ULF waves observed with ground-based magnetometers and GPS TEC

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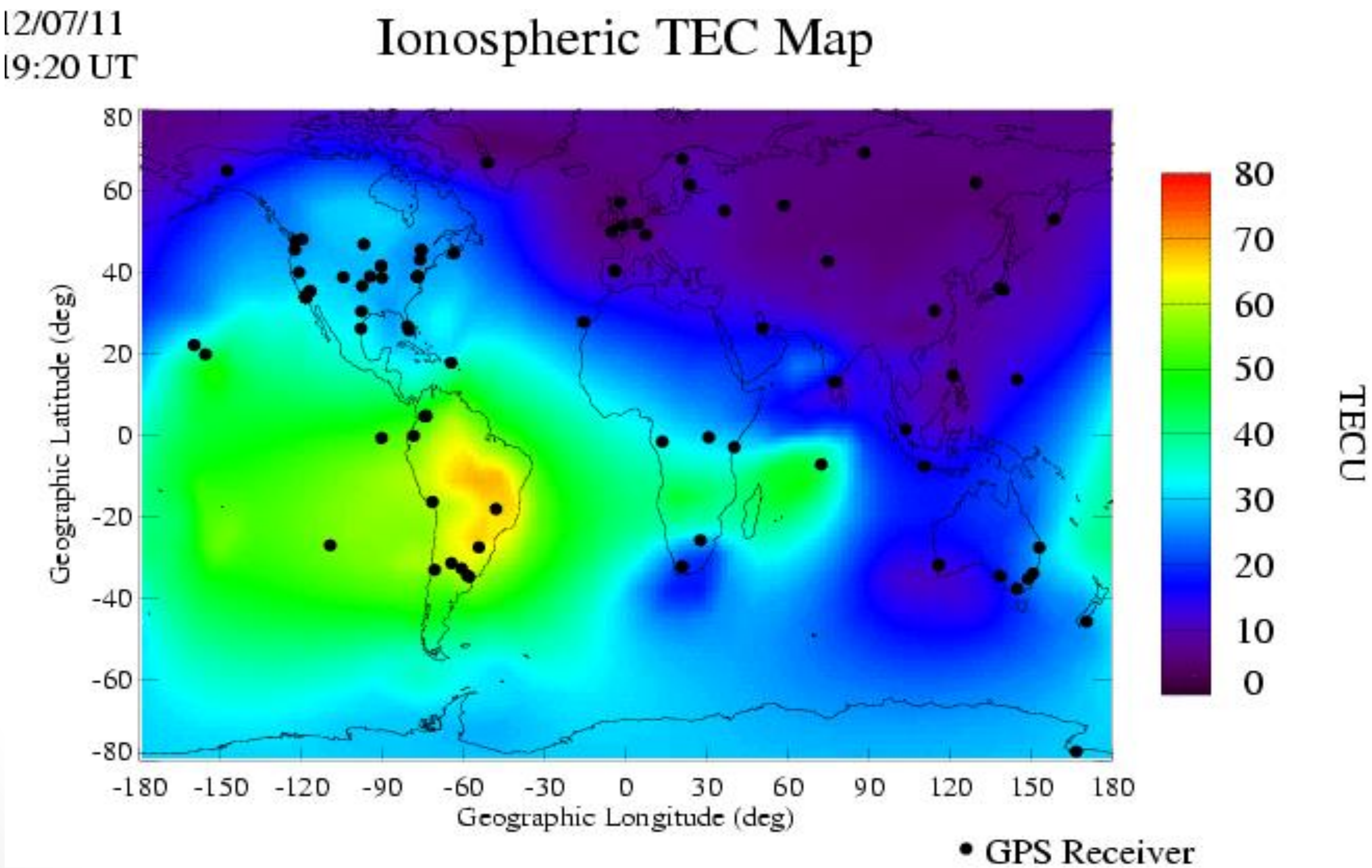
2015 Mini-GEM ULF Waves: Space-Ground Coordination

Overview

- Several studies have now shown that some ULF waves are detectable with GPS TEC
- Most of these studies have been event-based and many of the details, particularly the mechanisms involved in creating the signal, are not yet resolved
- We will review these developments:
  - Some general background on GPS TEC measurements
  - GPS TEC variations during large amplitude (storm time) Pc5 waves
  - TEC variations during more “typical” Pc5 waves
  - Revisit studies of TEC variations associated with Pc3 waves

Background: GPS TEC can be used to investigate ionospheric structure on global scales



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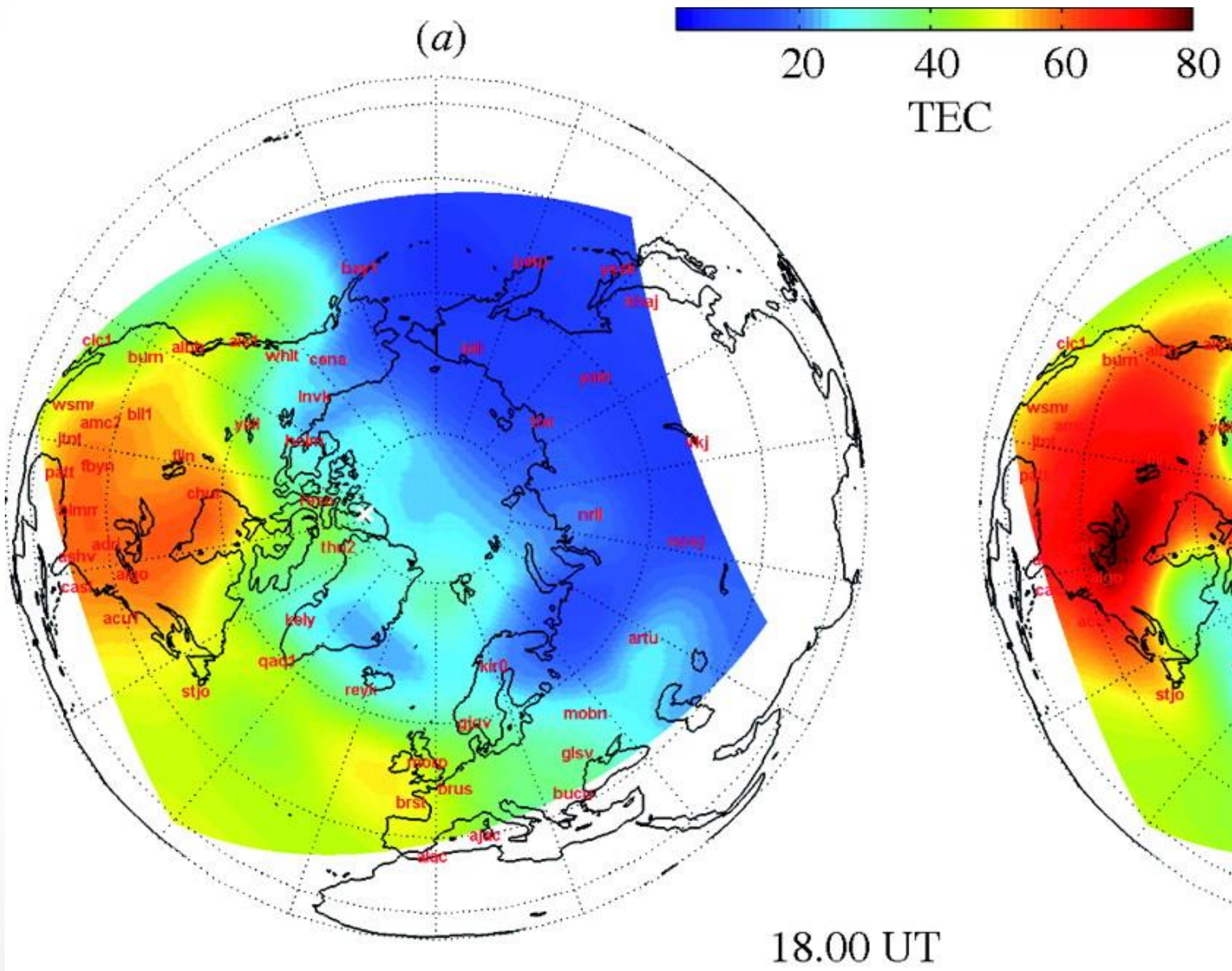
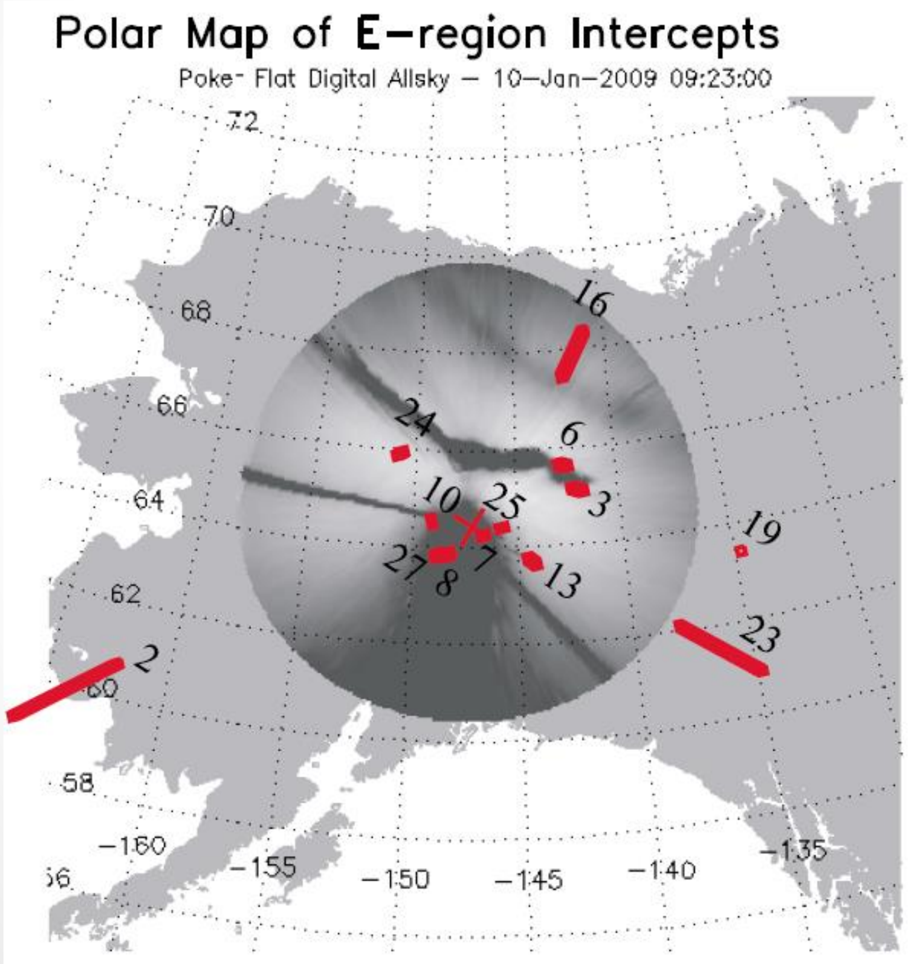
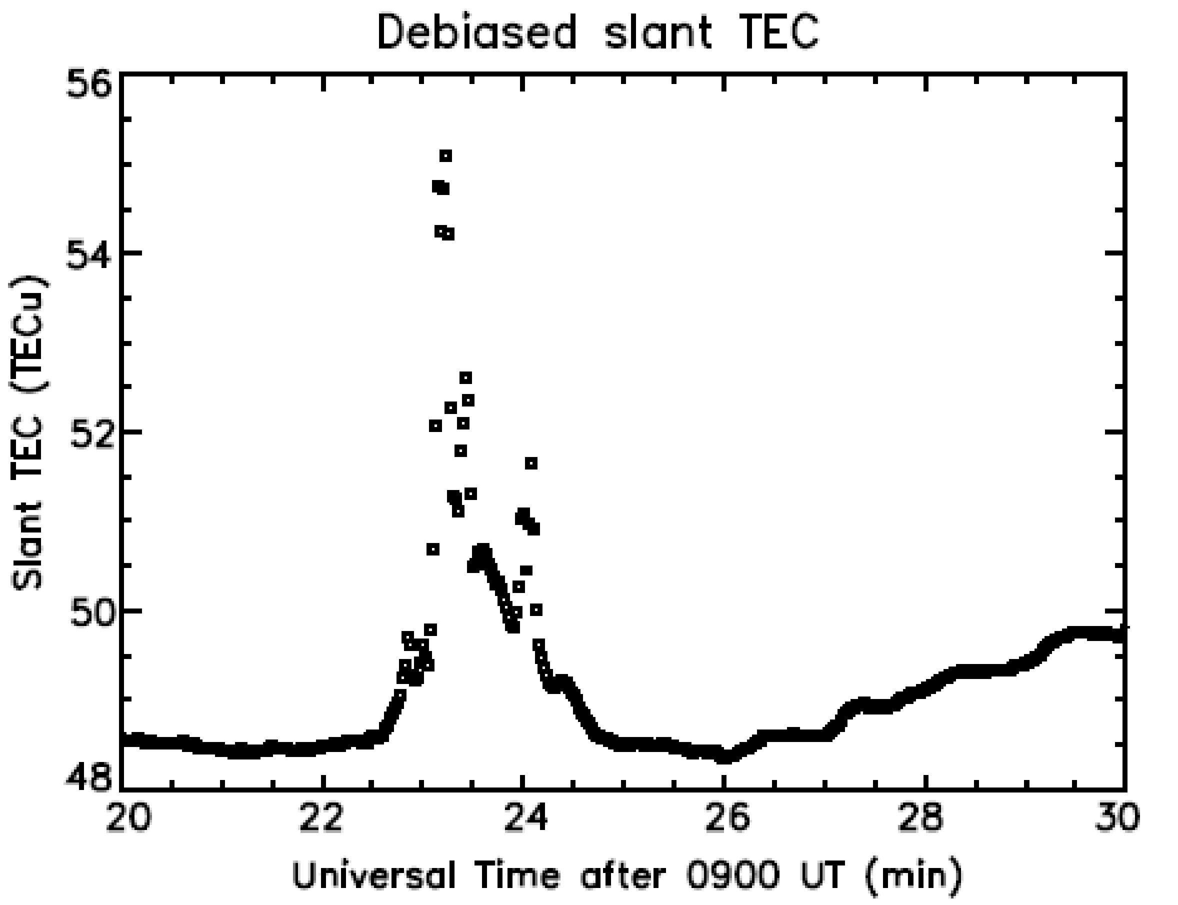


Pokhotelov et al., 2010

Background: TEC is enhanced in individual auroral arcs (with associated scintillation)

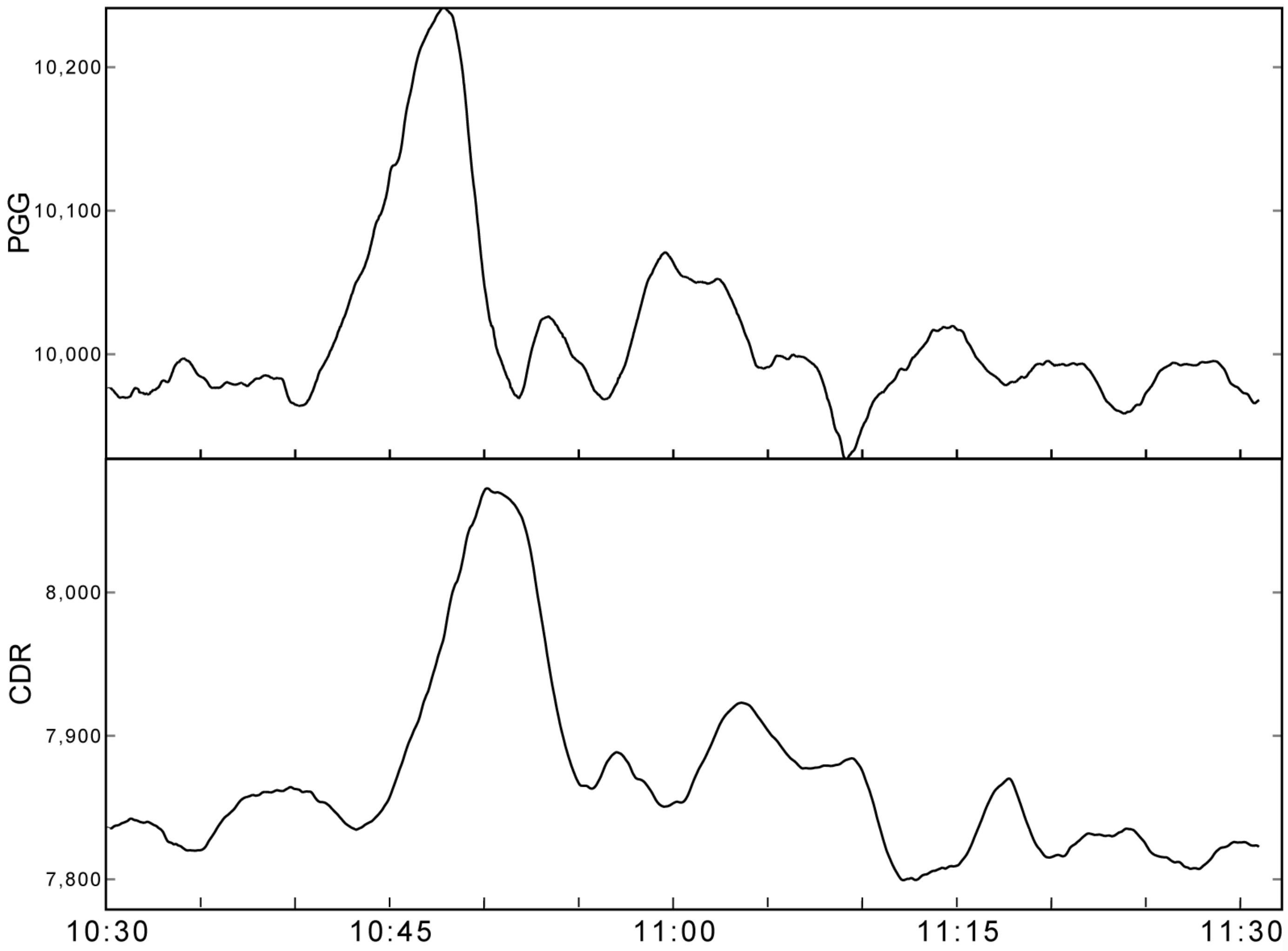




Garner et al., 2011

Background: TEC variations associated with passage of transient field-aligned current systems

- A large amplitude dayside transient (TCV) event was investigated for variations in TEC.
- We found that the TEC variations followed the presumed <u>westward</u> path of the associated field-aligned current system.
- Essentially, anything that changes the ionospheric density will register a GPS perturbation.



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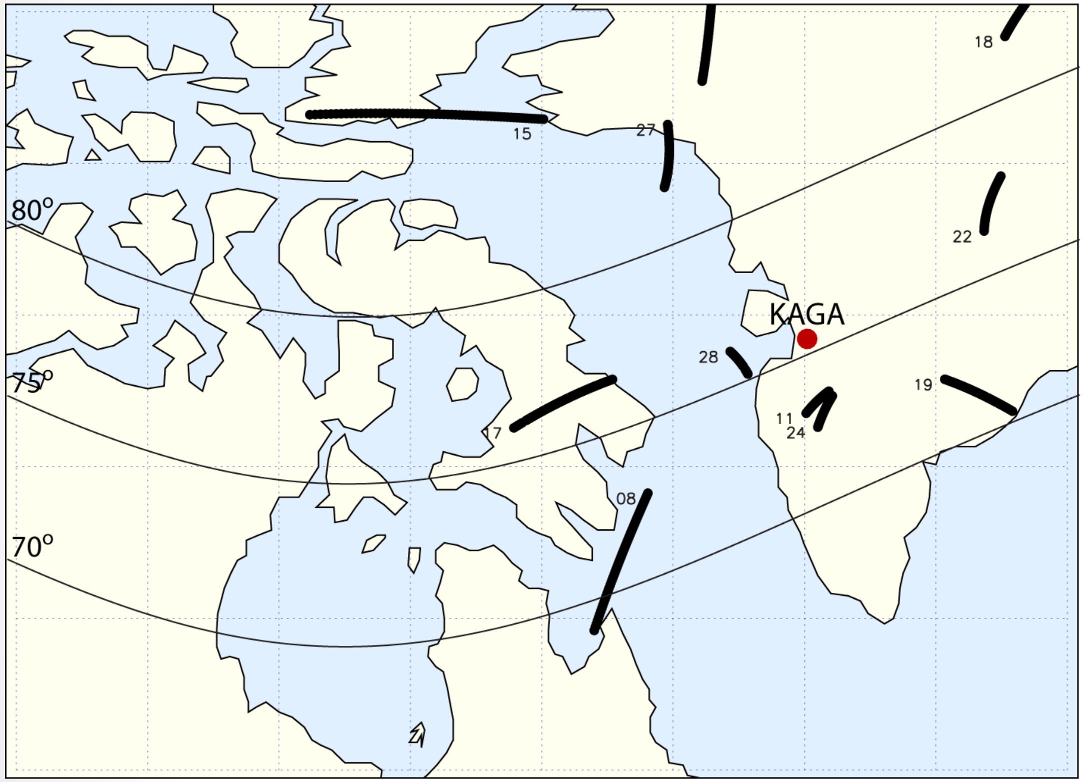

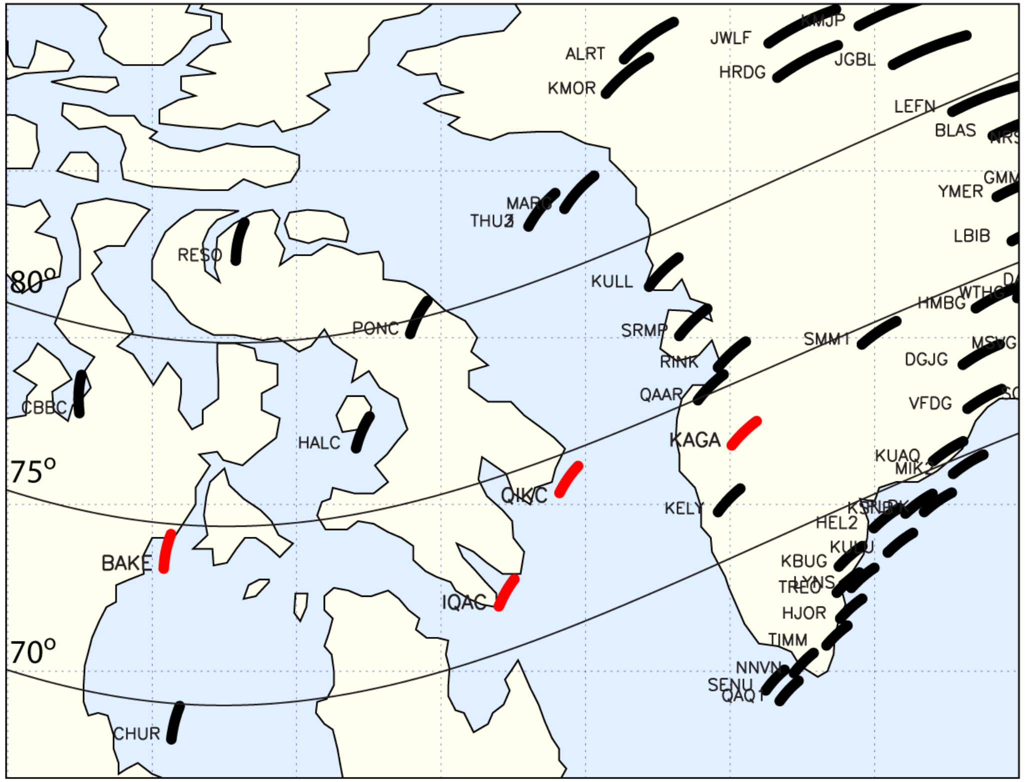

ULF Waves: Space-Ground Coordination

2015 Mini-GEM

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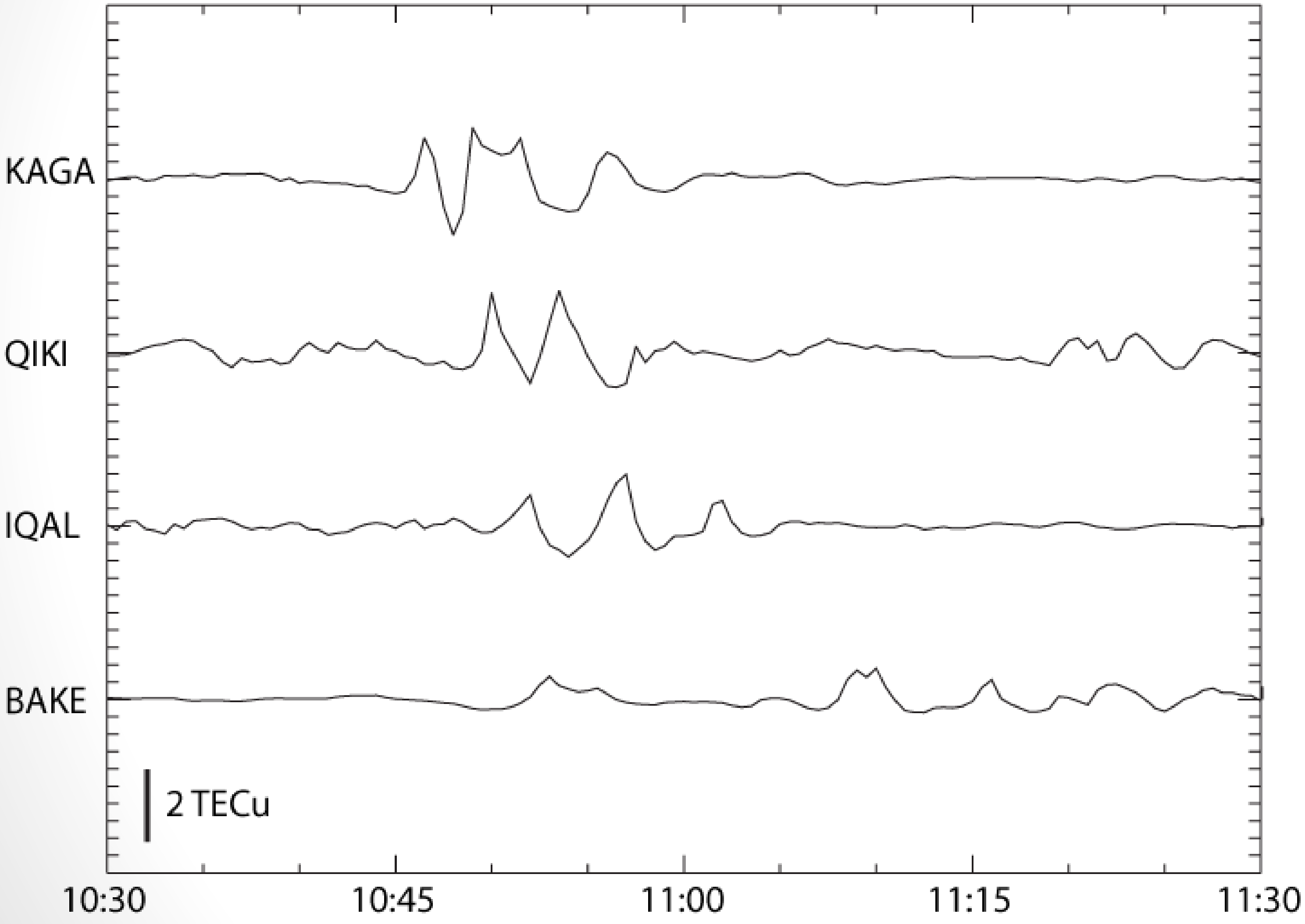
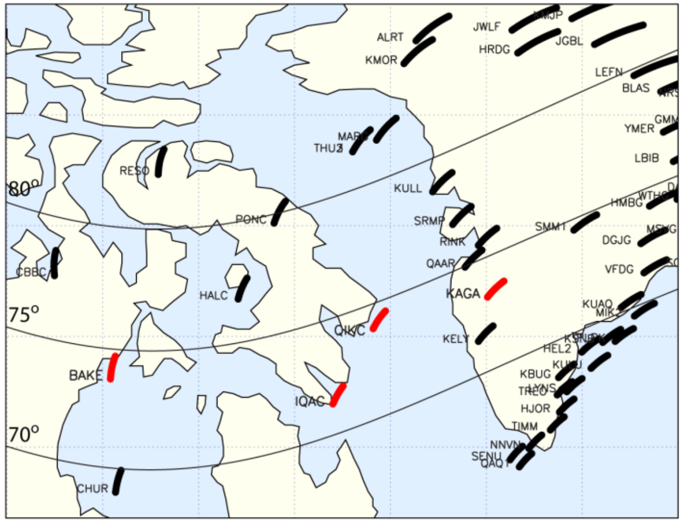




Propagation is westward.

TEC variations associated with ULF waves: A pre-GPS result by Davies and Hartmann [1976].

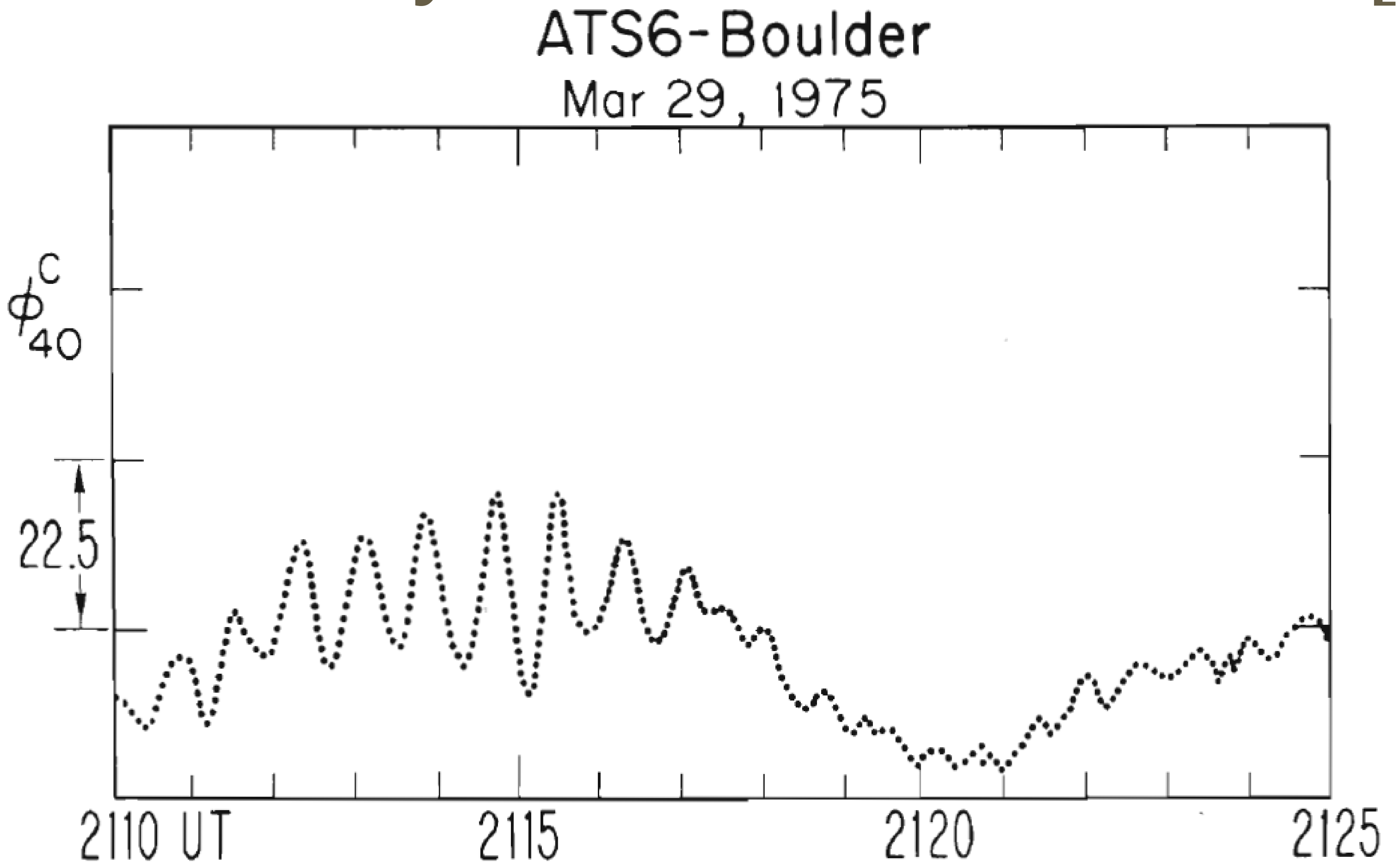
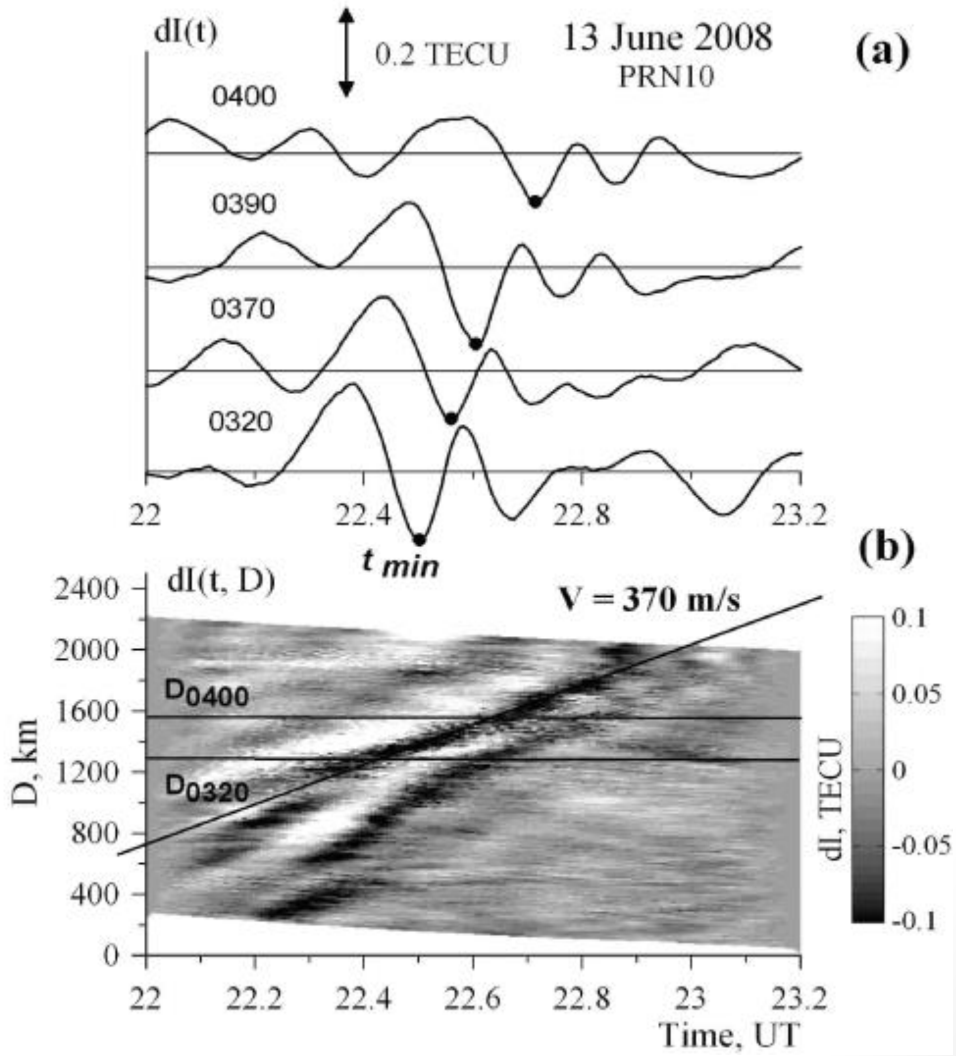


Fig. 5. Computer output at Boulder on March 29, 1975, showing oscillations in the ATS 6 40-MHz carrier phase with periods near 50 s.

Davies and Hartmann, 1976

TEC variations associated with ULF waves

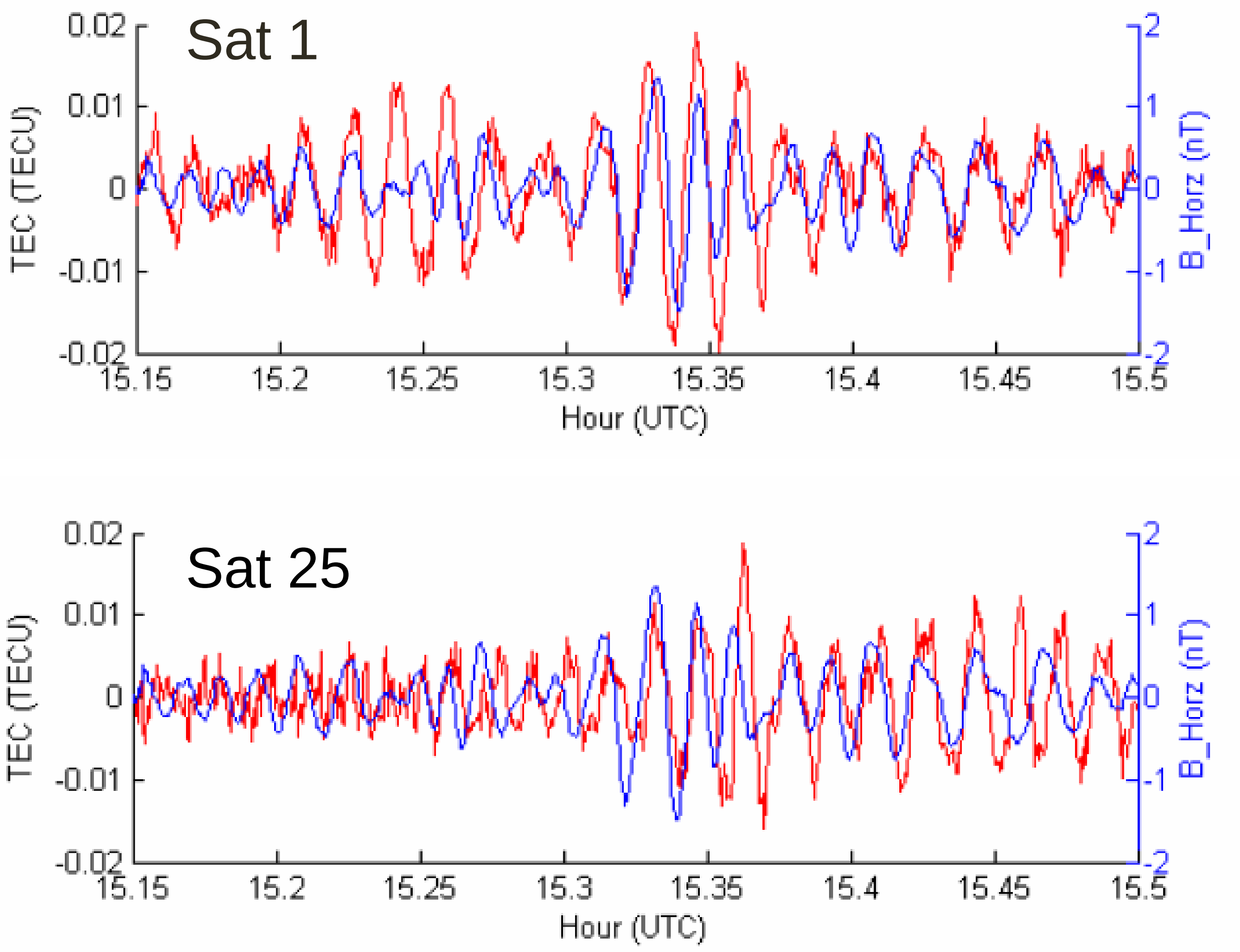
- The *Davies and Hartmann* results initiated theoretical studies to explain the observed variations in TEC. Several authors have used increasingly sophisticated models of the ULF wave fields in the ionosphere to explain and predict the impact on GPS signals (e.g., *Poole and Sutcliffe*, 1987; *Pilipenko and Fedorov*, 1995; *Waters and Cox*, 2009)
- Short-time variations in TEC are known to be caused by non-magnetospheric sources as well, such as traveling ionospheric disturbances, inertial gravity waves, or tsunamis.



Afraimovich, 2009

TEC variations associated with ULF waves

- *Skone et al*. [2006] presented several examples of large variations in TEC associated with geomagnetic Pc3 observations (using ground magnetometers).
- The mechanisms that could drive these variations are still not well understood.



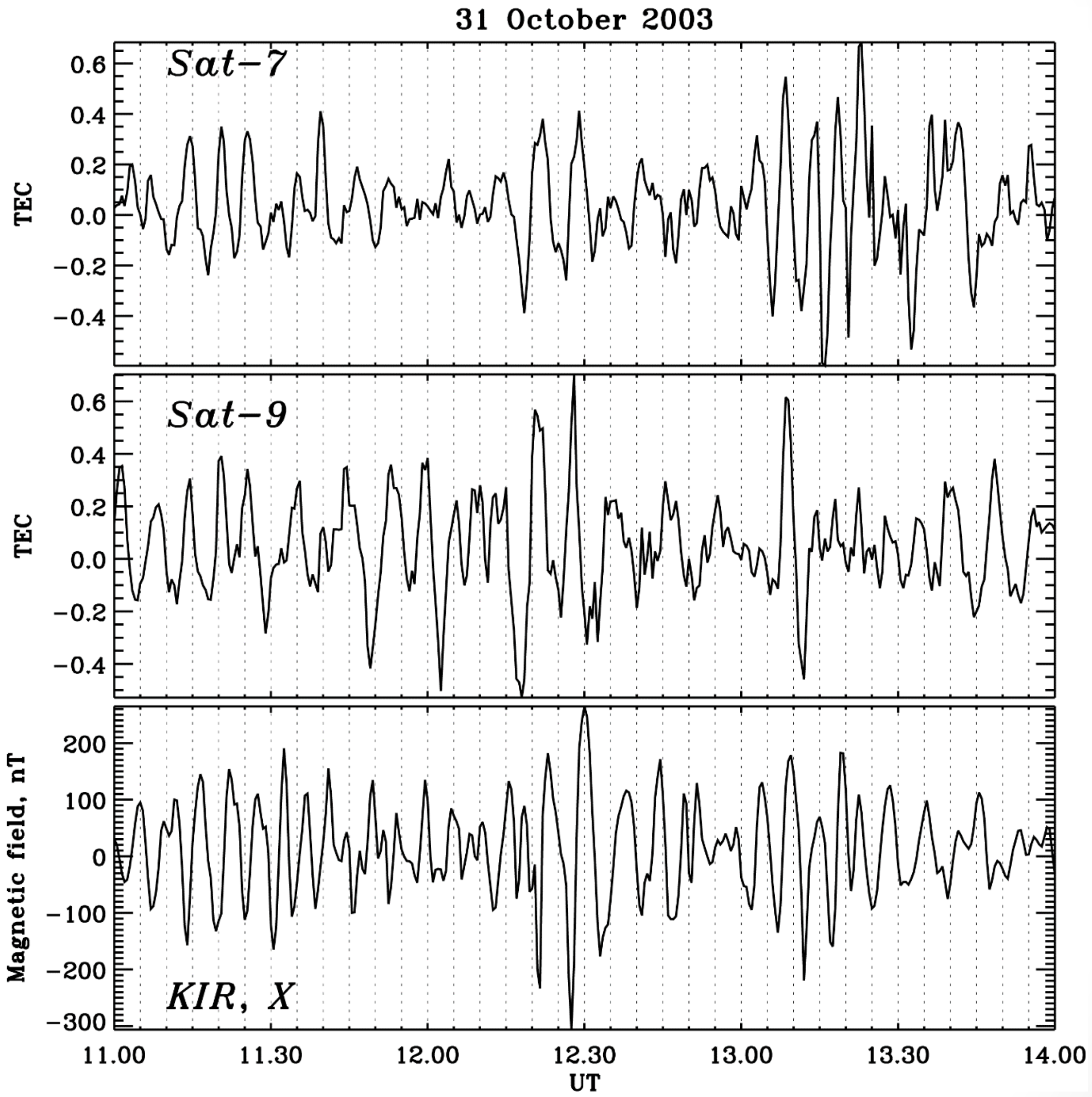
Skone, 2006

TEC variations associated with ULF waves

- Several mechanisms have been proposed, such as:
  - Periodic Particle Precipitation
  - Plasma Compression by Reflected Fast Mode Waves [*Pilipenko and Federov*, 1995]
  - Lateral Plasma Gradient [*Waters and Cox*, 2009]
  - Periodic Shifts of the Plasma Vertical Profile [*Poole and Sutcliffe*, 1987]
  - Ion Heating
  - Field-Aligned Plasma Transport [*Pilipenko et al.*, 2014]

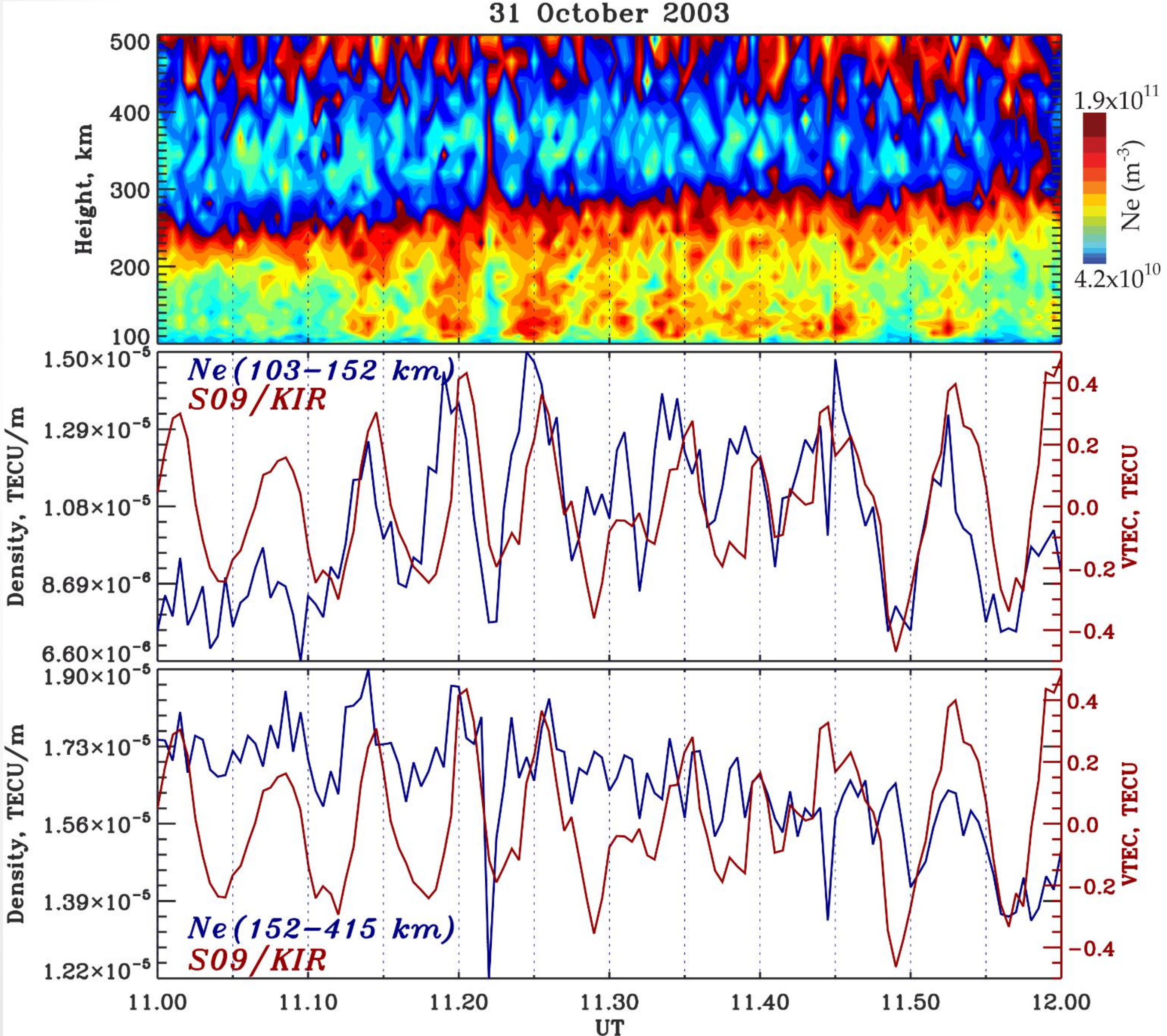
Our Work: Large Amplitude ULF waves during the 2003 "Halloween" storms

- During the recovery phase of some storms, large amplitude (>400 nT) Pc5 ULF waves can be observed on the dawn and dusk flanks
- *Pilipenko et al.*, 2012 have studied the ionospheric response to such waves using the EISCAT radar facility on 31 Oct, 2003 11-14 UT. A more full assessment of the possible mechanisms is treated in *Pilipenko et al.*, 2014.
- The absence of riometer absorption features (from IRIS) during the interval suggests observed ionospheric density variations were not due to accelerated electron precipitation



Pilipenko et al., 2014

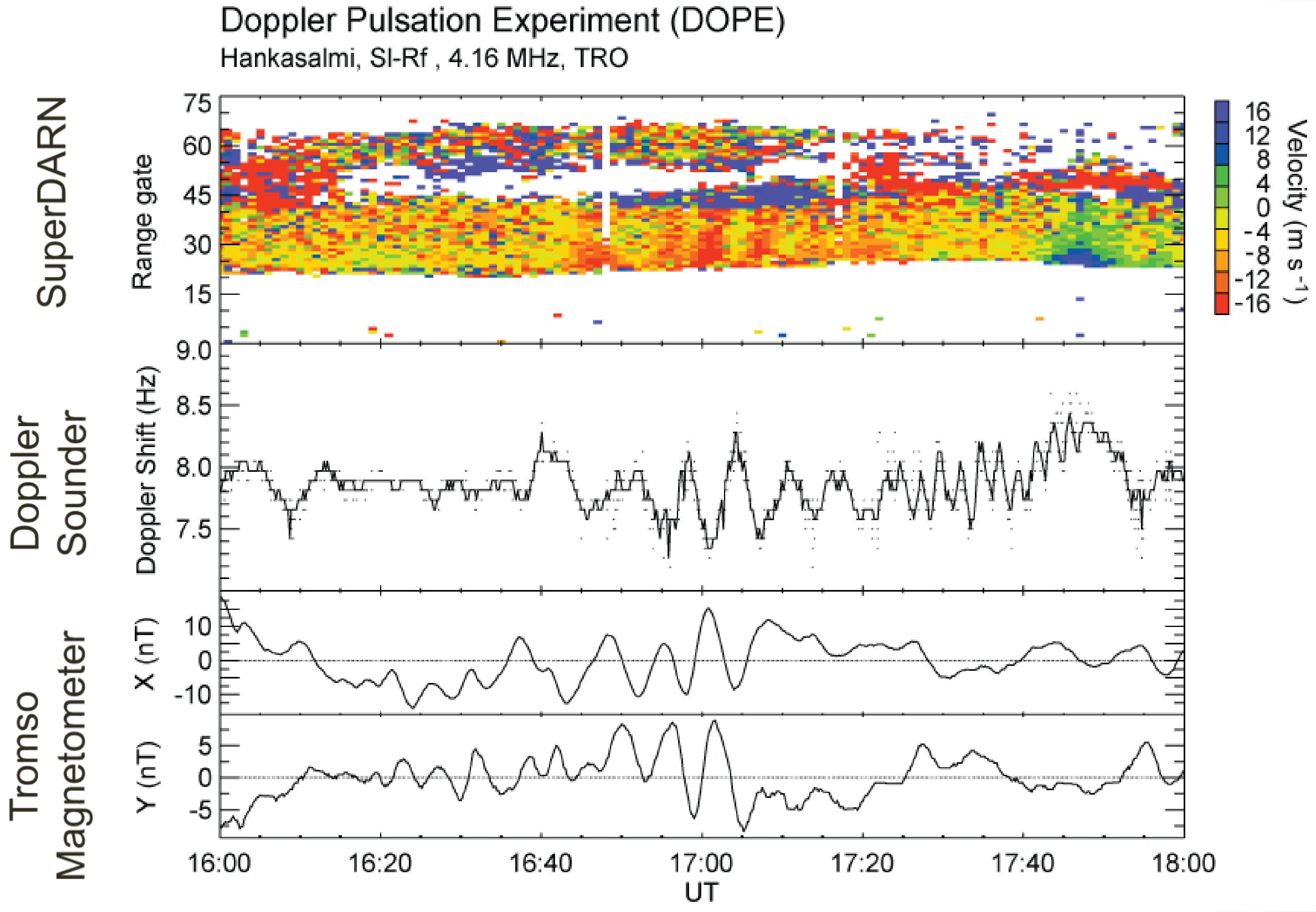
Our Work: Large Amplitude ULF waves during the 2003 "Halloween" storms



- EISCAT observations show that the TEC variations are a response to variations in the plasma density at the E- and lower F-region

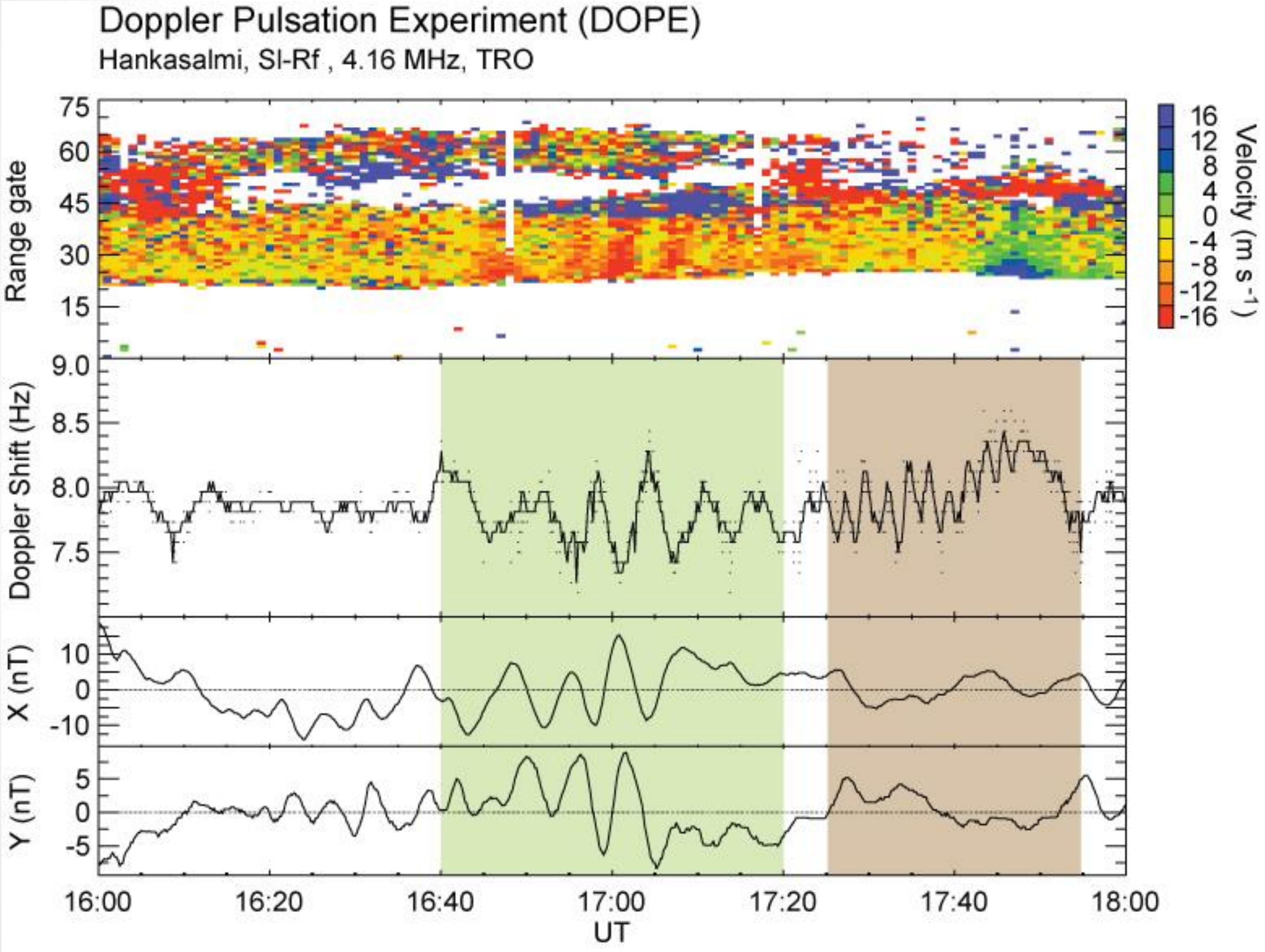
More "typical" (Pc5) ULF waves

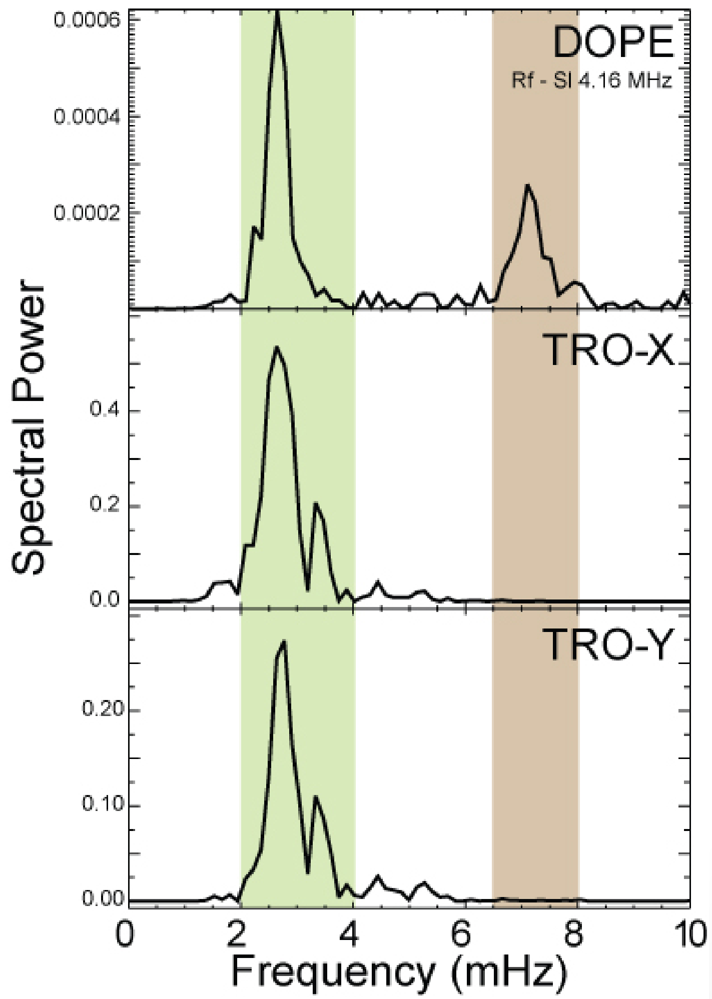
- Assessing the various mechanisms realistically requires simultaneous knowledge of all principal ionospheric parameters.
- We investigated previously published examples that included radar measurements.



Waters et al., 2007

More "typical" (Pc5) ULF waves

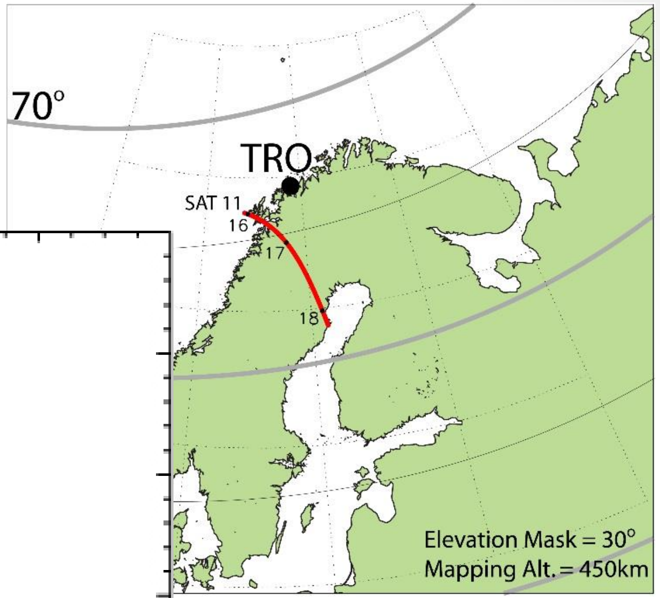


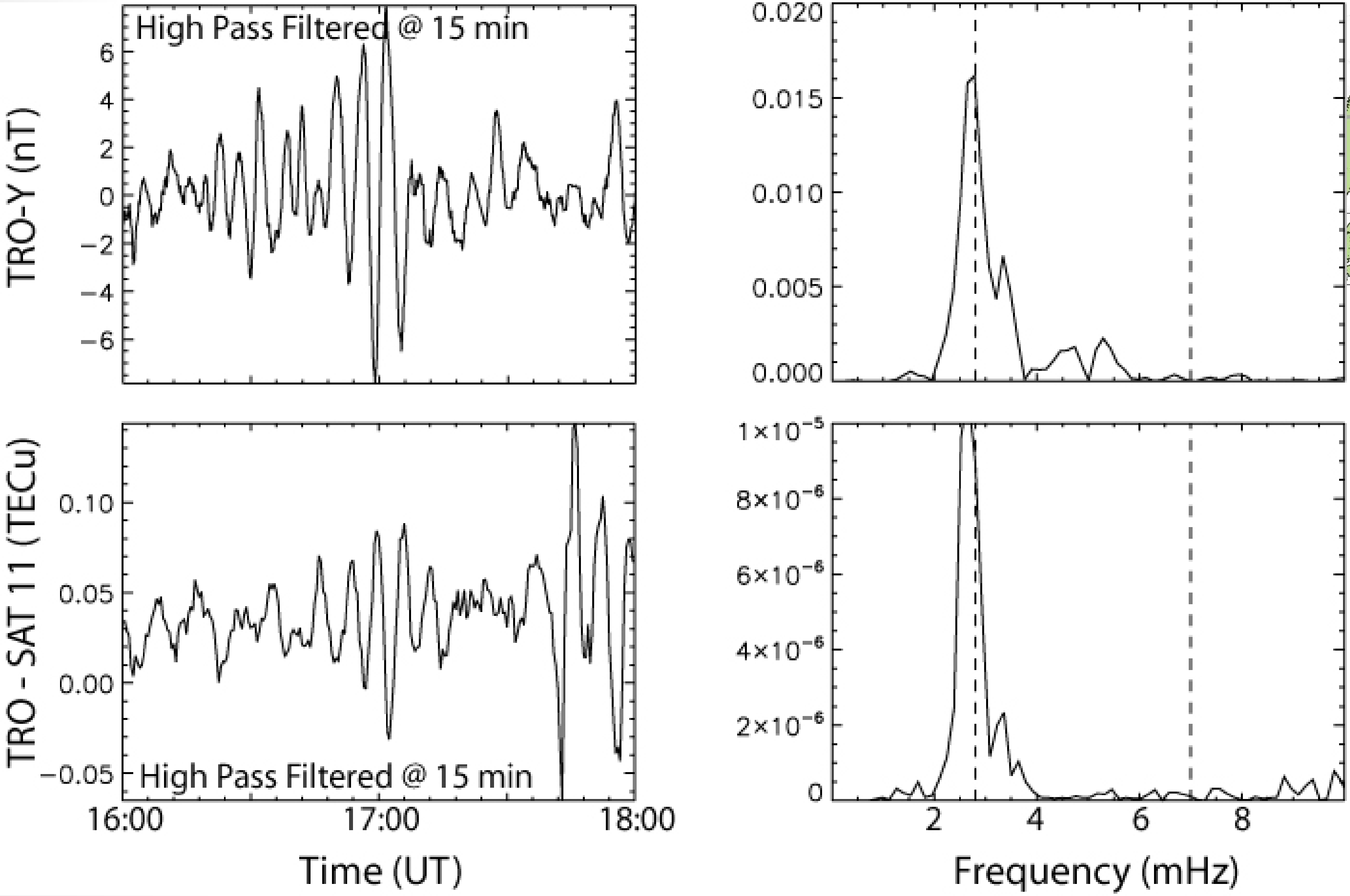


Two frequencies: Mag and Doppler see the lower one, only Doppler the higher one (high-m pulsation?). What about GPS?

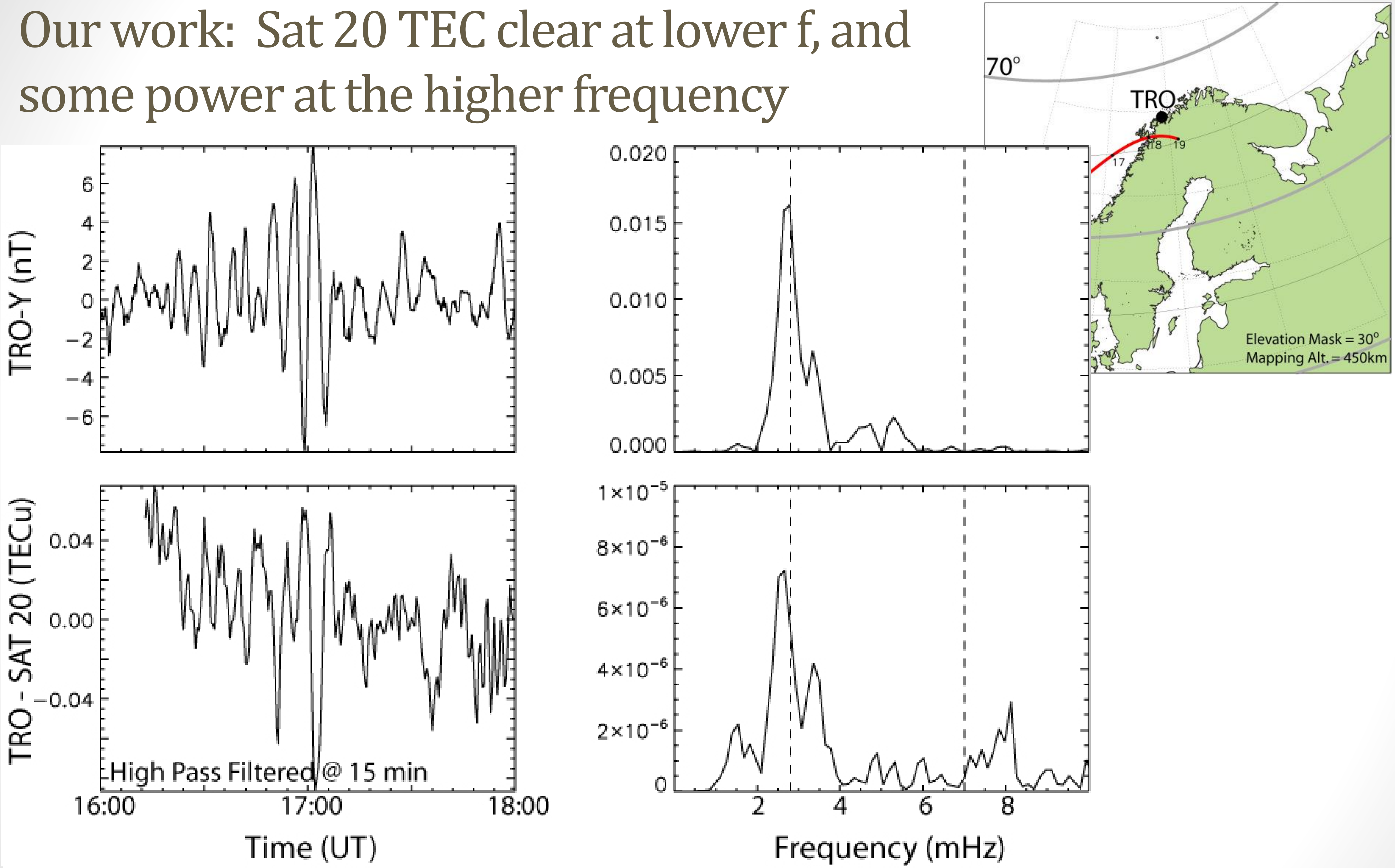
Waters et al., 2007

Our work: Sat 11 TEC clear at lower frequency

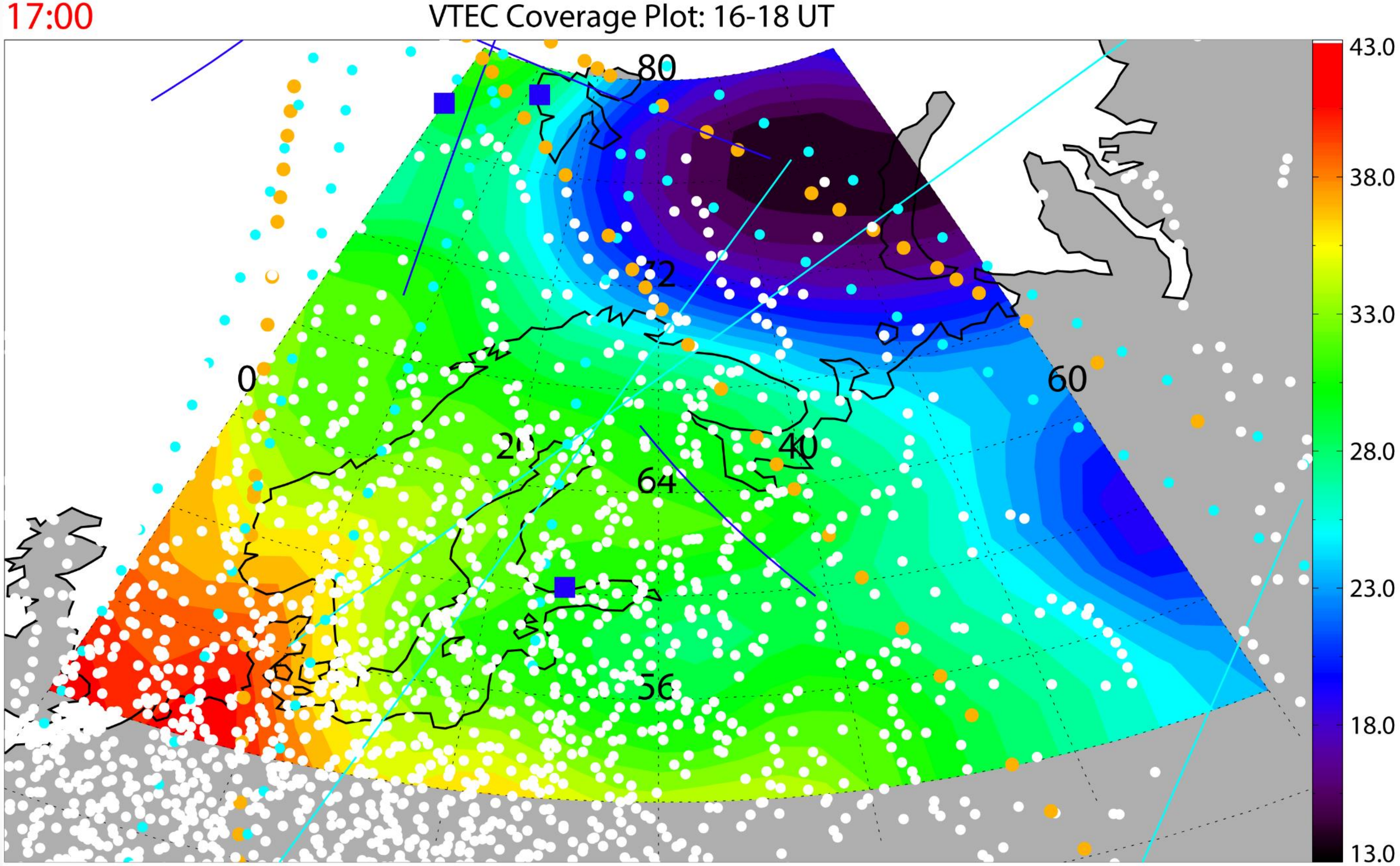




Our work: Sat 20 TEC clear at lower f, and some power at the higher frequency



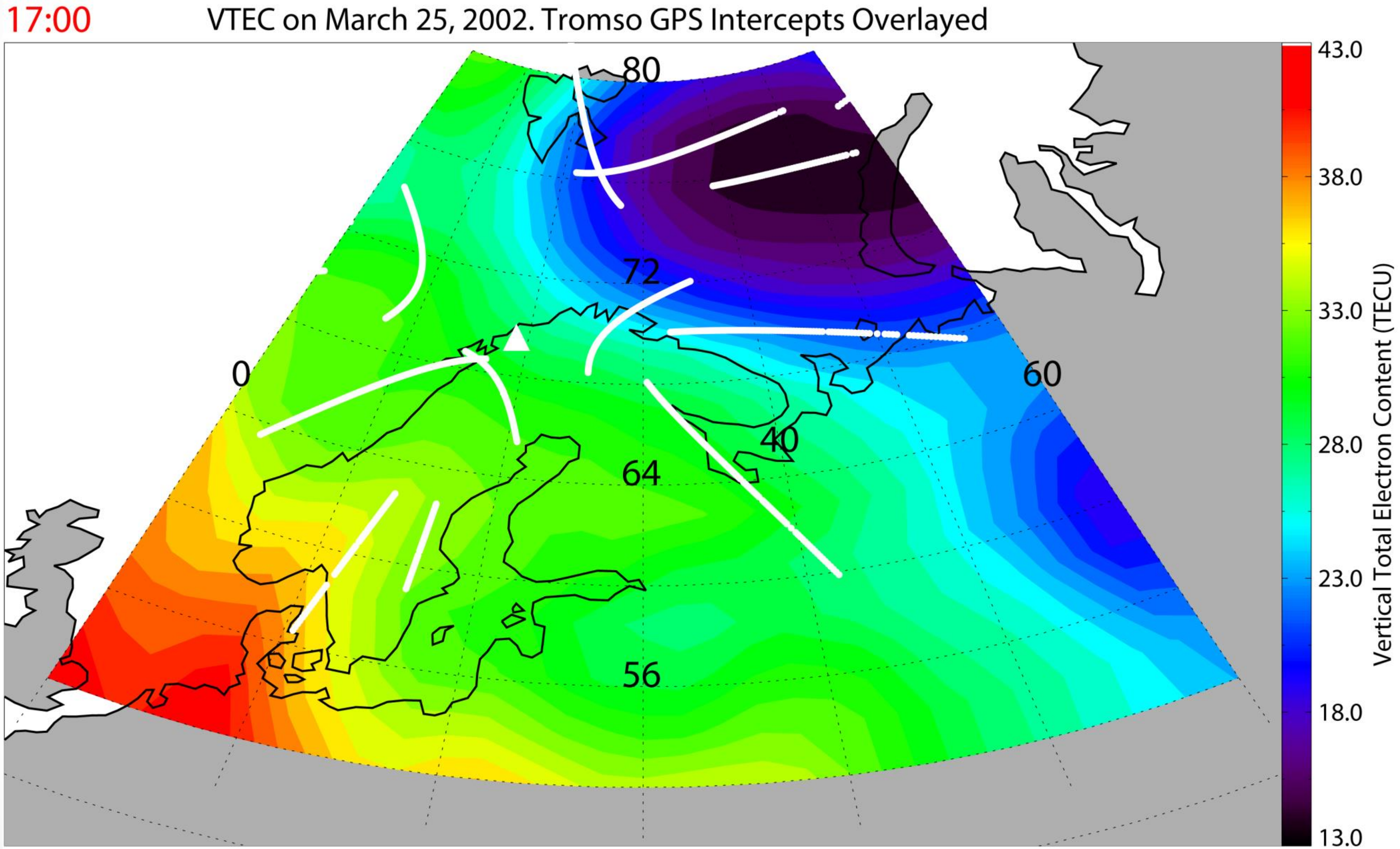
Broader GPS View: A Lateral Gradient? Yes.



Each dot represents a TEC receiver.

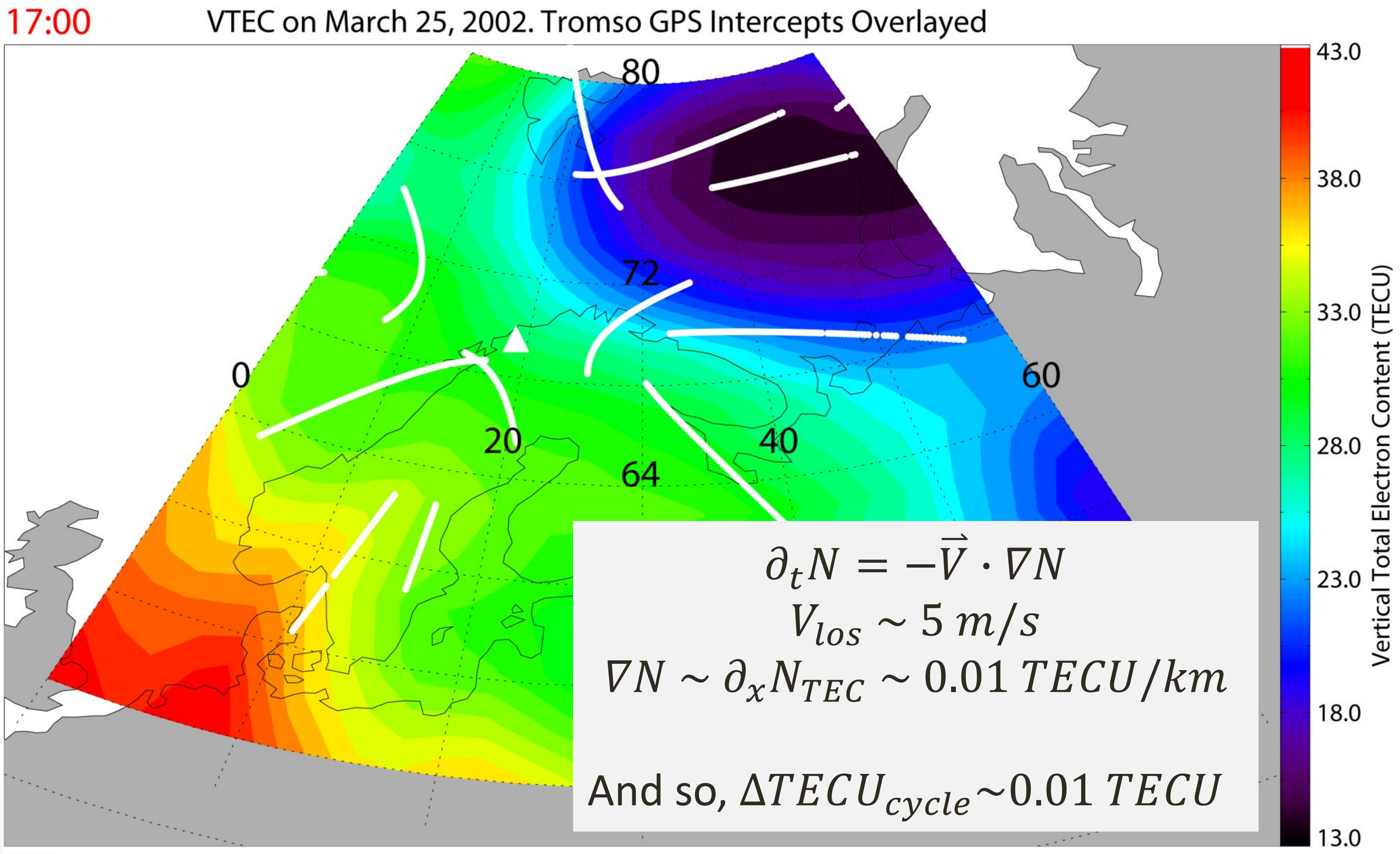
IAD3D ***Bust et al.***

Passage of a Lateral Gradient is the simplest of several mechanisms



IAD3D *Bust et al.*

Lateral Gradient theory applied here



$$\partial_t N = -\vec{V} \cdot \nabla N$$

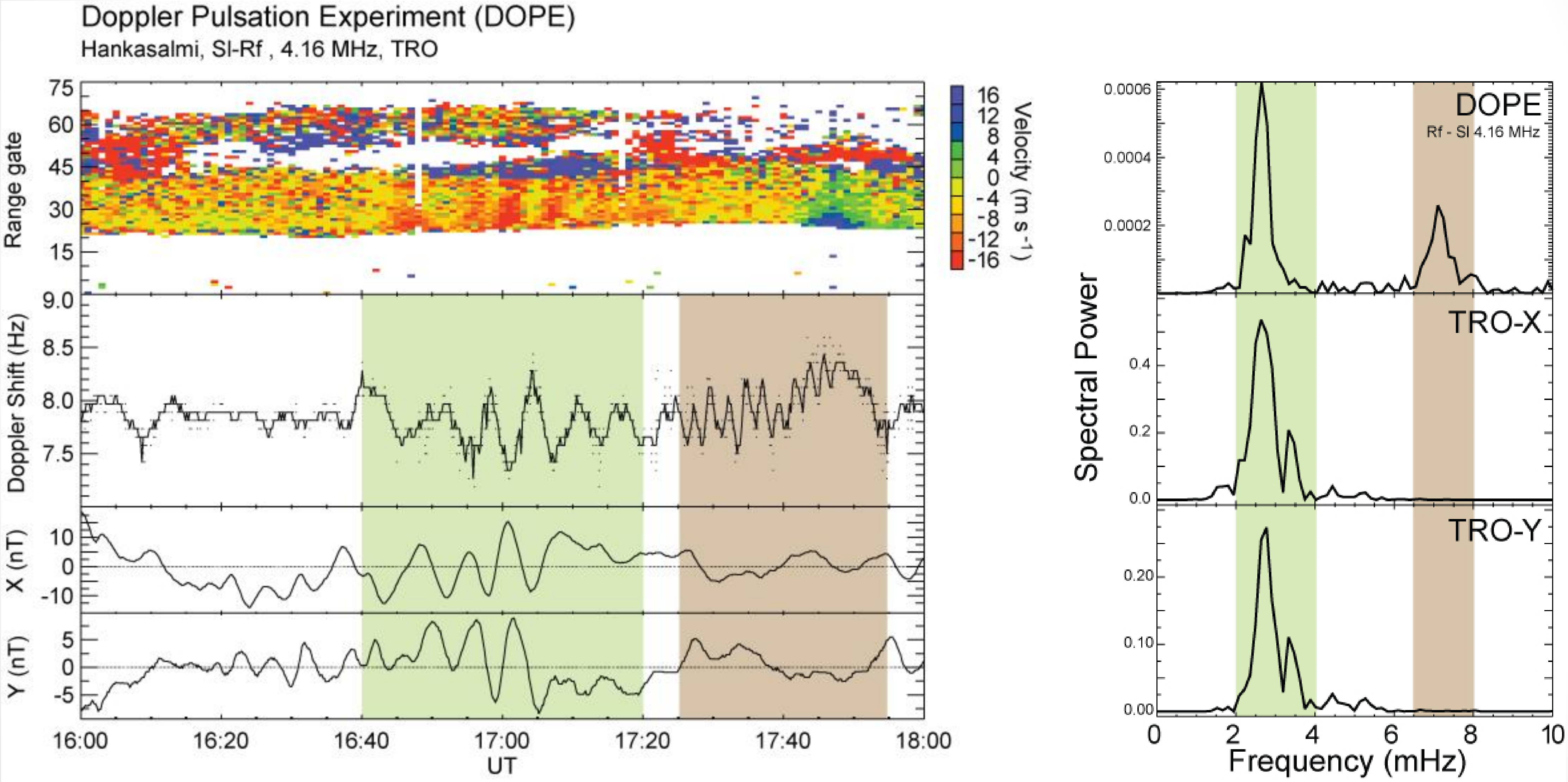
$$V_{los} \sim 5\, m/s$$

$$\nabla N \sim \partial_x N_{TEC} \sim 0.01\, TECU/km$$

And so, $\Delta TECU_{cycle} \sim 0.01\, TECU$

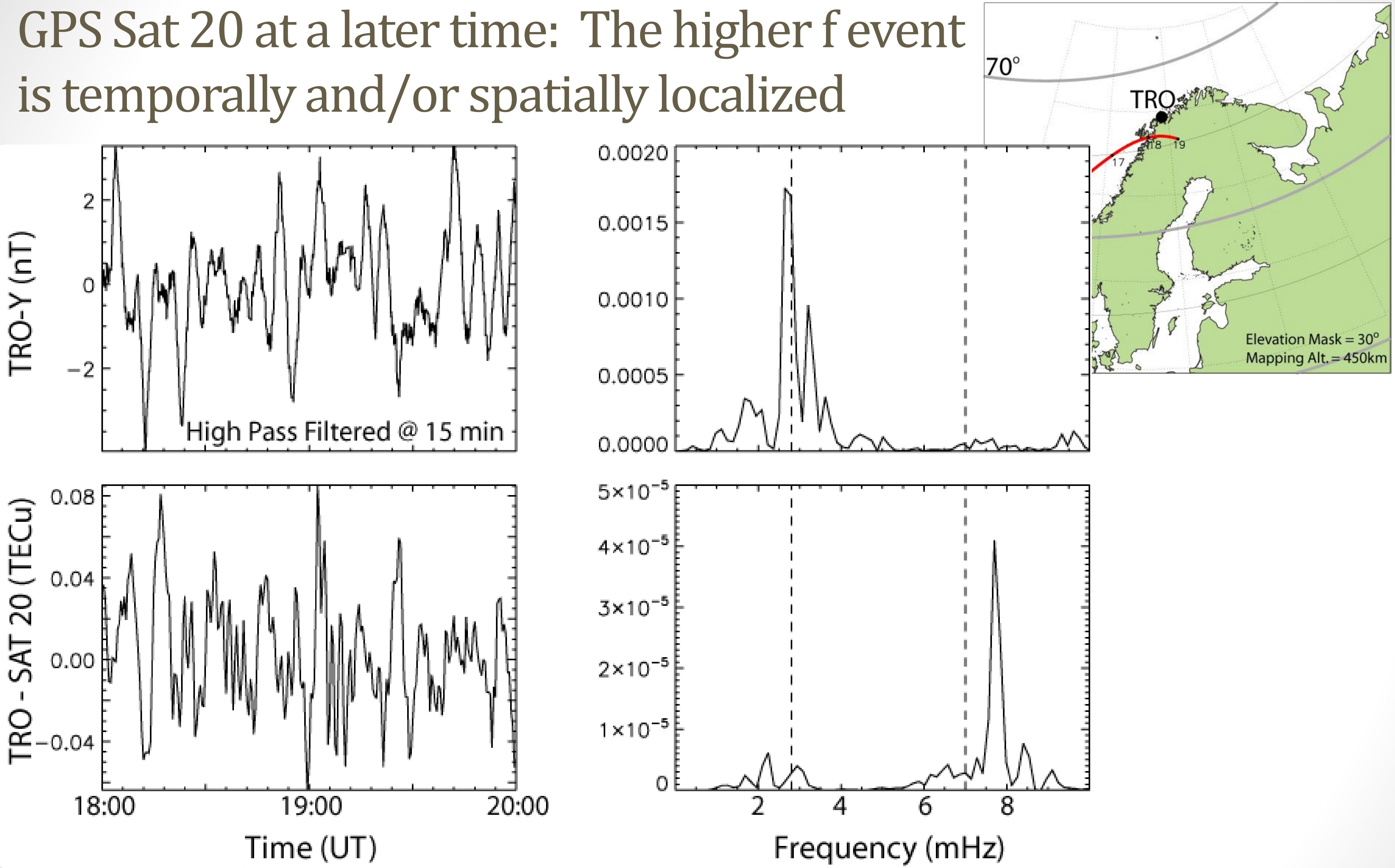
IAD3D *Bust et al.*

Back to this event: Look for the higher f signal in GPS TEC



Waters et al., 2007

GPS Sat 20 at a later time: The higher f event is temporally and/or spatially localized



What about Pc3?

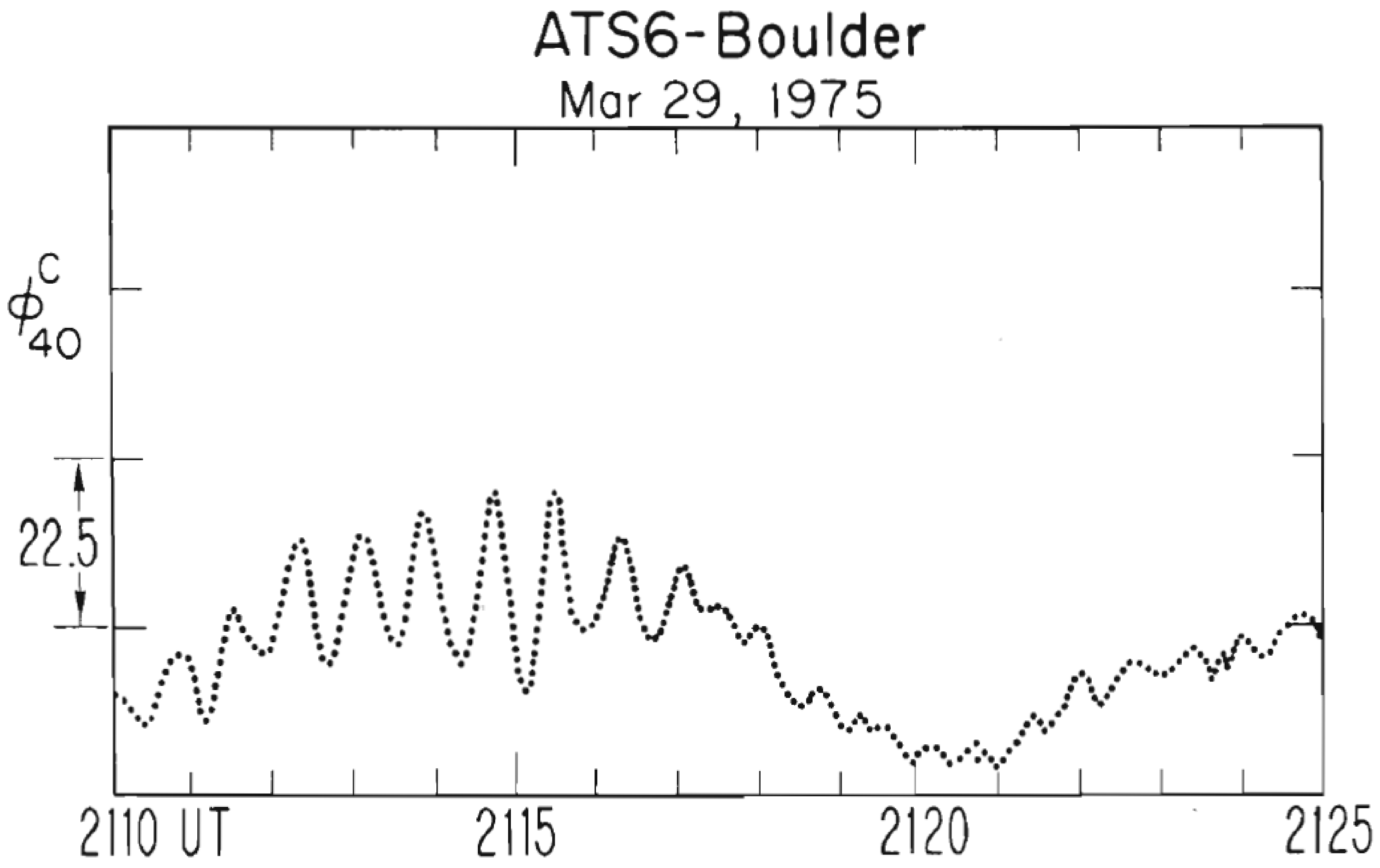
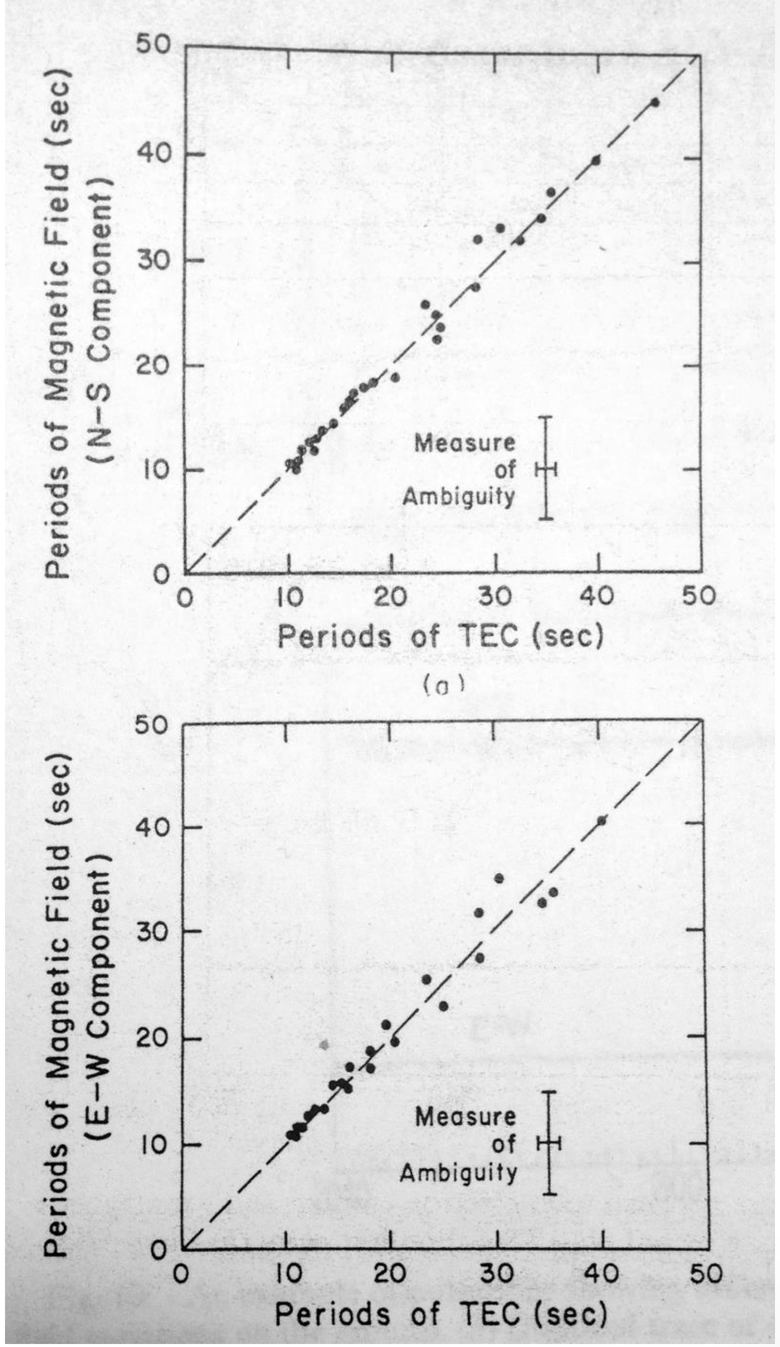


Fig. 5. Computer output at Boulder on March 29, 1975, showing oscillations in the ATS 6 40-MHz carrier phase with periods near 50 s.

Davies and Hartmann, 1976

What about Pc3?

- Only *Skone et al*. has shown a correspondence between TEC and geomagnetic fluctuations in the Pc3 band since the 1980s.
- *Skone et al*. reported TEC peak-to-peak amplitudes as large as 0.2 TECU and showed correlations with both geomagnetic observations and IMF orientation.
- The original *Davies and Hartmann* [1976] paper was followed by a more extensive set of events by *Okuzawa and Davies* [1981]. These studies used a beacon experiment on ATS 6 to probe the ionosphere. The TEC variations were compared to the local magnetic variations at mid-latitudes (Boulder, CO).
- **The average TEC peak-to-peak amplitude was ~0.006 TECU. (Their instrument was more sensitive than nearly all current GPS receivers!)**



Okuzawa and Davies, 1981

Current GPS arrays and sampling rates

- There are now over 2000 GPS receivers sampling at 1 Hz or better in the U.S. alone
- Possibility of imaging mid-latitude ULF wave activity

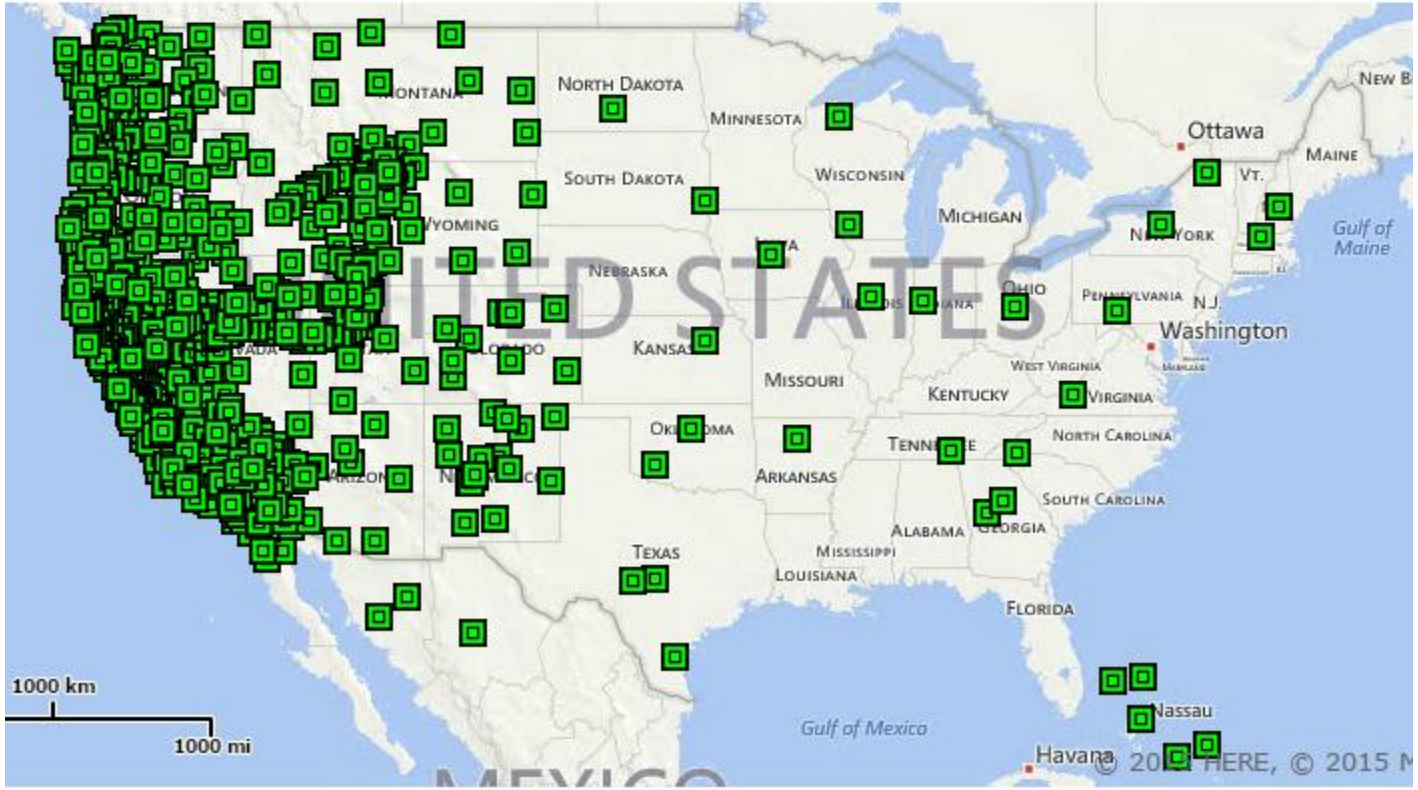
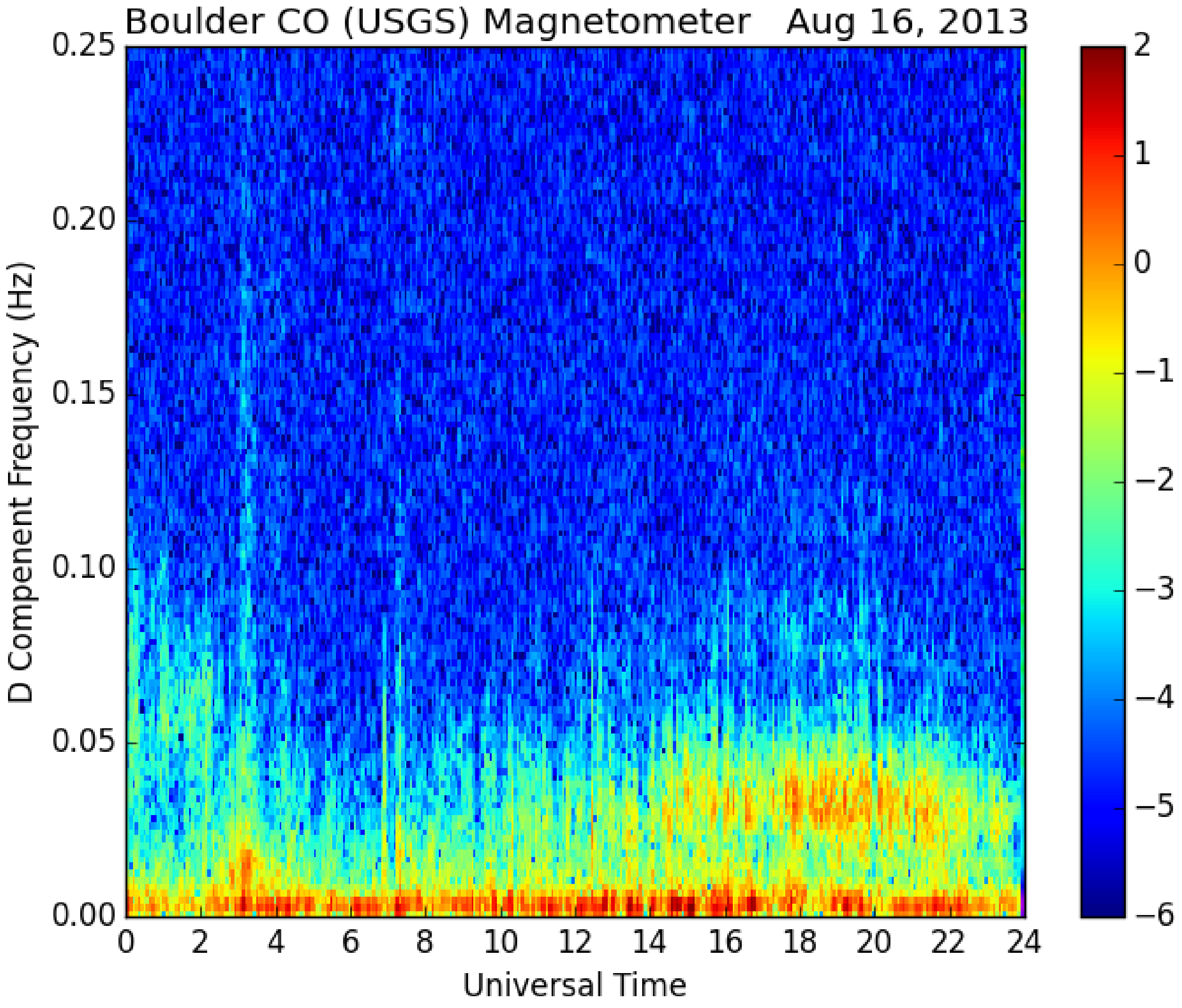


Plate Boundary Observatory (PBO) - UNAVCO

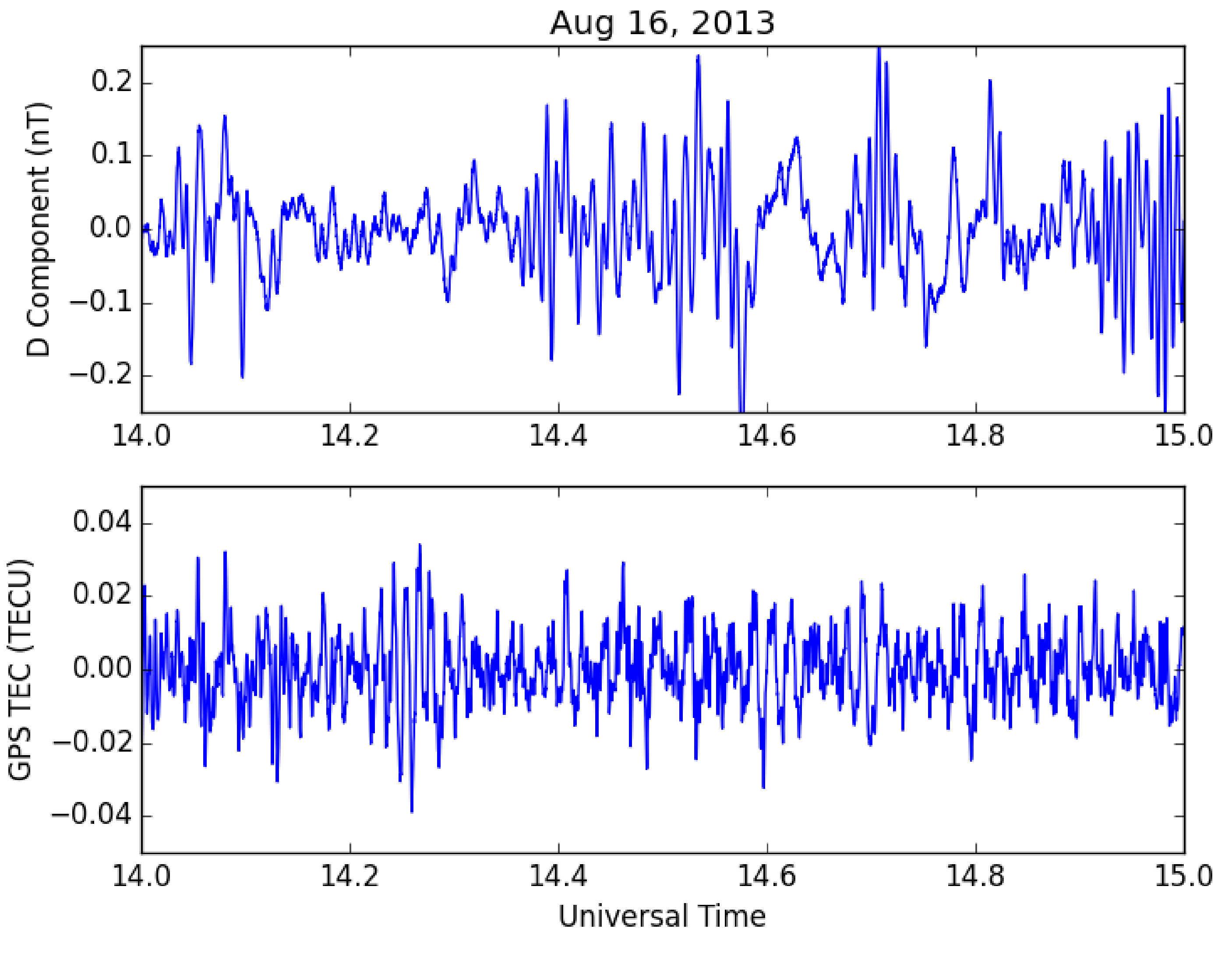
Can we recreate the *Okuzawa and Davies* results?

- Initial survey of 2013-2015 data
- Examined 6-7 GPS stations near Boulder (a lot of data!)
- Two main results:
  - **Typical receiver noise is around 0.01 TECU – about twice the average amplitude in *Okuzawa and Davies*.**
  - Difficult to run automated analysis due to presence of interference.



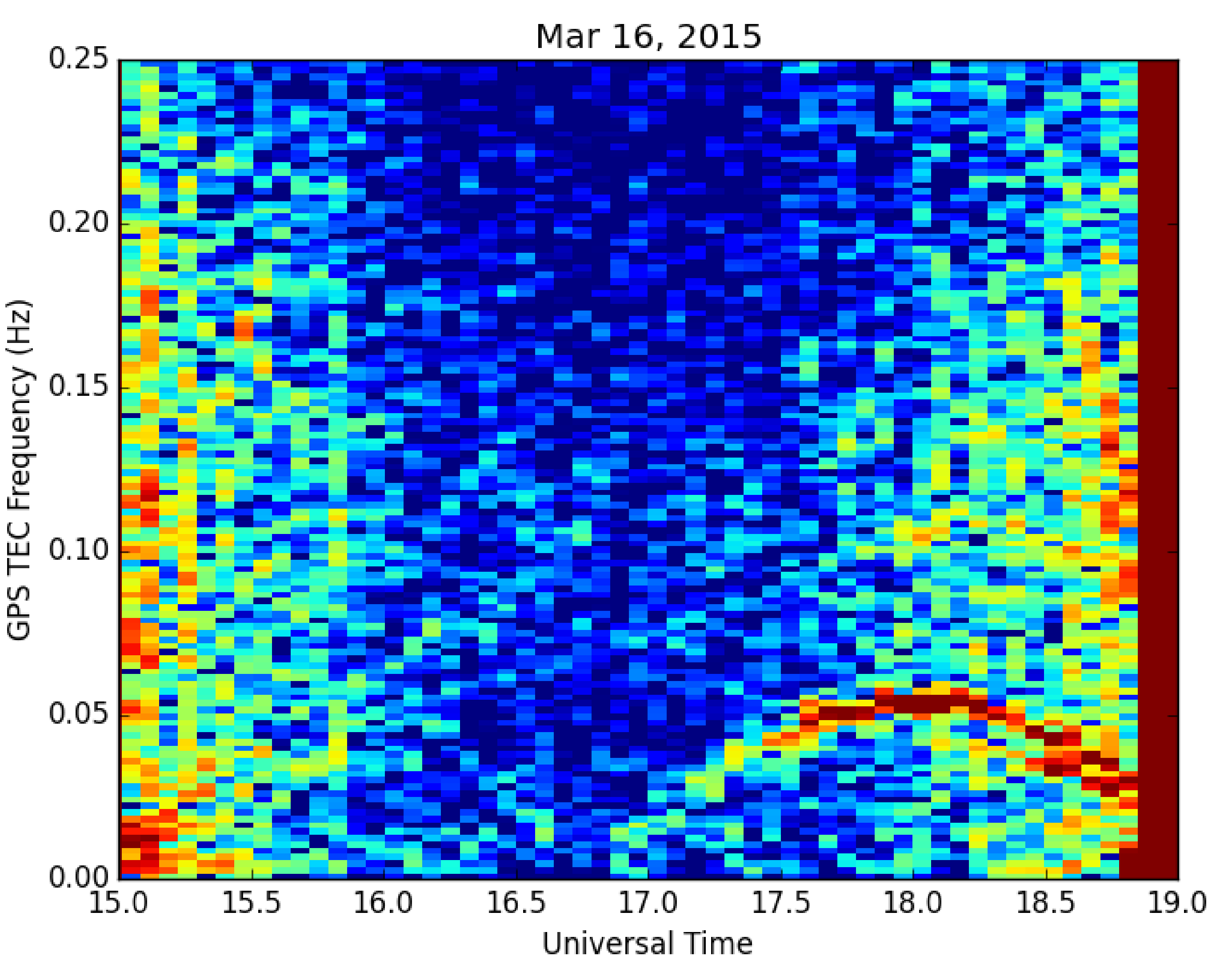
Can we recreate *Okuzawa and Davies*?

- During strongest wave events "good correlations can be found," but probably not enough for thorough statistics.
- *Okuzawa and Davies* noted that the TEC Pc3 amplitude did not always follow the ground magnetometer signal. Overall they found a ~66% correspondence rate.



Can we recreate *Okuzawa and Davies*? Probably not.

- GPS interference patterns often dominate the Pc3 band.
- It is interesting to note that *Okuzawa and Davies* were limited to a ~40° elevation angle. For GPS TEC this elevation angle typically results in interference in the middle of the Pc3 band.
- Very little such interference is observed looking upward.



Conclusions

- Although GPS TEC measurements appear to be a promising (or a possible) new means to investigate ULF waves, more detailed and extensive studies are required to fully understand the physical mechanisms that produce the signal
- New GPS observational arrays and higher sampling rates may allow for greater progress, but higher sensitivity may be essential.
- Some instrumental tradeoffs may be needed to optimize GPS receivers to see ULF pulsations consistently.
- Better processing software, geared toward ULF wave studies, may allow for more members of the community to more easily participate.