SuperDARN Workshop 2025

Session: Ionospheric Physics and Irregularities

Rapid Lower Ionospheric Responses During the April 2023 Geomagnetic Storm Revealed by Very Low Frequency (VLF) Transmitter Signals

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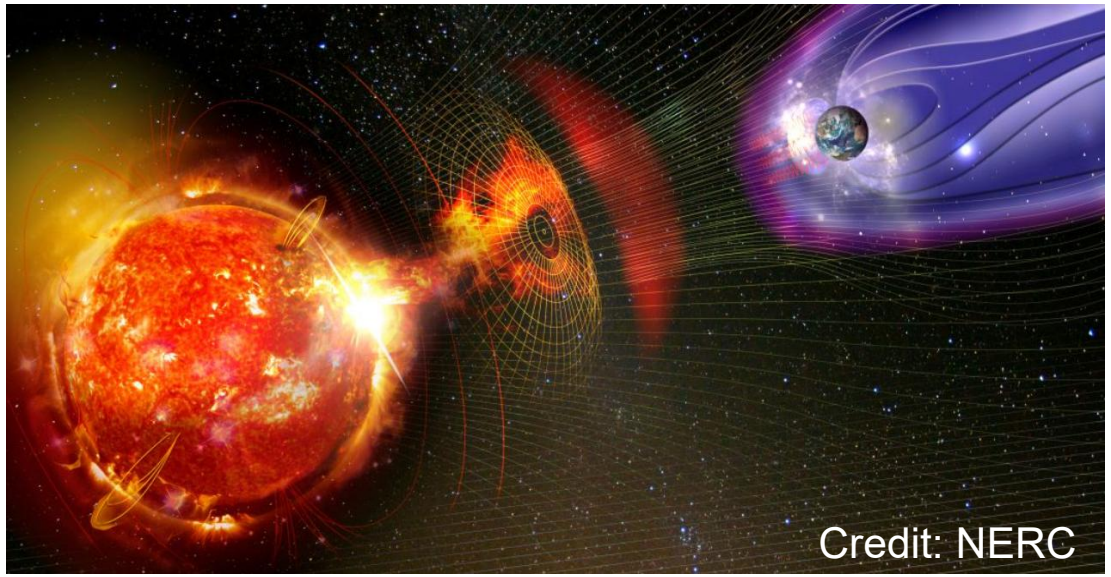
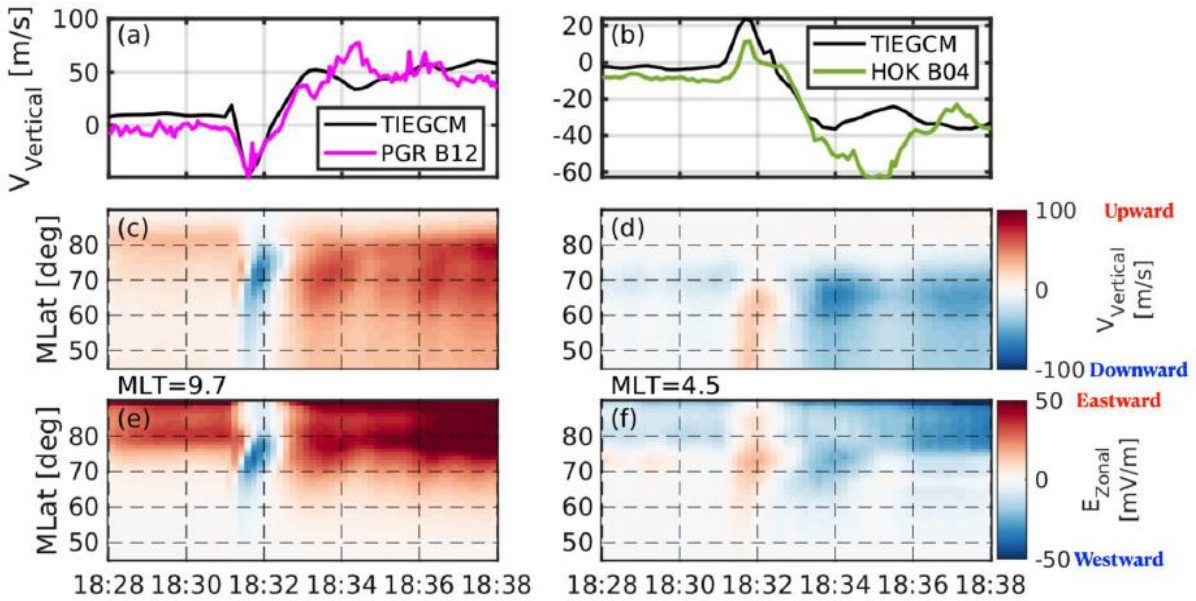
Background

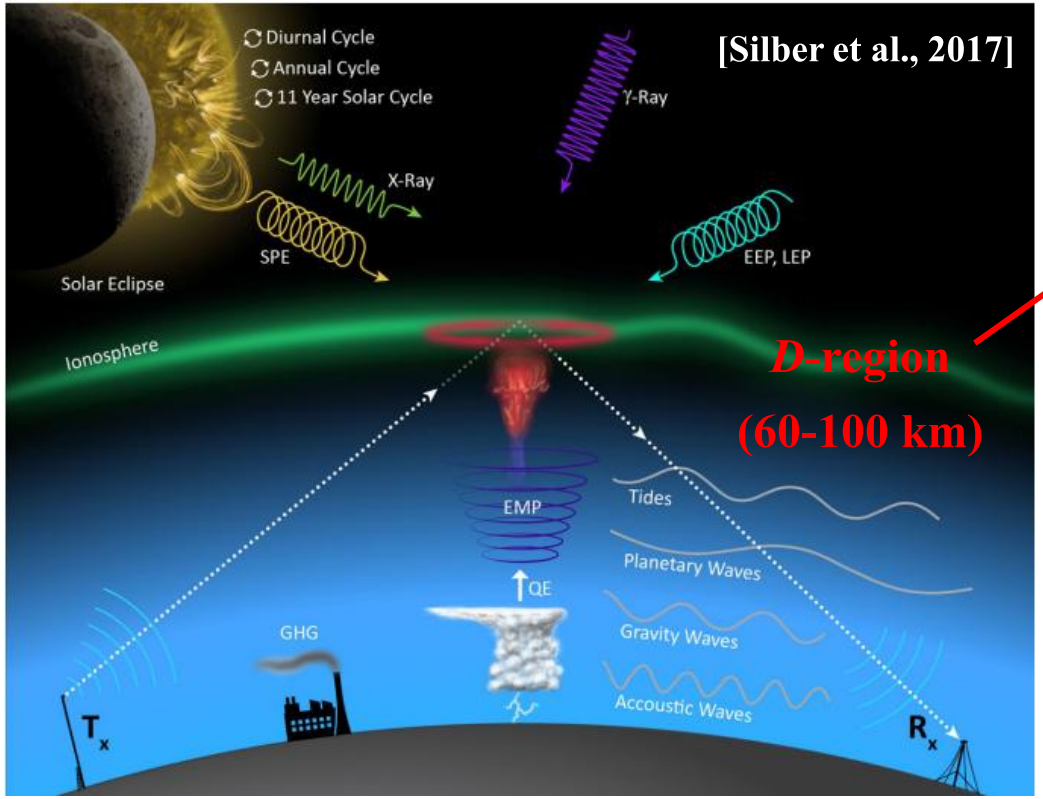


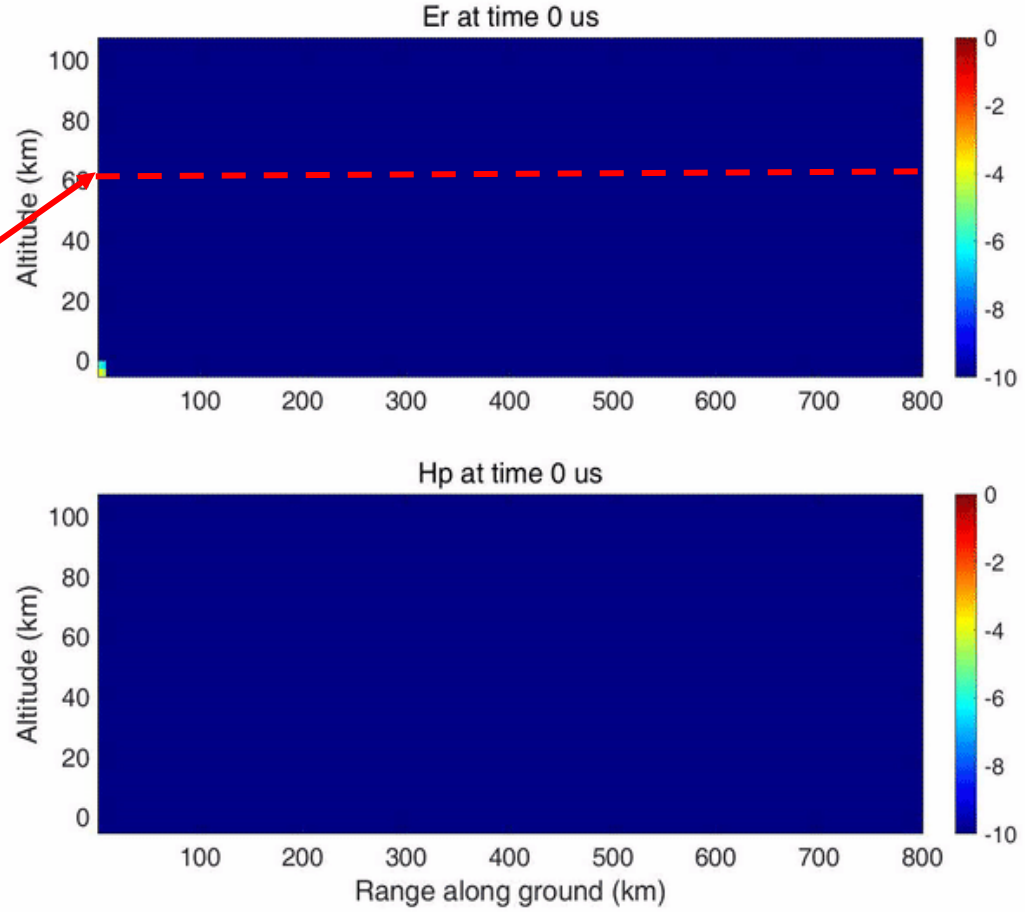
[Shi et al., 2022]



- Geomagnetic storm is one of the extreme space weather events, which can significantly affect the partially ionized atmosphere, or ionosphere
- The interplanetary shock suddenly compresses the magnetosphere-ionosphere system, inducing the vertical upwards/downwards motion of ionosphere via the prompt penetration electric field (PPEF) effects

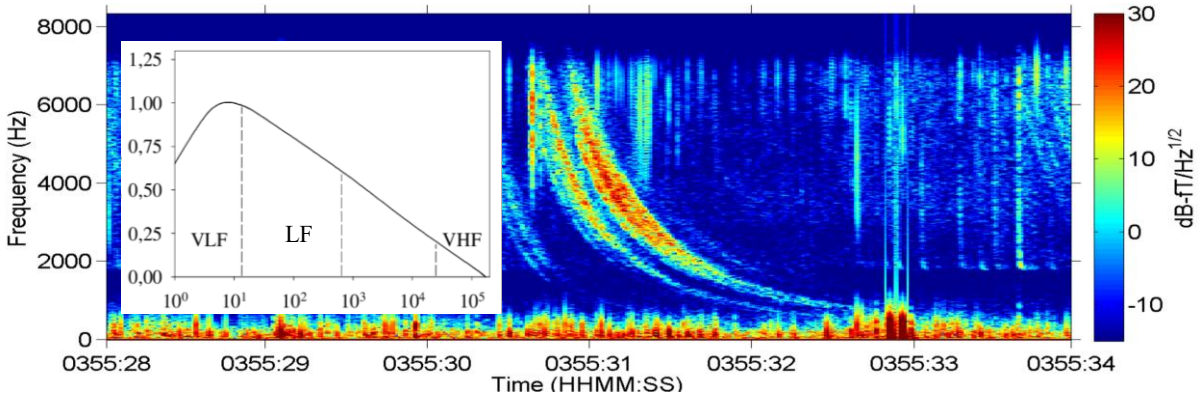
What is *D*-region?

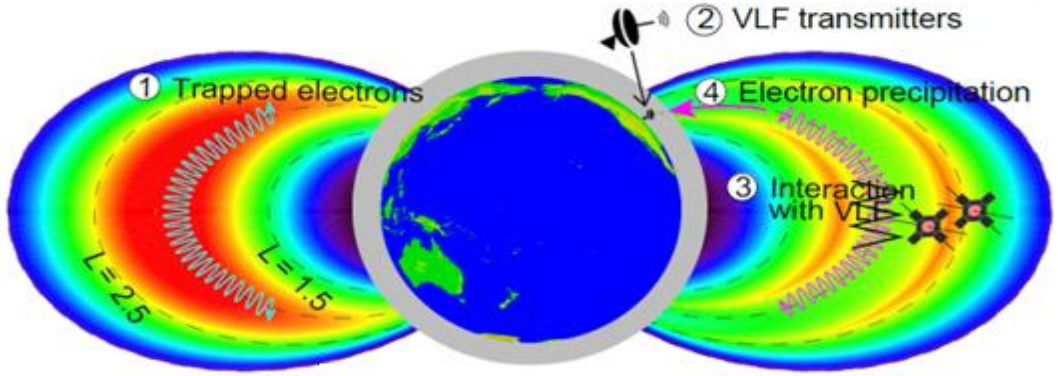




- *D*-region specifically corresponds to the altitude range between 60 and 100 km, a partially-ionized region that resides between the neutral atmosphere and the upper ionosphere

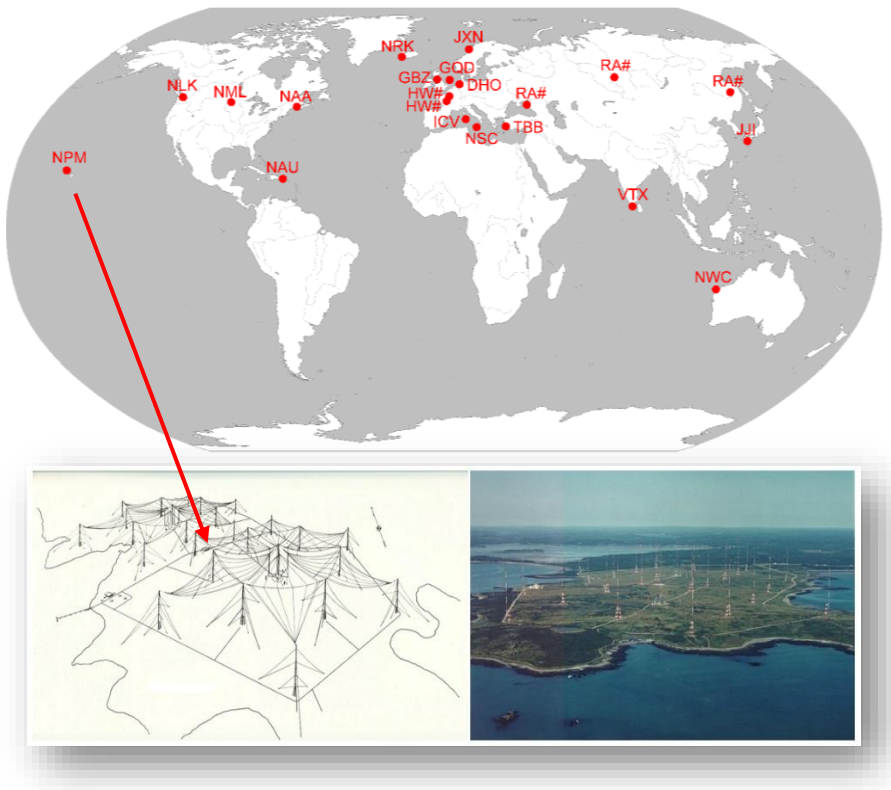
How to monitor the D-region?



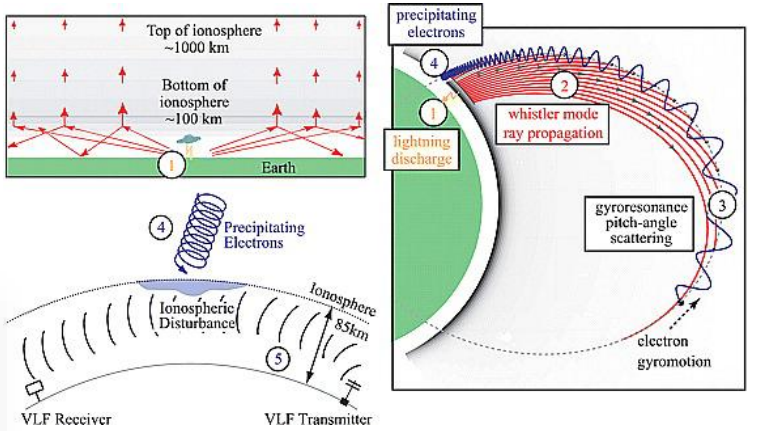


- Frequency Range: **3-30 kHz**
- Main Sources: **Lightning activities** and **VLF transmitters**
- VLF waves bound within the Earth-ionosphere waveguide, carrying direct information about the lower ionosphere

What Can VLF Waves Tell Us about the Space?

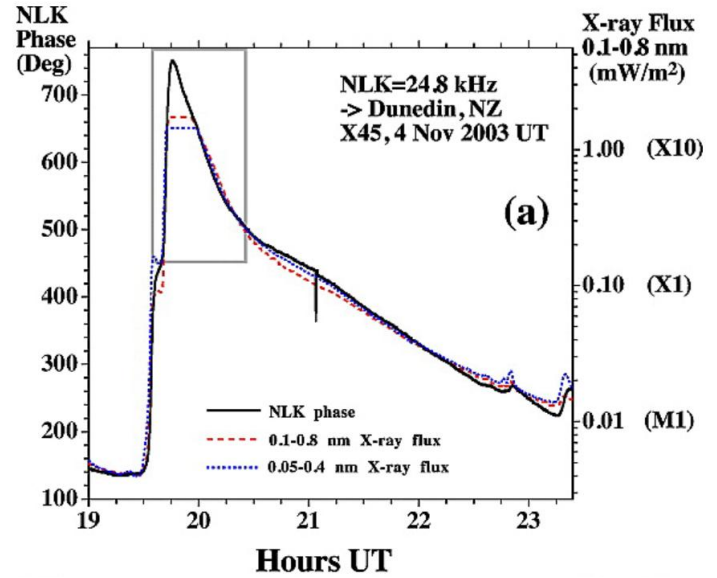


Particle Precipitation



[Lauren et al., 2001]

Solar Flares



[Thomson et al., 2004]

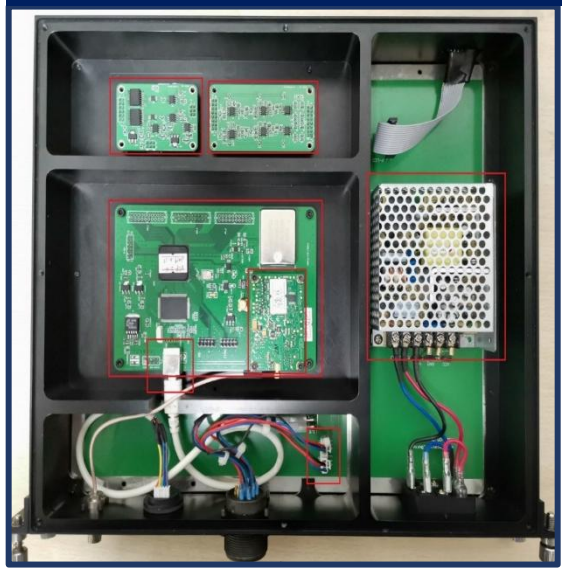
- The VLF measurements have been widely used to investigate various events that influence the *D*-region, including **energetic particle precipitation from the radiation belts** (Inan et al., 1999), **flares** (Žigman et al., 2007) , **eclipse** (Singh et al., 2012), **lightning activities** (Marshall et al., 2008)

WHU VLF Receiver

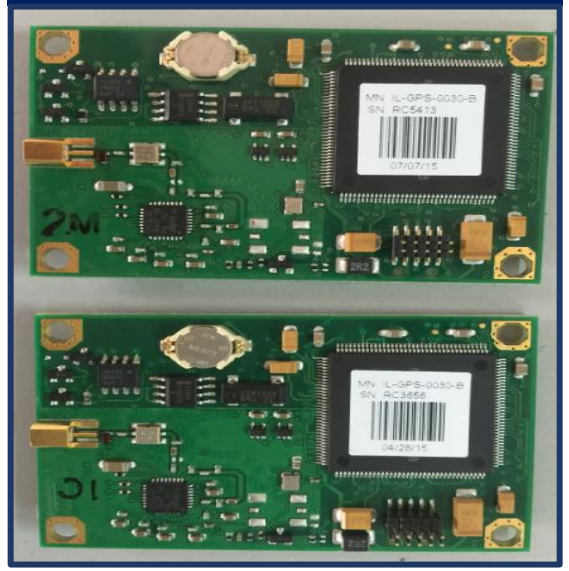
Antenna

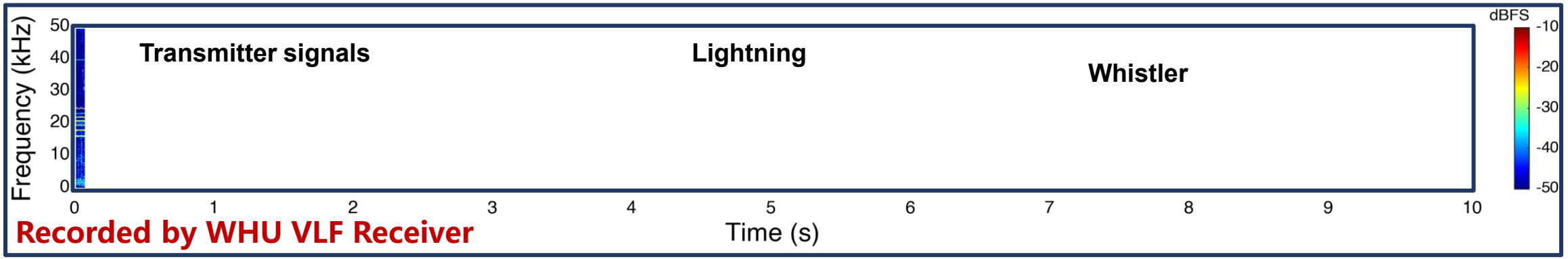
Receiver

Control Module



Synchronization





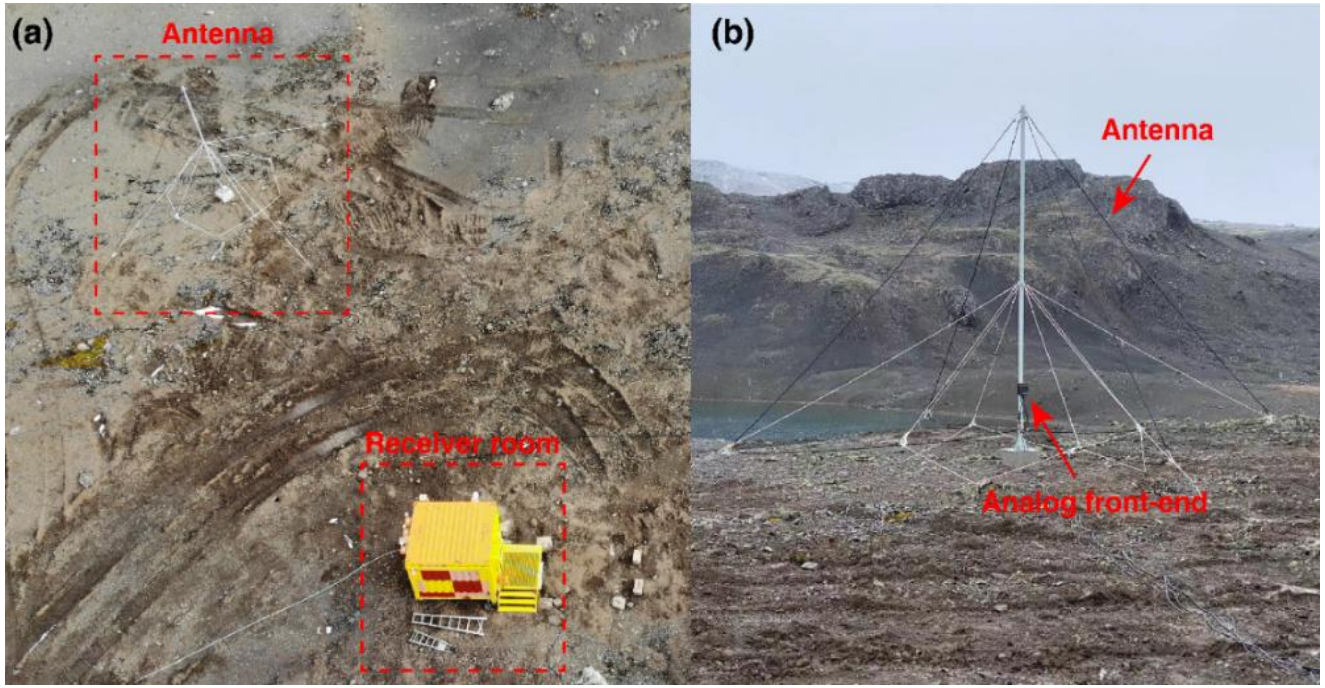
Recorded by WHU VLF Receiver

Detection Network Developed by WHU

Set up the VLF waves detection network

Detection Network

The Great Wall Station



- **10** sites established in central China
- Site at the Great Wall Station in Antarctica
- Recorded data: **~200TB**

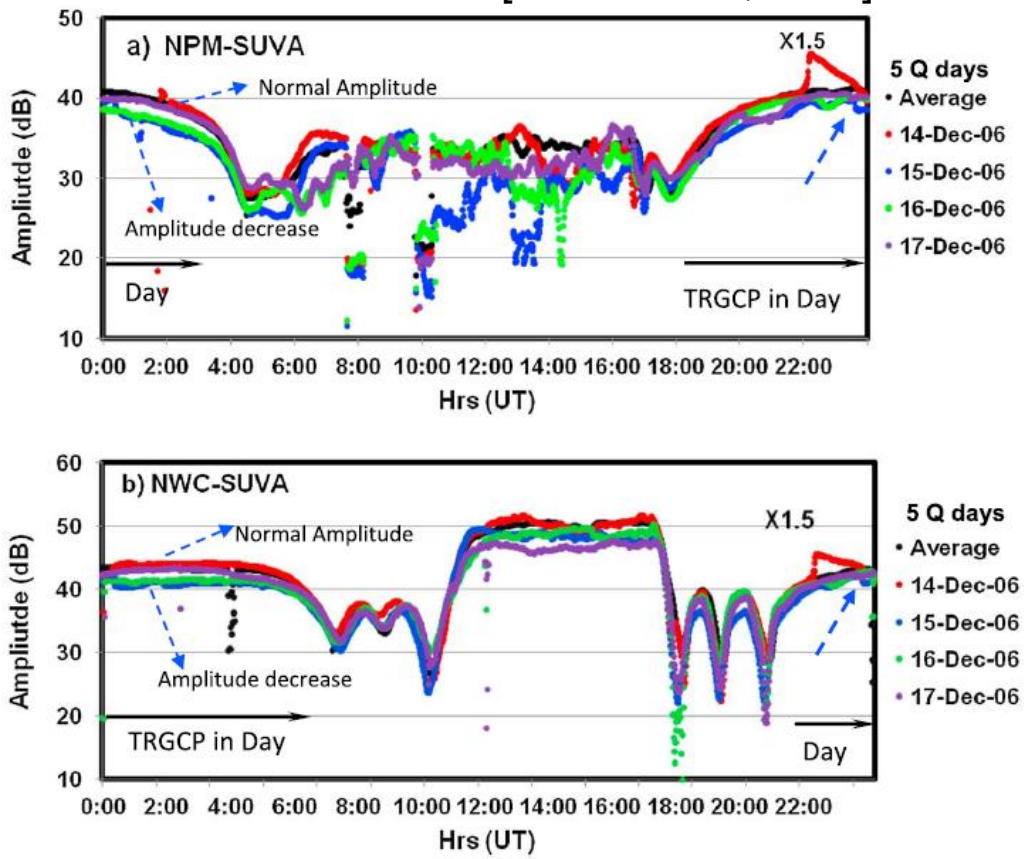
Motivation

武漢大學 WUHAN UNIVERSITY

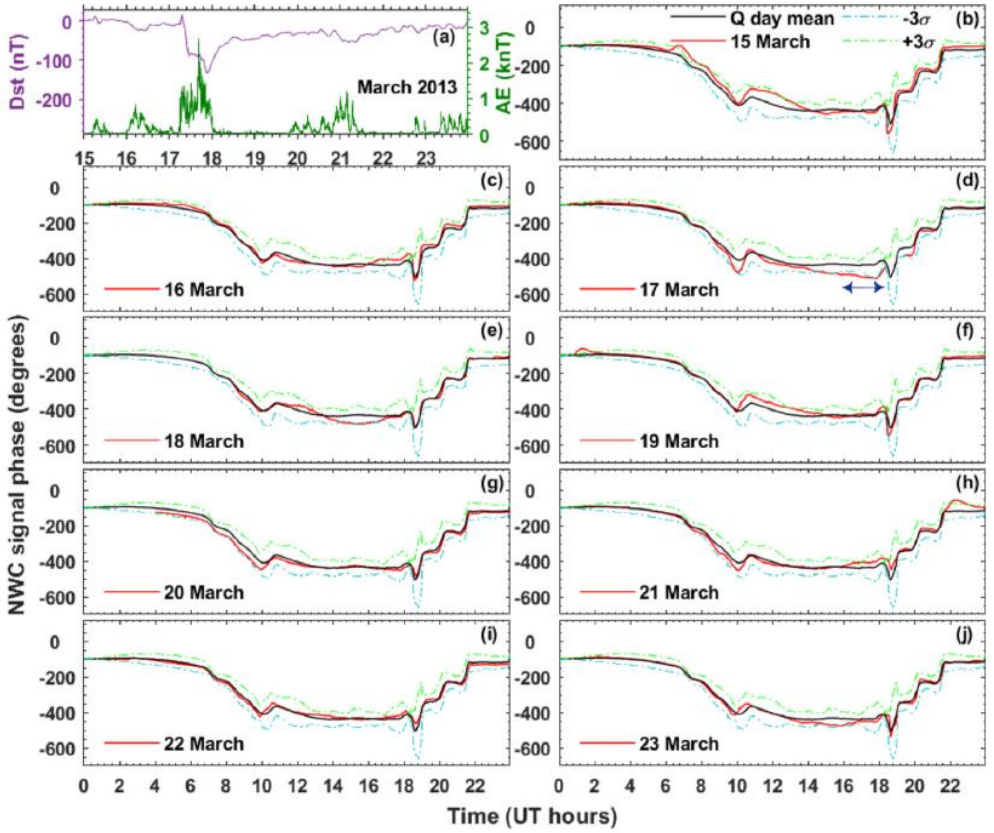
Q: How does the lower ionosphere respond to PPEF?

Motivation

[Kumar et al., 2014]

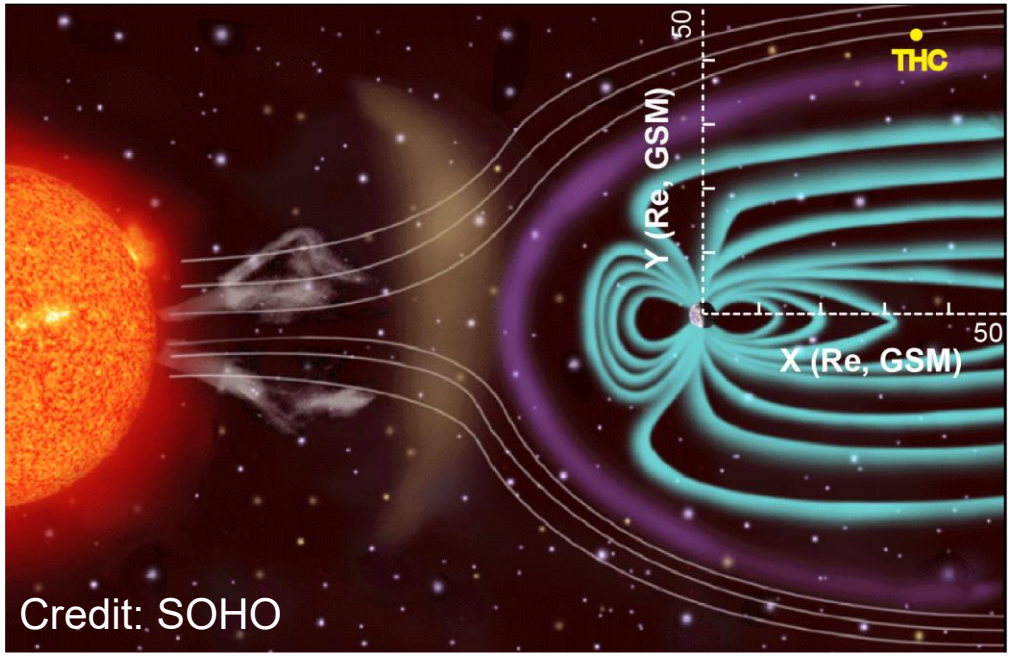


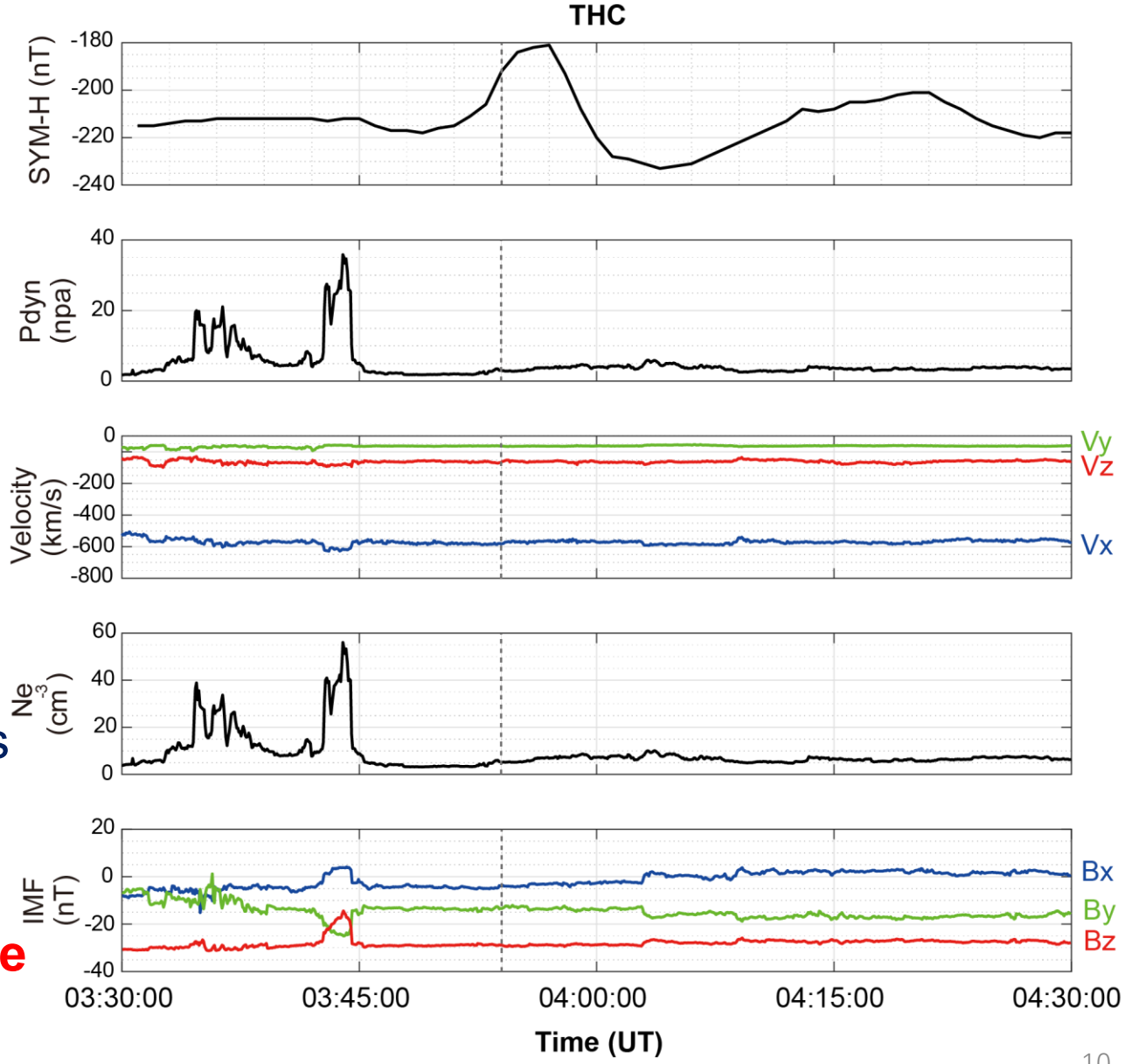
[Kumar et al., 2023]



- The previous studies have focused on long-term (several hours or longer) geomagnetic storm effects in the lower ionosphere
- **What about the transient responses (~1 minute) observed in VLF measurements?**

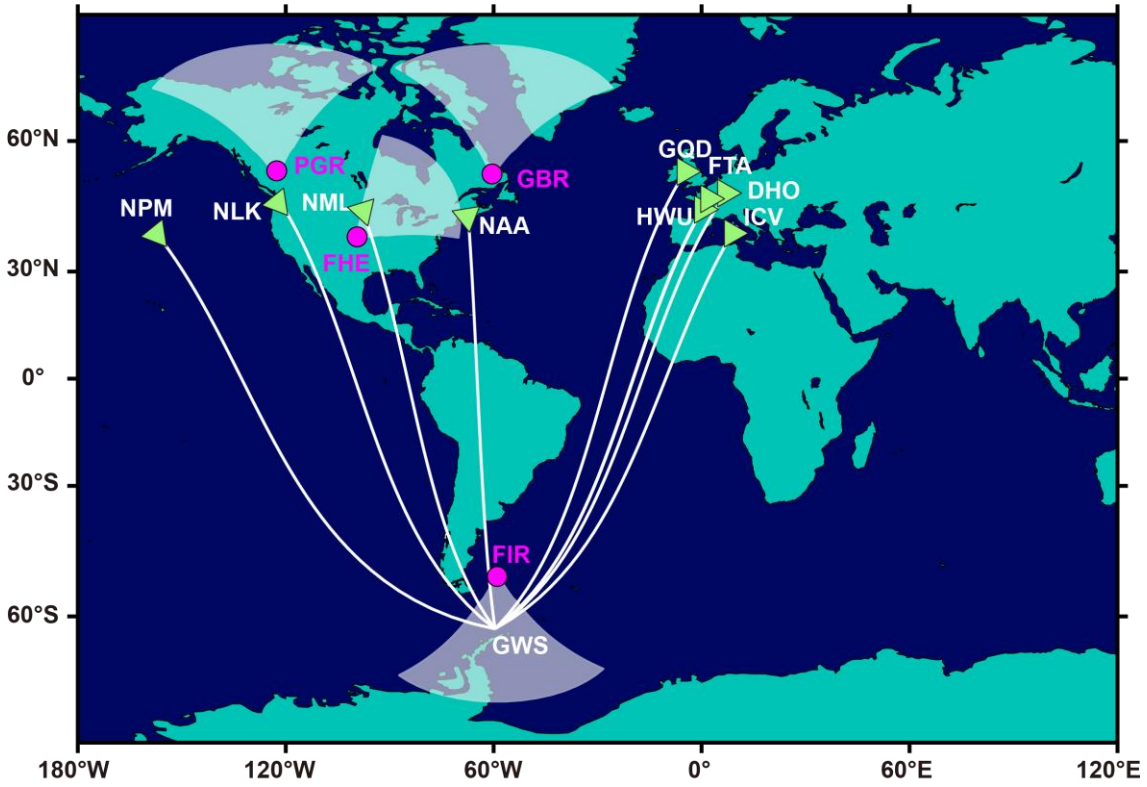
Geomagnetic Storm on April 24, 2023

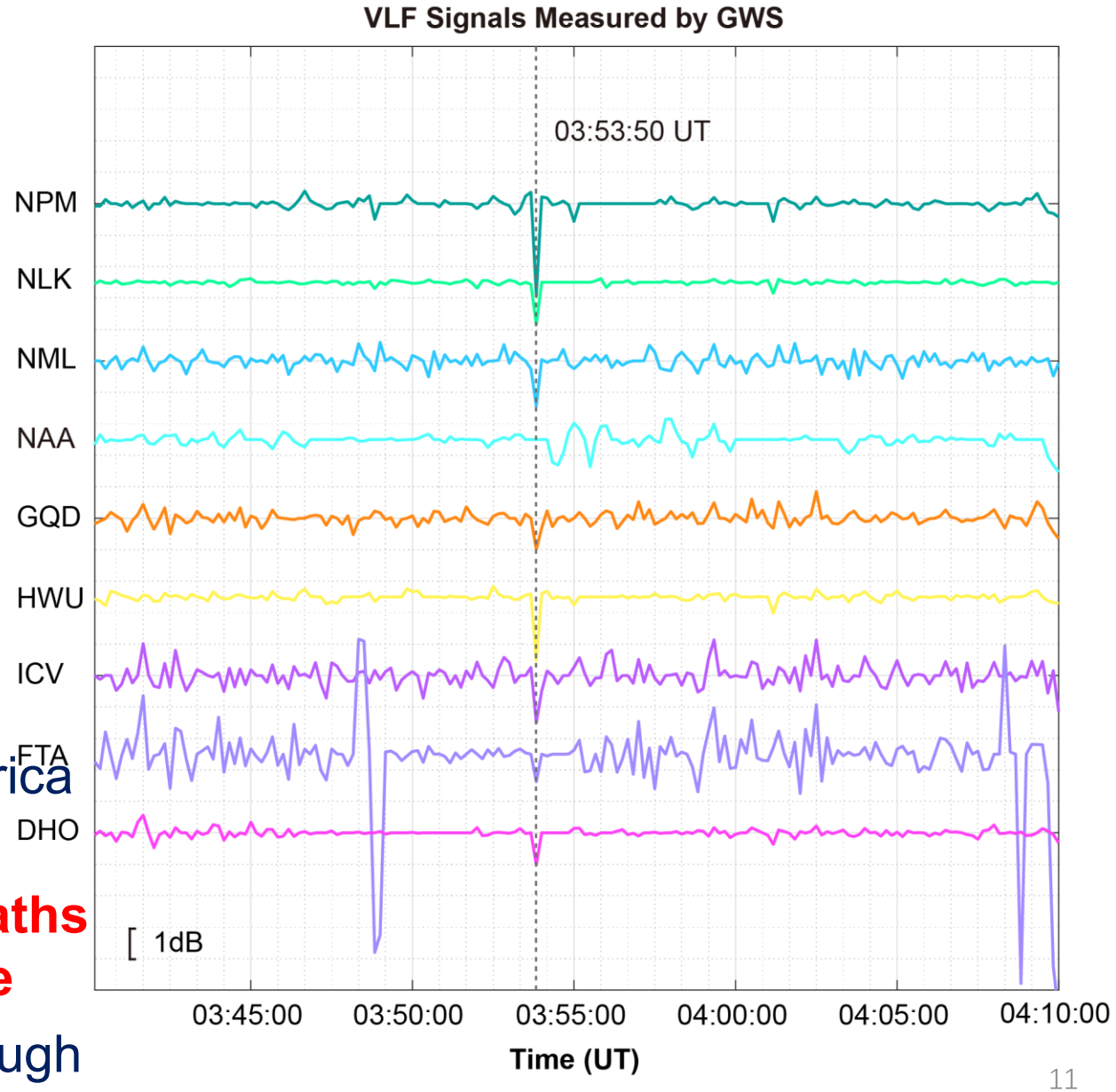




- SYM-H suddenly increased around 03:49:00 UT and decreased within ~3 mins
- Sharp enhancements of dynamic pressure and Ne were observed simultaneously
- **An interplanetary shock compressed the magnetosphere-ionosphere system**

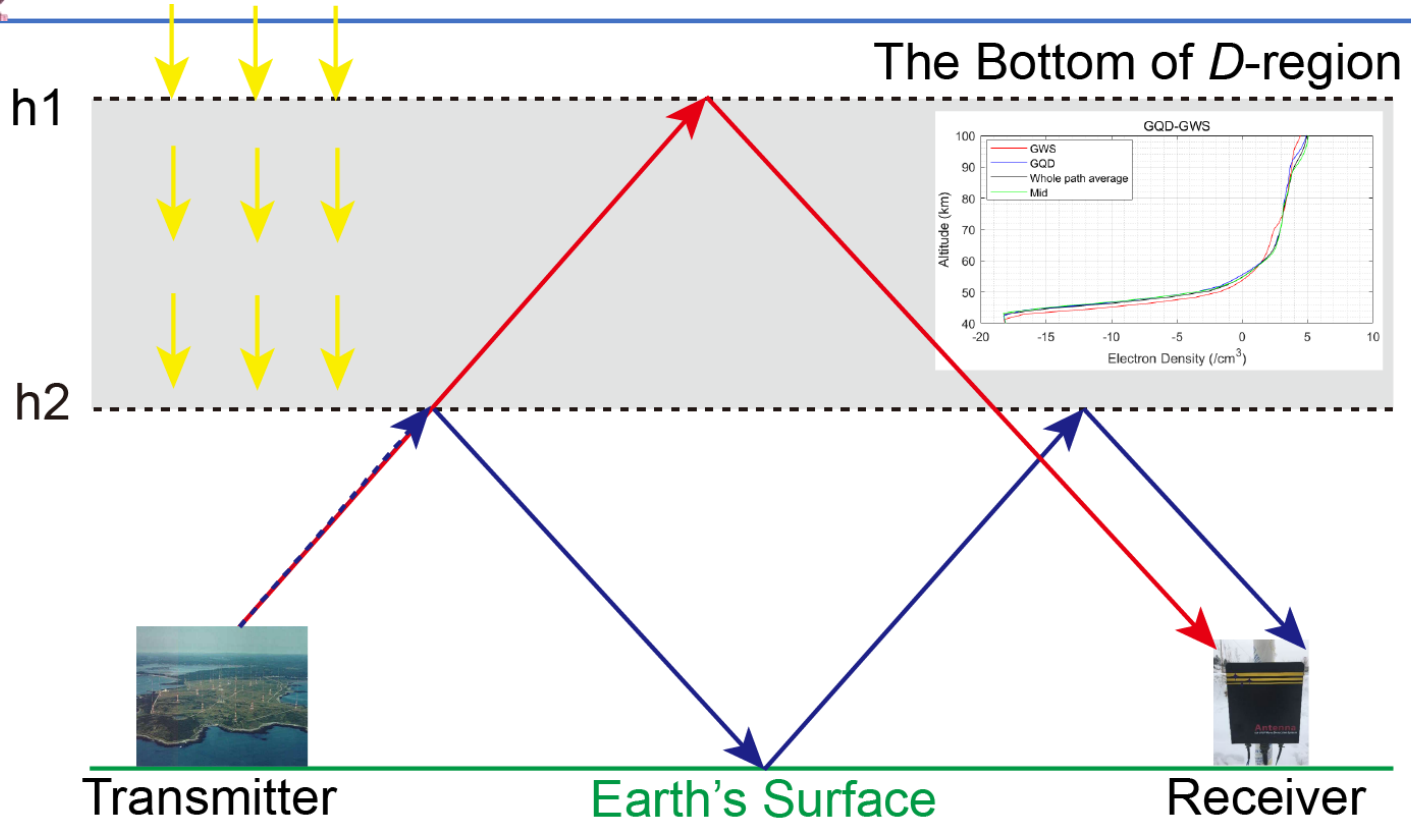
VLF Measurements on April 24, 2023

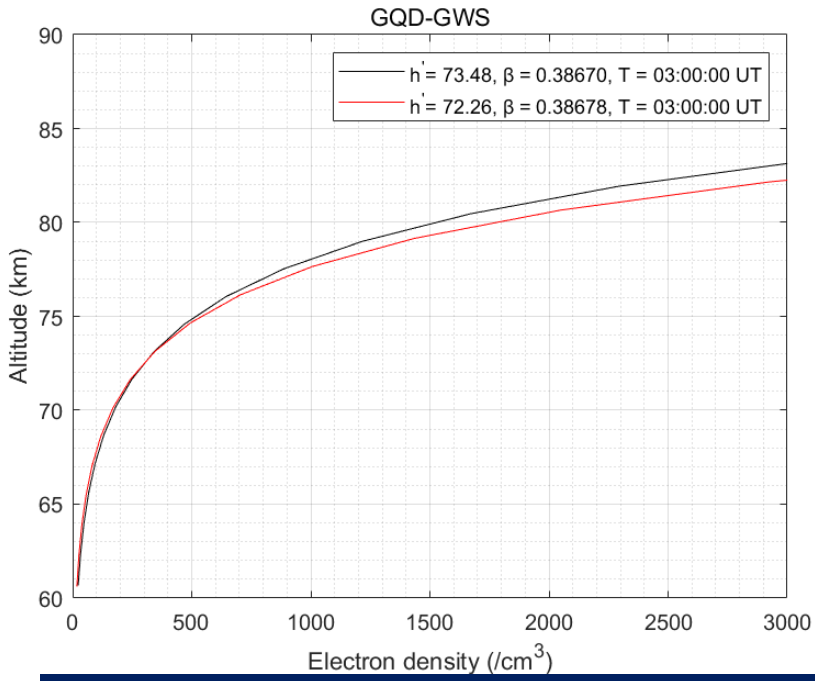




- VLF signals were transmitted from North America and Europe, and recorded by GWS
- **The sharp declines in VLF signals for all paths indicated disturbances in lower ionosphere**
- Note that the NAA-GWS path propagates through the SAA region

The Factors Associated with VLF Variations

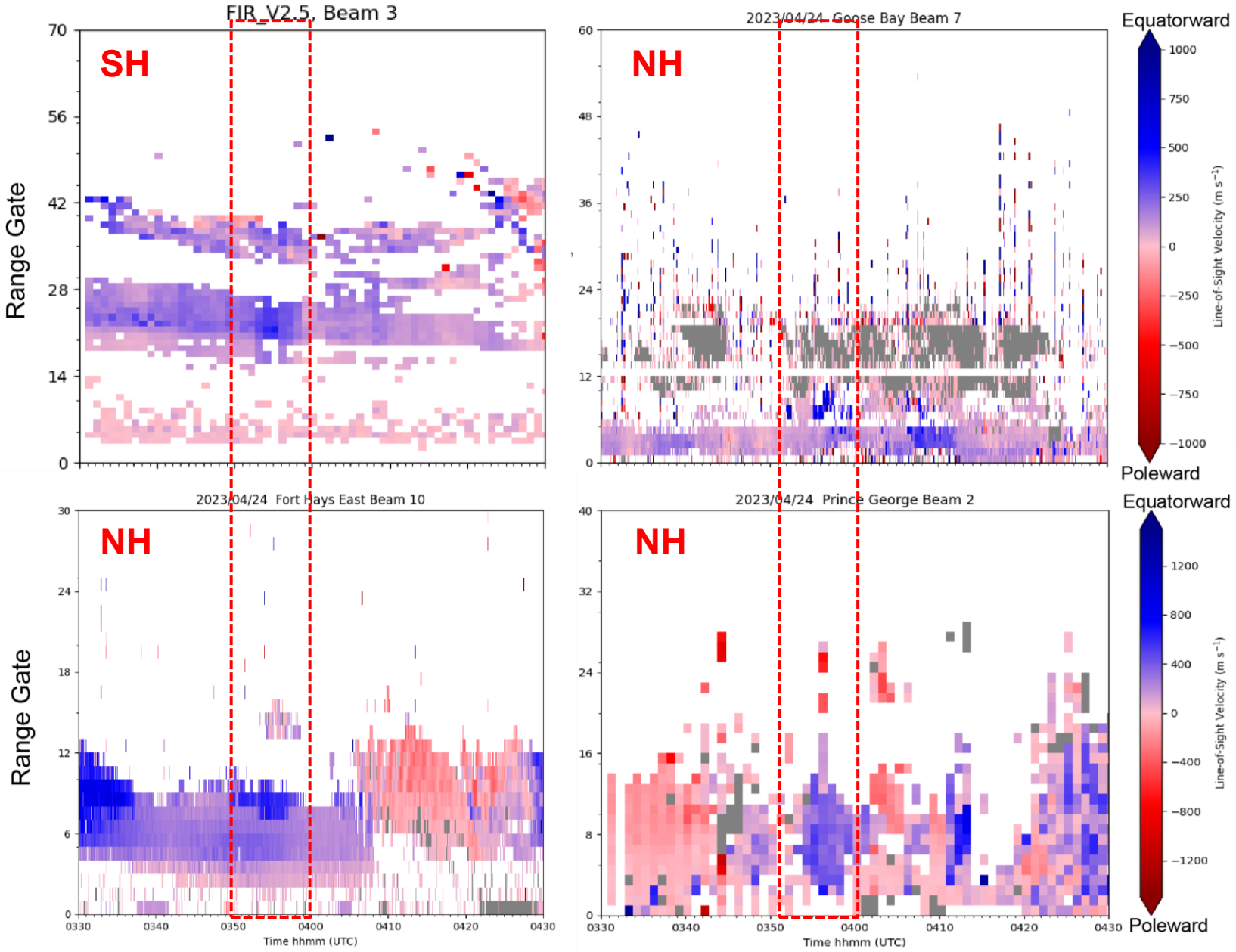




Δ Amplitude ≈ 1 dB

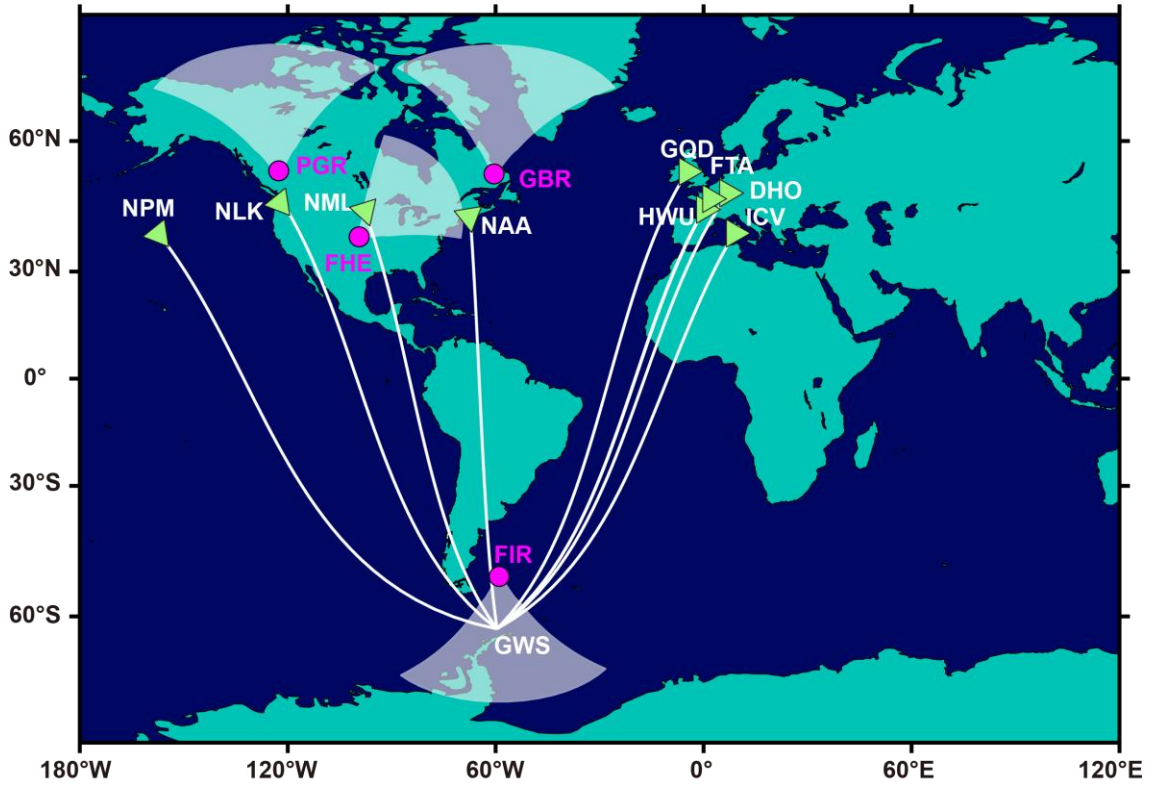
- Ne and reflection height are the major factors affecting VLF signals
- The VLF amplitude is positively correlated with reflection height, while negatively correlated with Ne
- **The VLF signal rapid variation suggests that the ionosphere underwent a transient downward motion like geospace concussion**

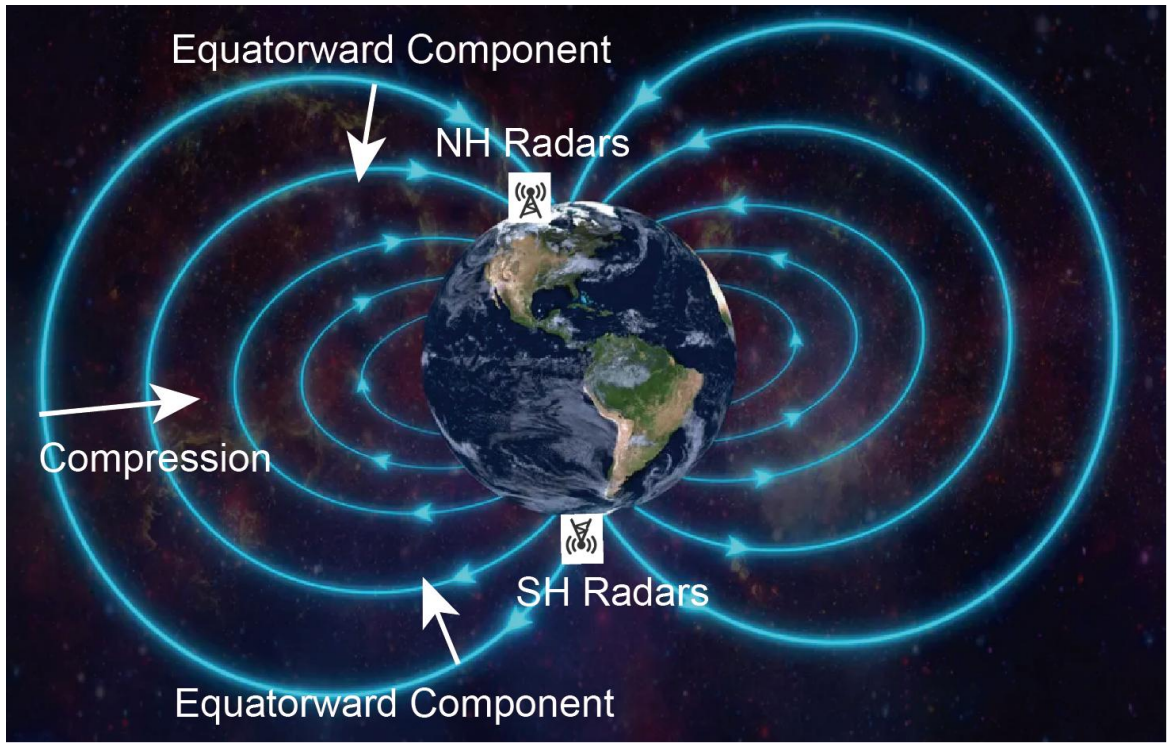
The Observations of SuperDARN



- We have checked four SuperDARN radars near the VLF propagation paths, including **FIR** (SH), **GBR**, **FHE** and **PGR** (NH)
- The radar-measured velocity exhibited a **clear reversal in direction** during the period of 03:50:00 to 04:00:00 UT, and recovered afterwards
- The observed reversal indicated that **the electric field reversed**

The Observations of SuperDARN





- The direction of velocity changed: **away from radars→towards to radars**
- The velocities measured by NH and SH radars all have **equatorward components**
- We can assume that **the ionosphere was compressed during the storm, which is consistent with the result of VLF observation**

Summary

- The VLF transmitter signals turns out to be a suitable and unique approach to probe the lower ionosphere, which is a relatively rarely explored geospace region.
- We observed transient abnormal variations (~1 minute) of VLF signals during the storm, and the amplitude decreased by approximately 1 dB
- The joint observations from VLF measurements and SuperDARN radars indicated that the ionosphere moved downwards in the period of storm, probably related with the reversed $\vec{E} \times \vec{B}$ vertical drift caused by PPEF
- Even the *D*-region is considered unmagnetized, the electrons and ions can not move together. We assume that the electrons might move upwards/downwards firstly which can create a new electric field, and the ions will move afterwards, like charge separation. Thus, the process should be slower and weaker

Thanks!

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