the time of the IP shock at (A) 19:18:05 UT, and (B) 15 s later. **The inferred apparent radial earthward propagation speed is consistent with typical fast magnetosonic speeds in the plasmasphere.** The time series on the right highlight how the TEC response (no response, impulse, or impulse + pulsations) depends on the plasmaspheric region sampled, with the later pulsations indicating a mechanism distinct from the initial impulsive fast-mode response.

ULF Waveguide Mode During IP Shock

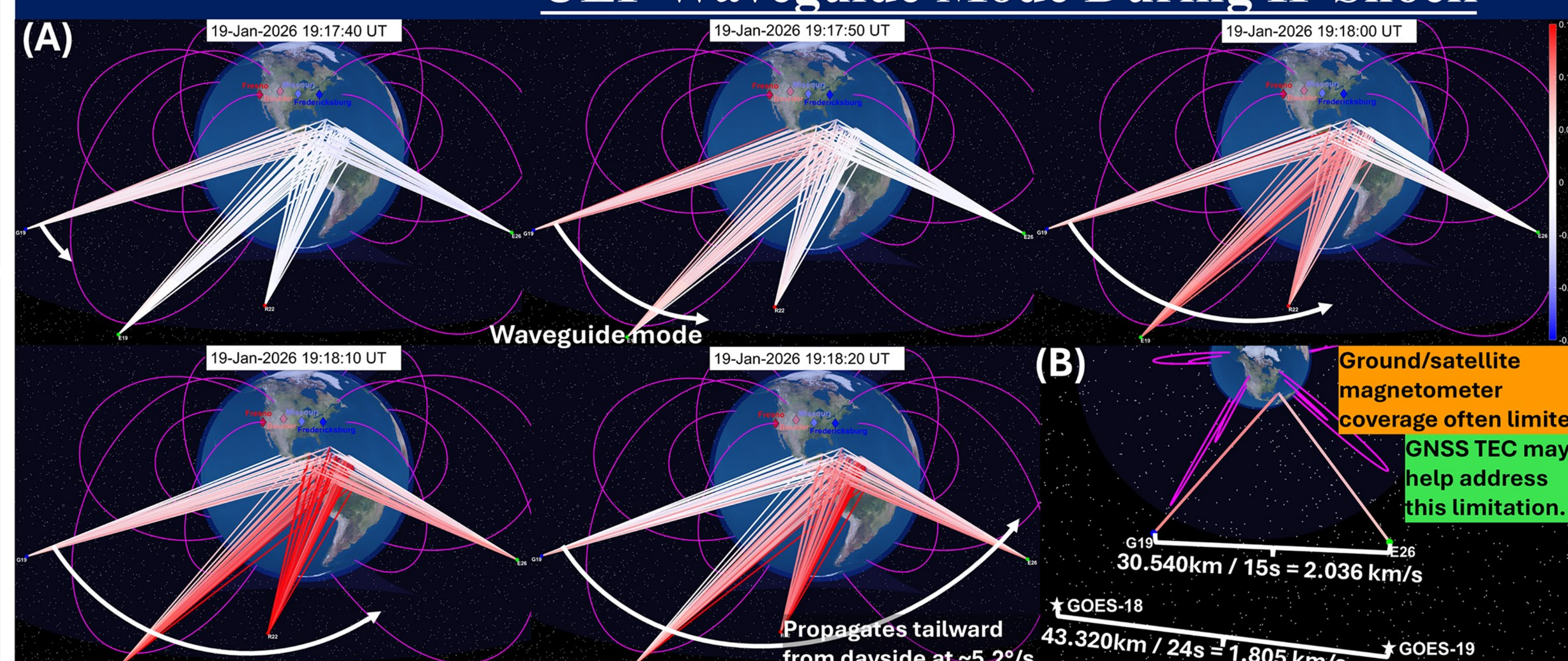


Figure 3 – **(A)** Time evolution of the TEC response through a near-zonal slice of a 3D TEC map, **revealing a waveguide mode propagating azimuthally from dayside at ~5.2°/s, as estimated from TEC.**
(B) Corresponding propagation speed estimates in km/s, derived from the geometric distance between satellites and the observed time delay of the impulse peak for both GNSS TEC and GOES magnetometer measurements.
Such phase speeds are commonly inferred from satellite magnetometers, but they are often not favorably positioned in space and time to resolve a given event. Here, GNSS TEC provides an alternative means of constraining the propagation speed.

ULF Cavity Mode Pulsations After IP Shock

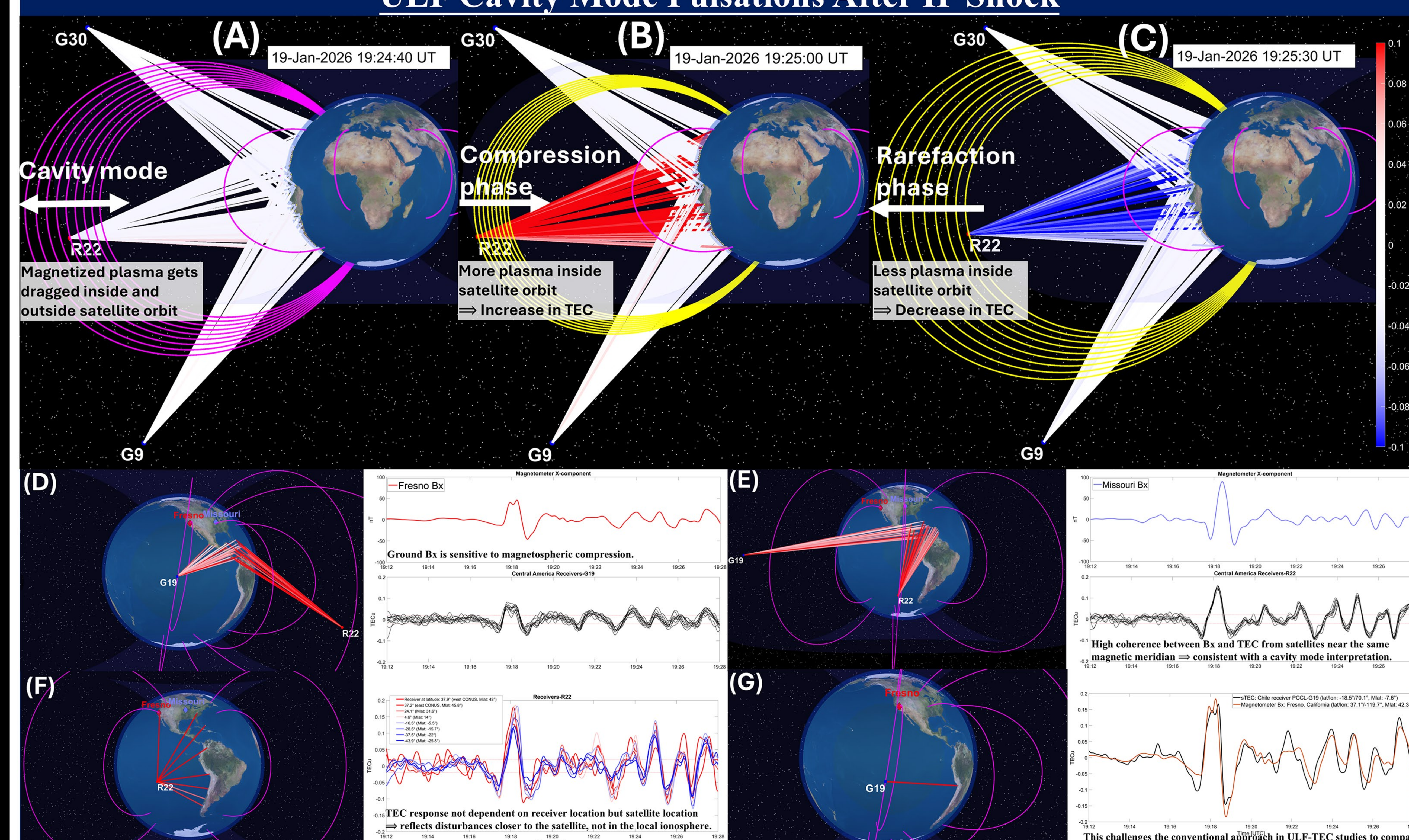


Figure 4 – **(A-C)** highlight the post-shock pulsation interval and suggest **a new mechanism for TEC perturbations, in which ULF cavity-mode oscillations move plasma inside and outside of the satellite orbit.** The cavity-mode **period is measured from TEC as 71±4 s (14±0.8 mHz), based on the mean ±std from more than 600 receivers** viewing satellite R22. **(D-E)** support this interpretation by showing high coherence between ground magnetometer measurements and TEC from satellites near the same magnetic meridian. **(F)** further supports this mechanism by showing nearly identical TEC responses from receivers separated by large geographic distances, indicating a perturbation origin near the satellite. **(G)** challenges the conventional approach in ULF-TEC studies of comparing only co-located instruments.

Conclusions

- **The new 3D TEC approach shows that TEC, commonly used to study ionospheric structure and dynamics, can characterize disturbances far above the ionosphere that are obscured by standard processing**, broadening the geospace applications of existing GNSS networks and providing strong potential for studying a wide range of magnetospheric phenomena.
- For the first time, **TEC is used to separate distinct magnetospheric ULF wave modes modulating electron density beyond the ionosphere, and to constrain their wave speeds and periods.**
- Satellite-position-dependent sampling geometry links TEC perturbations to magnetometer observations in distant regions, **challenging the co-located instrument notion in ULF-TEC studies.**
- Ground and satellite magnetometer spatial coverage is limited, often making it challenging to constrain ULF wave characteristics. **TEC may help address this limitation.**

Future work

- A manuscript describing this methodology and results is being finalized for submission to Geophysical Research Letters (GRL).
- Use this framework to investigate ULF waves and other space weather events where TEC may reveal plasma disturbances occurring beyond the ionosphere.

Acknowledgement

This work was supported by NASA LWS grant 80NSSC22K1022 and HSR grant 80NSSC21K1683.