Properties of Ionospheric Doppler Oscillations Driven by Downgoing ULF Waves

F. W. Menk and C. L. Waters

University of Newcastle, Australia

THE UNIVERSITY OF NEWCASTLE AUSTRALIA

CENTRE FOR SPACE PHYSICS NEWCASTLE AUSTRALIA

Background

ULF wave signatures are often observed in SD ground scatter returns at mid- to low latitudes.

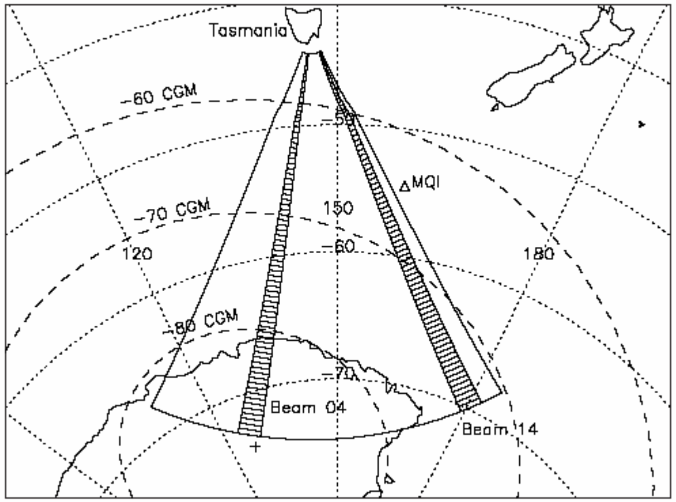
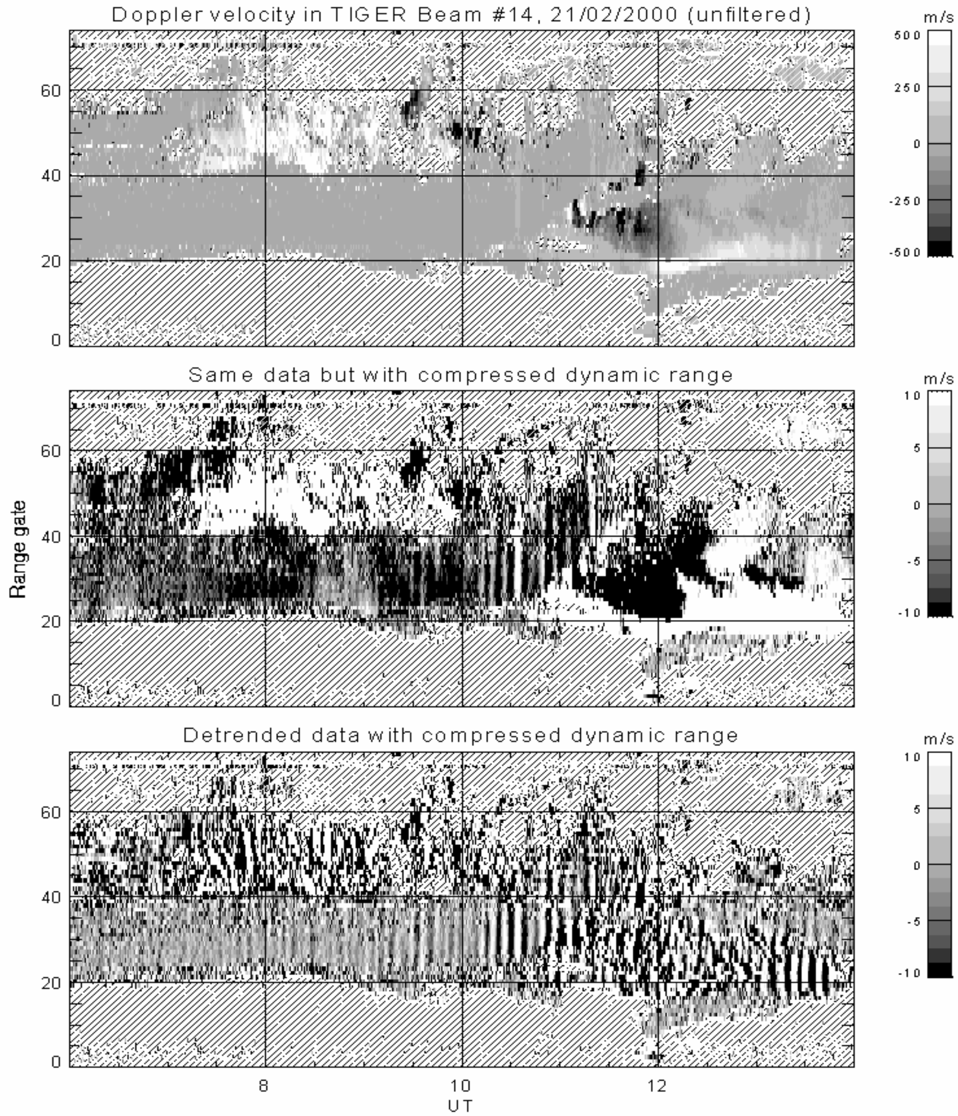


Figure 1. TIGER FOV in geographic coordinates. Triangle denotes Macquarie Island (MQI) magnetometer site.

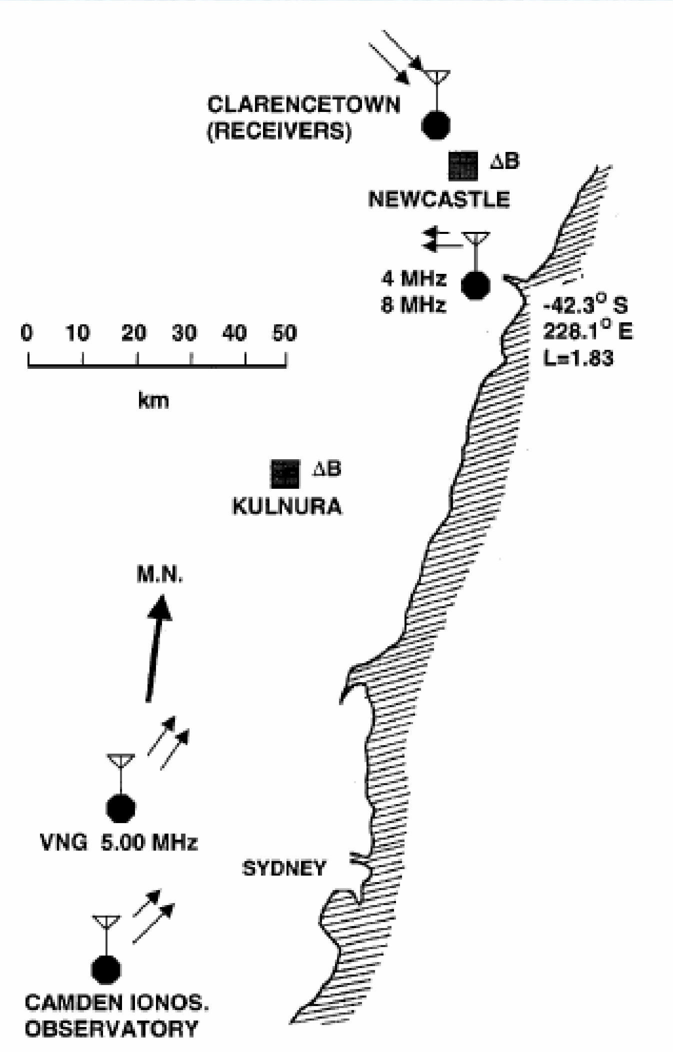


[Ponomarenko, Menk and Waters, *GRL*, **30**, 2003]

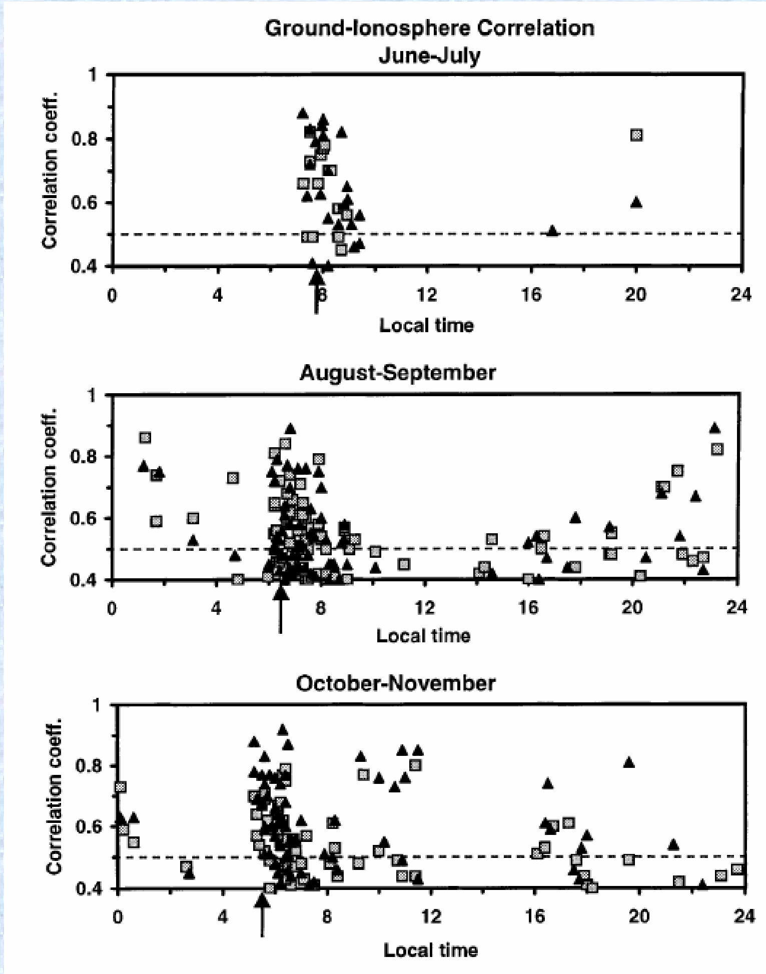
The Experiments

- We investigated the properties of ULF wave fields in the low-latitude ionosphere using HF Doppler radio sounders and ground magnetometers.
- The Doppler sounders monitored frequency shifts in O-mode reflections from HF frequency standard transmitters with a sensitivity of ≤0.005 Hz over 1-140 mHz.
- The magnetometers provided information on the ULF wave modes propagating from the magnetosphere through the ionosphere.
- There were two studies:
  - A preliminary study at L = 1.83
  - A detailed study spanning L = 1.57 – 2.77.

Preliminary Study



L = 1.83; Jun – Dec 1991
and Dec 1992 – Jul 1993.



Preliminary Study

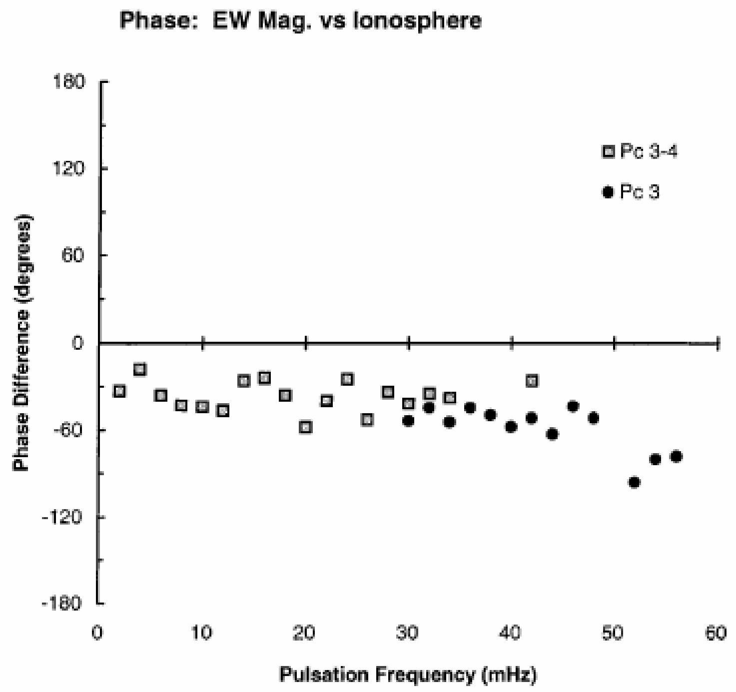


Fig. 7. Phase difference between Doppler shift oscillations and EW component magnetic pulsations as a function of pulsation frequency, for *Pc 3-4 events* (*squares*) and *regular Pc 3* (*solid circles*)

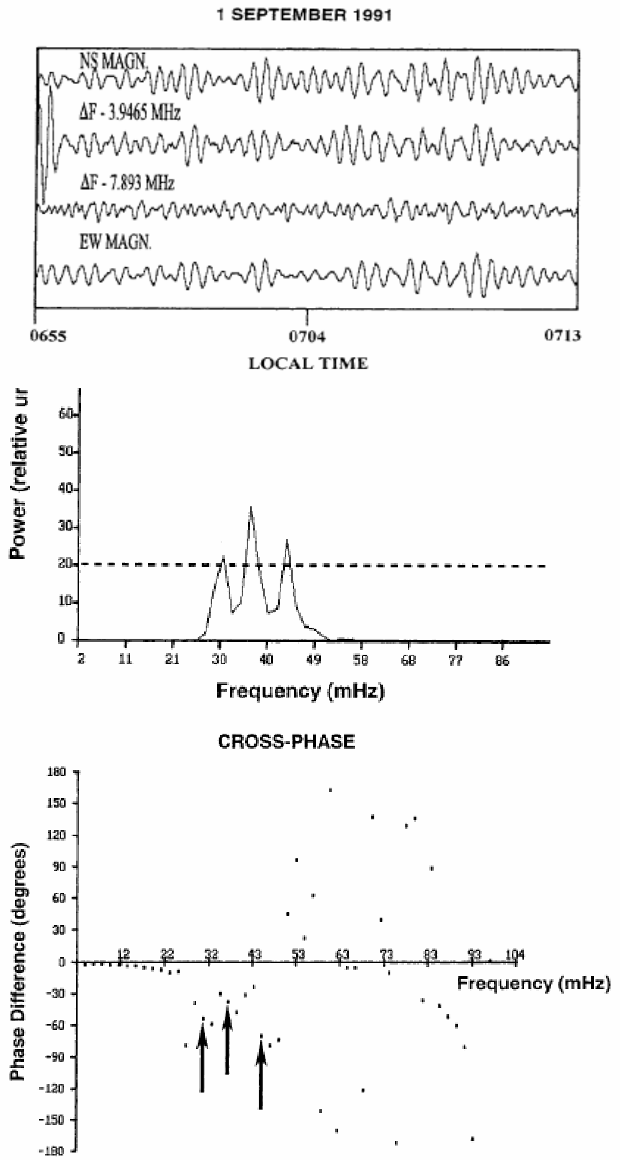
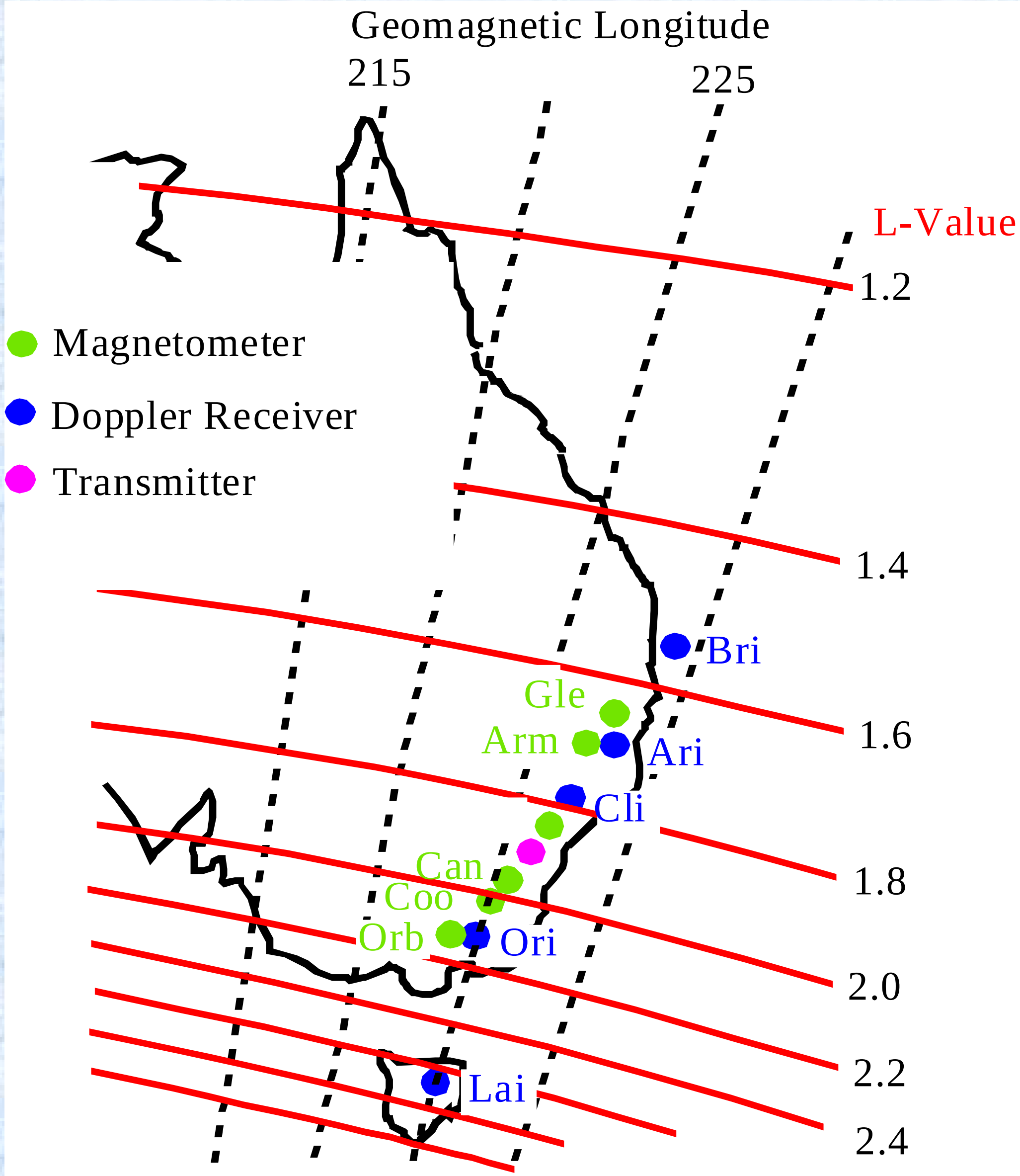


Fig. 8. Typical example of *regular Pc 3*, 1 September 1991. *Top panel* shows Doppler and magnetometer time series, highpass filtered at 30 mHz, in the same format as for Fig. 2. *Middle panel* presents EW magnetometer/4 MHz Doppler cross-power spectrum for this event; *bottom panel* shows corresponding cross-phase spectrum. Values with acceptable cross-power are *arrowed*. Negative cross-phase denotes the ground pulsation lagging the ionospheric Doppler oscillation

[Marshall and Menk,
Ann. Geophys., **17**, 1999]

Detailed Study



HF transmitters at L = 1.94.

5 Doppler receivers

10 magnetometers arranged in 5 pairs beneath ionospheric midpoints.

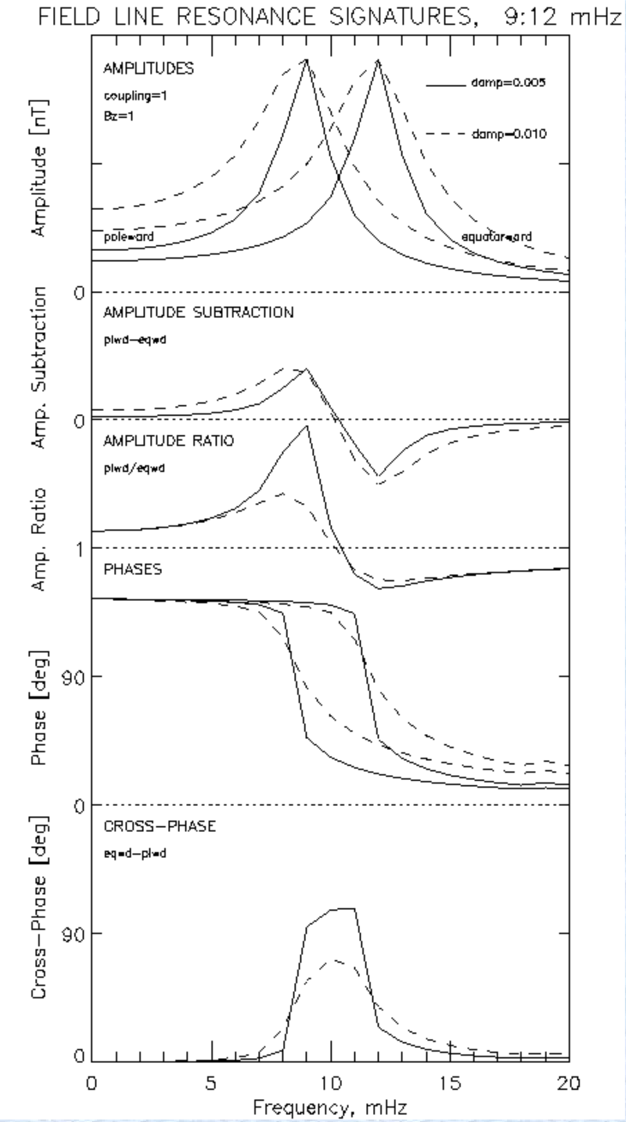
Dec 1992 – Jul 1993 and Jan – April 1994.

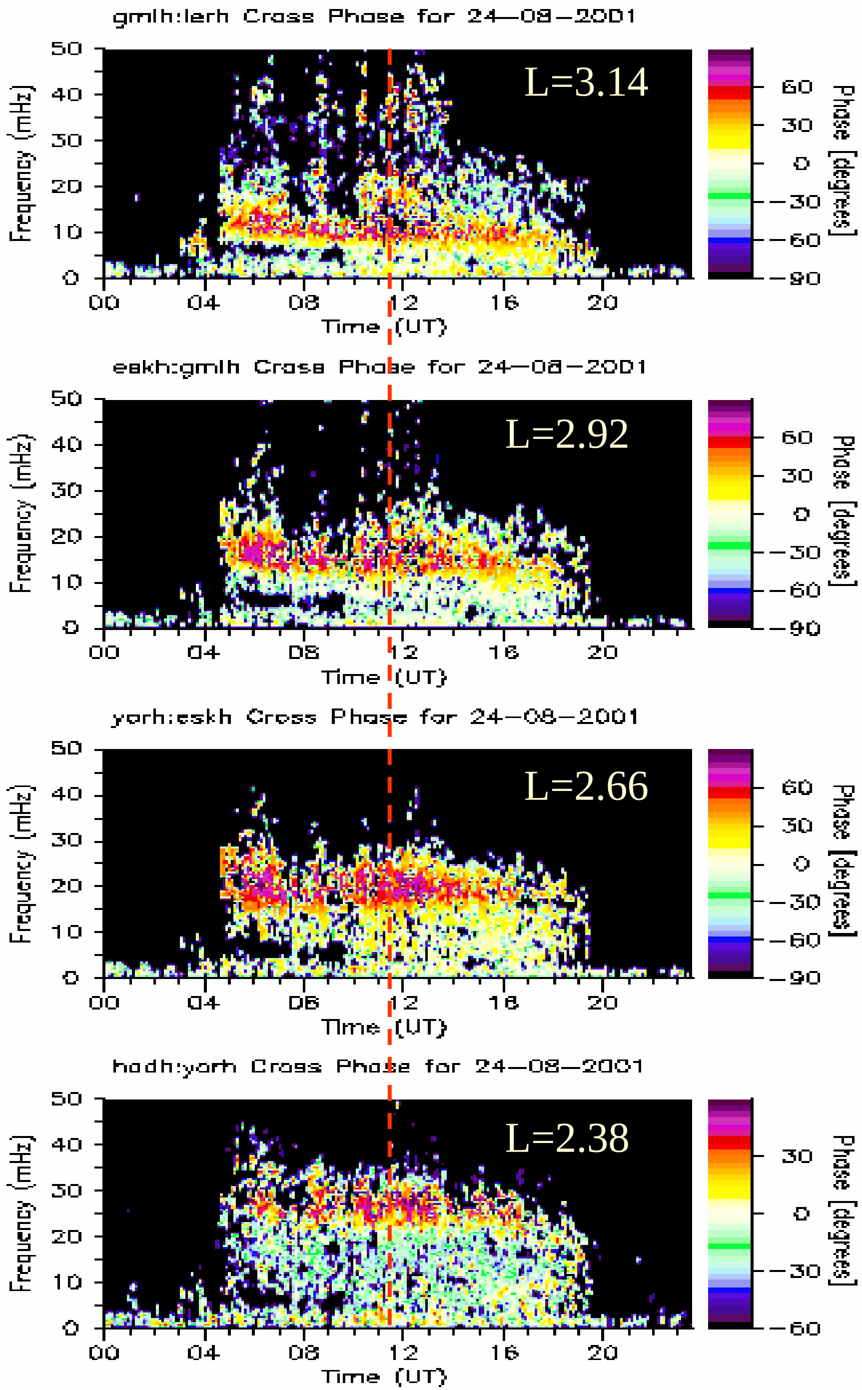
[Menk et al., *GRL*, **34**, 2007]

Data Analysis

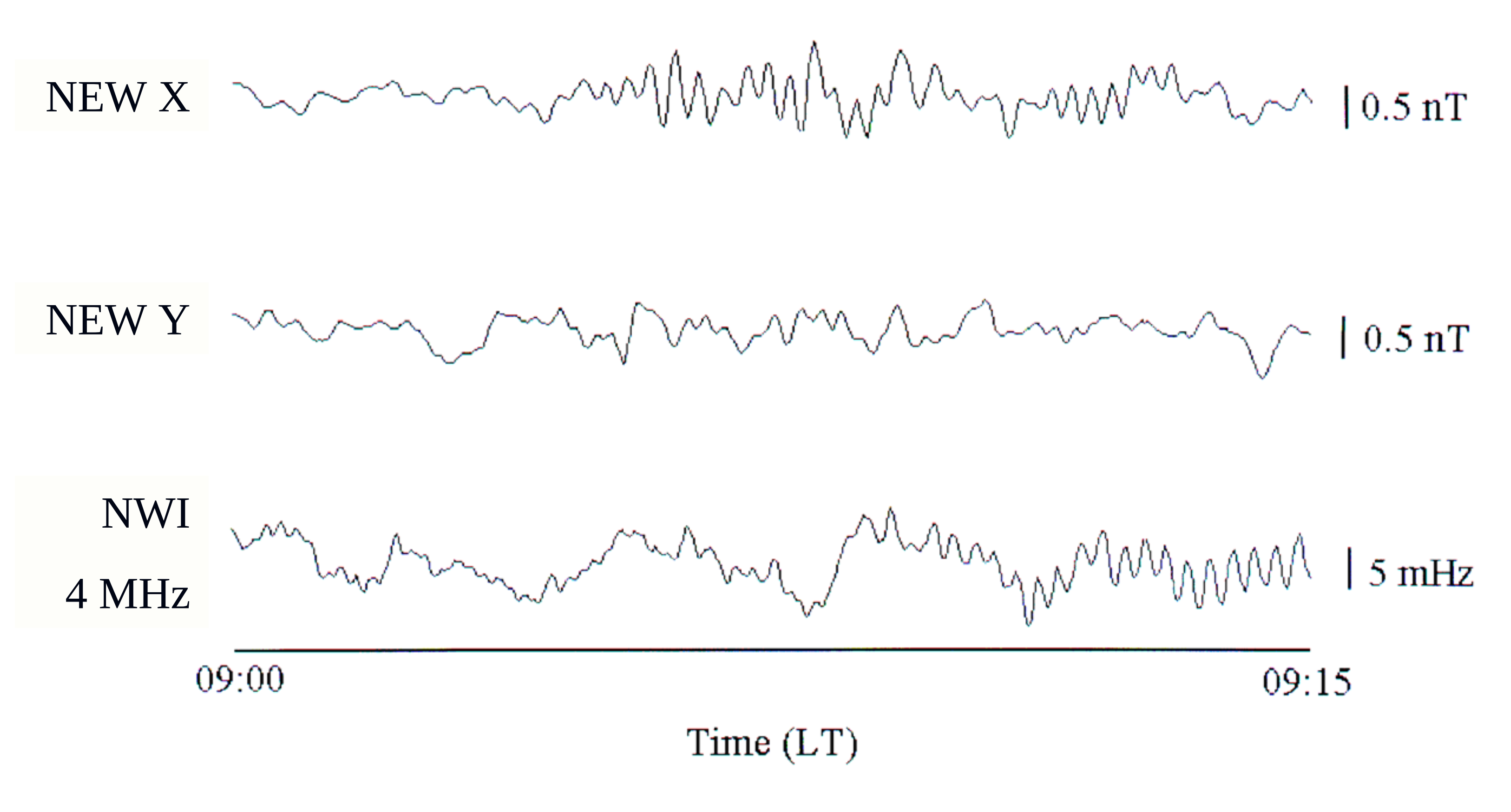
- Radio frequencies chosen gave similar F-region reflection height across the array.
- Examined time series, power and phase spectra of ULF pulsations in the ionosphere and on the ground.
- Ionosphere-ground power ratio and cross-phase were determined as a function of ULF frequency.
- Pure state vector filtering used on the Doppler data, set to a polarization state best representing azimuth and ellipticity over 25 days of noise-free data in 1993.

Magnetometer Analysis

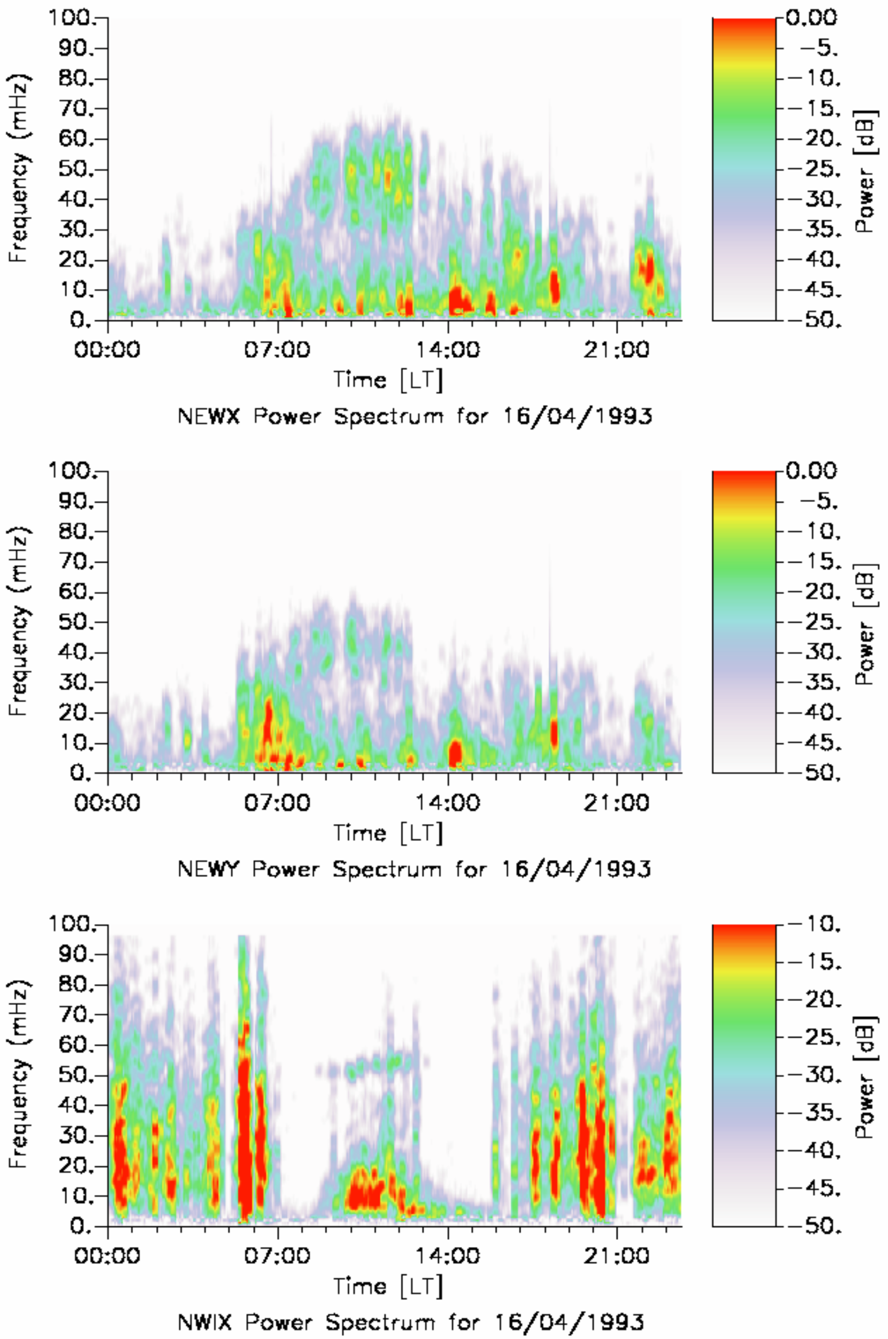




Example 1

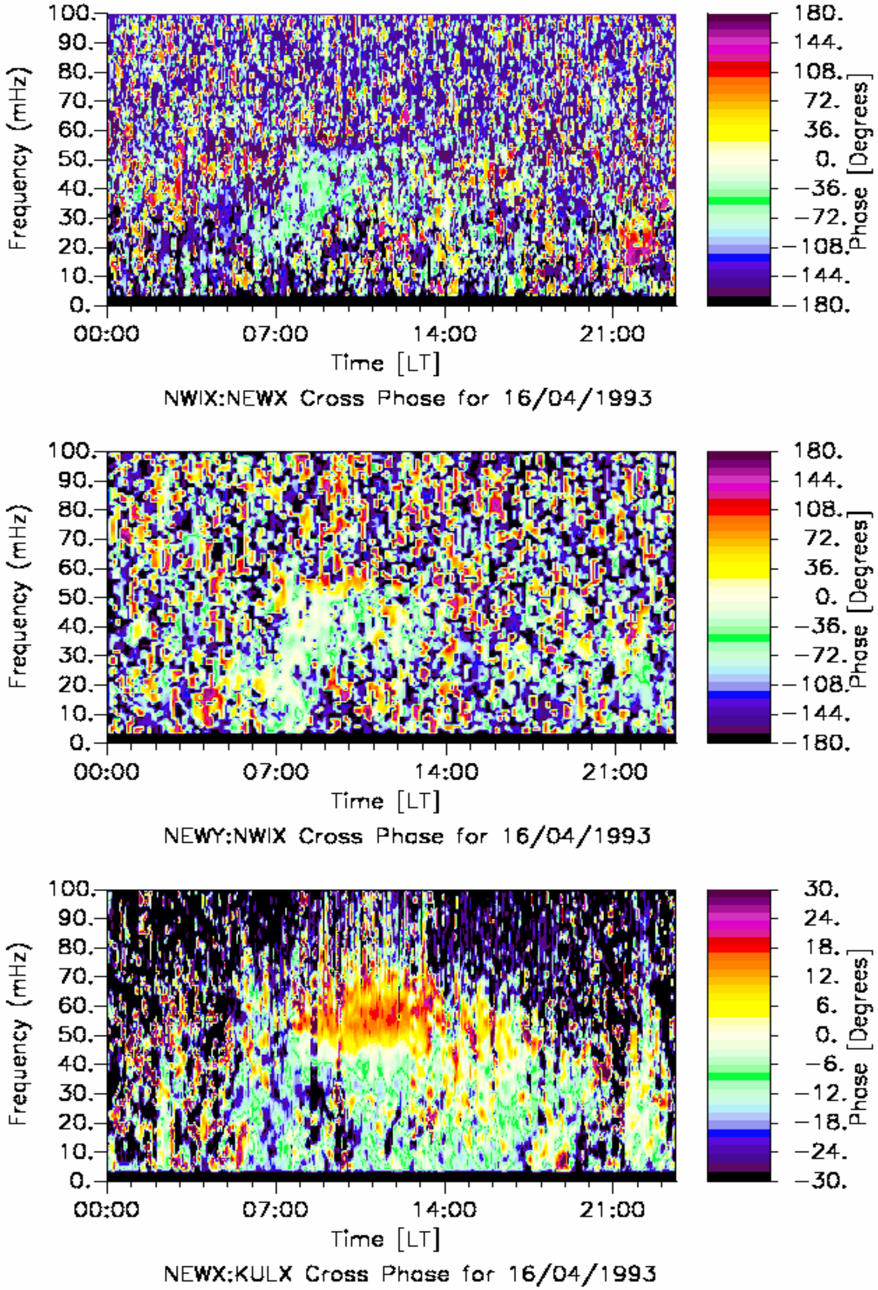


Example time series for L=1.9 magnetometer (upper panels) and co-located Doppler sounder, 16 April 1993.



Example 1

Whole-day power spectra for L=1.9 magnetometer (top two panels) and co-located Doppler sounder, 16 April 1993 (Kp=2 – 5).



Example 1

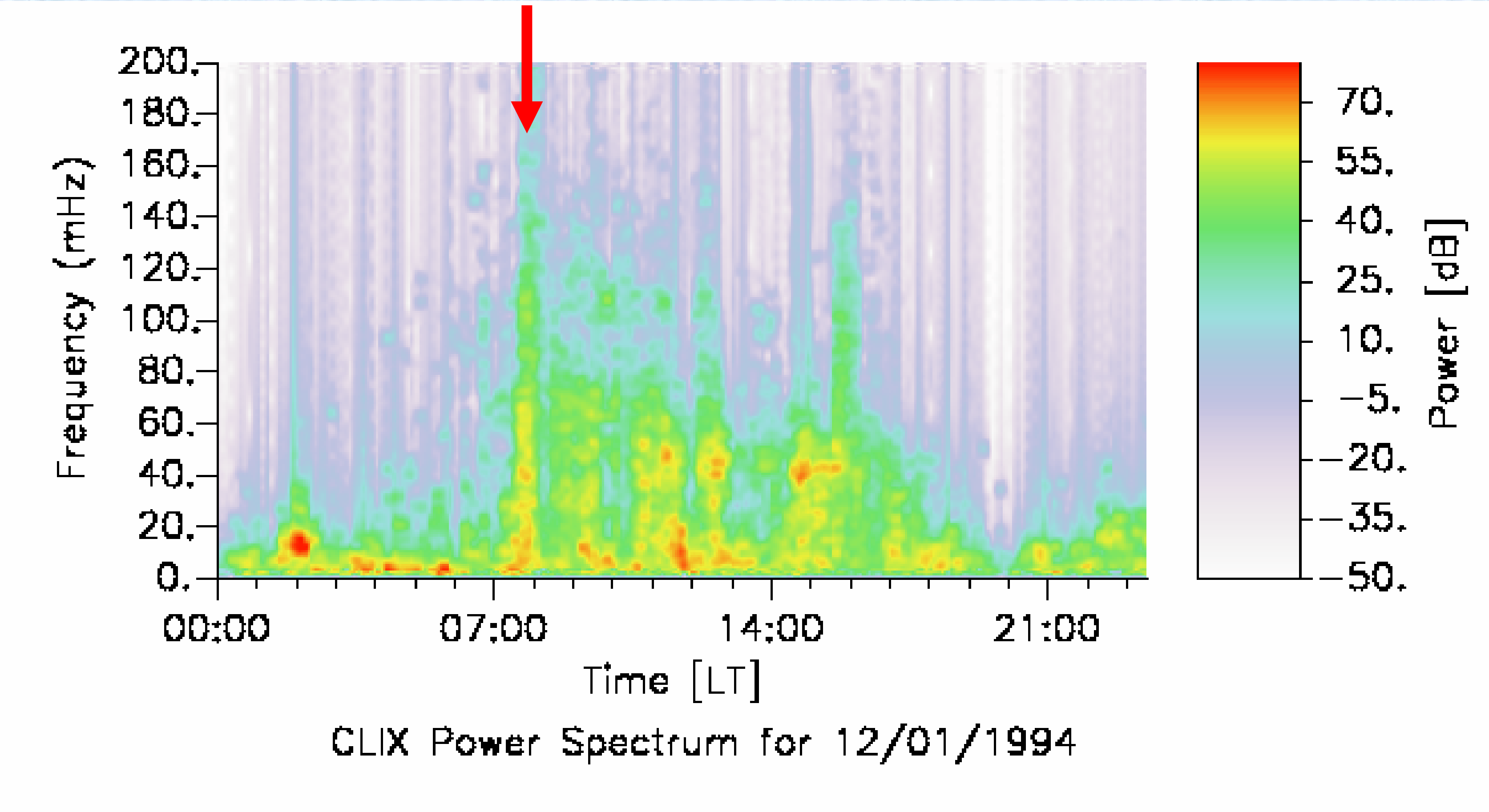
Whole-day cross-phase spectra at L=1.9 on 16 April 1993, between

(a) Doppler & NS mag

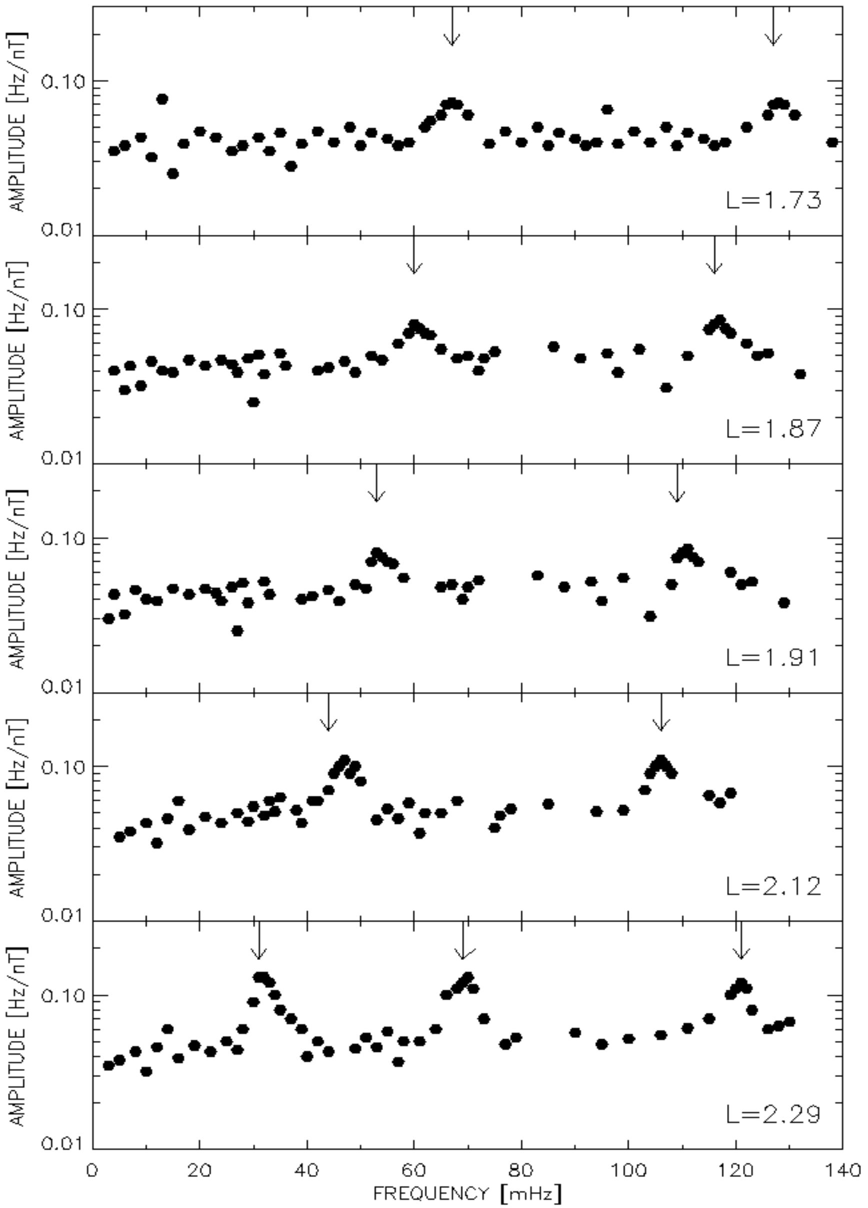
(b) Doppler & EW mag

(c) Closely spaced mags, NS component.

Example 2



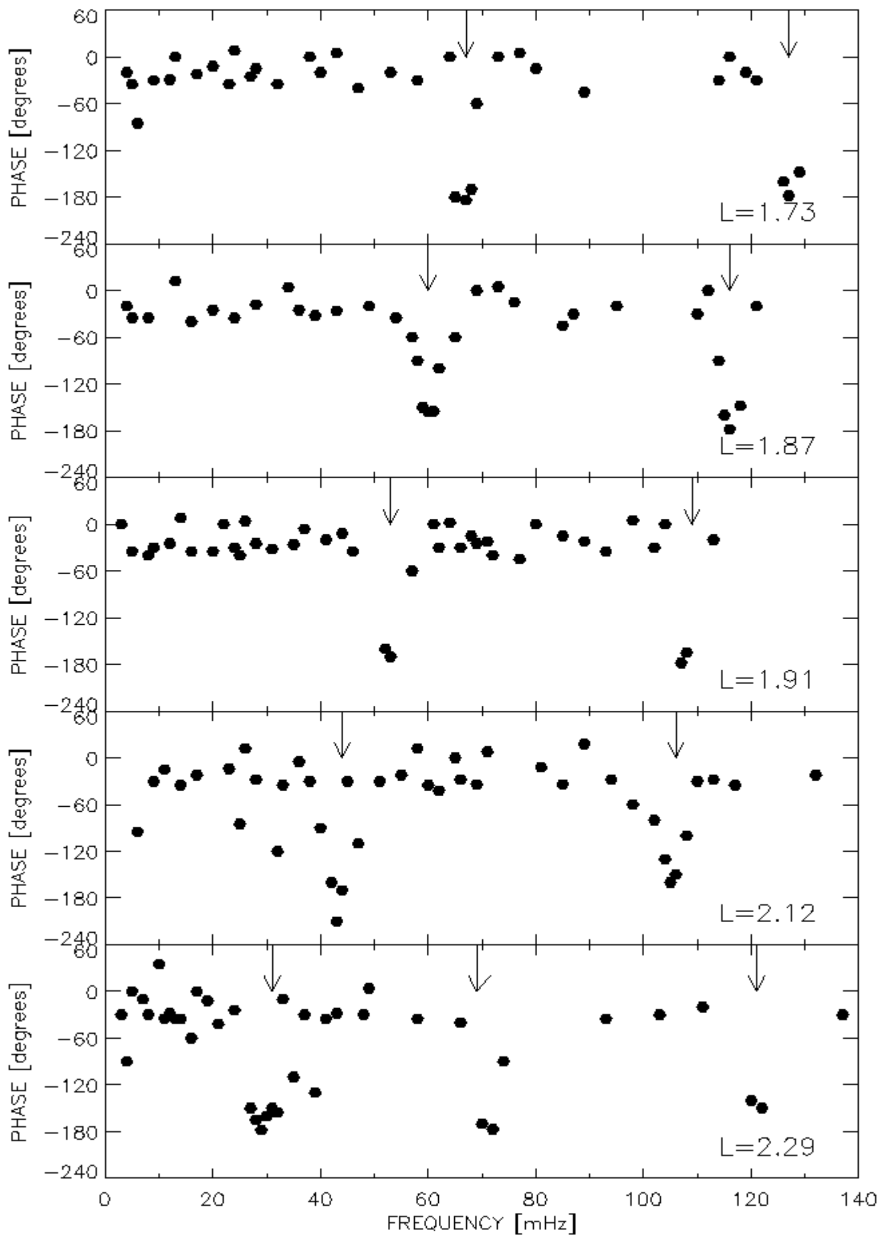
Pure state filtered Doppler power spectrum for 12 Jan 1994.



Example 2

Normalized amplitude of ionospheric Doppler oscillations as a function of frequency and latitude; 12 Jan 1994.

Arrows indicate local field line resonance.



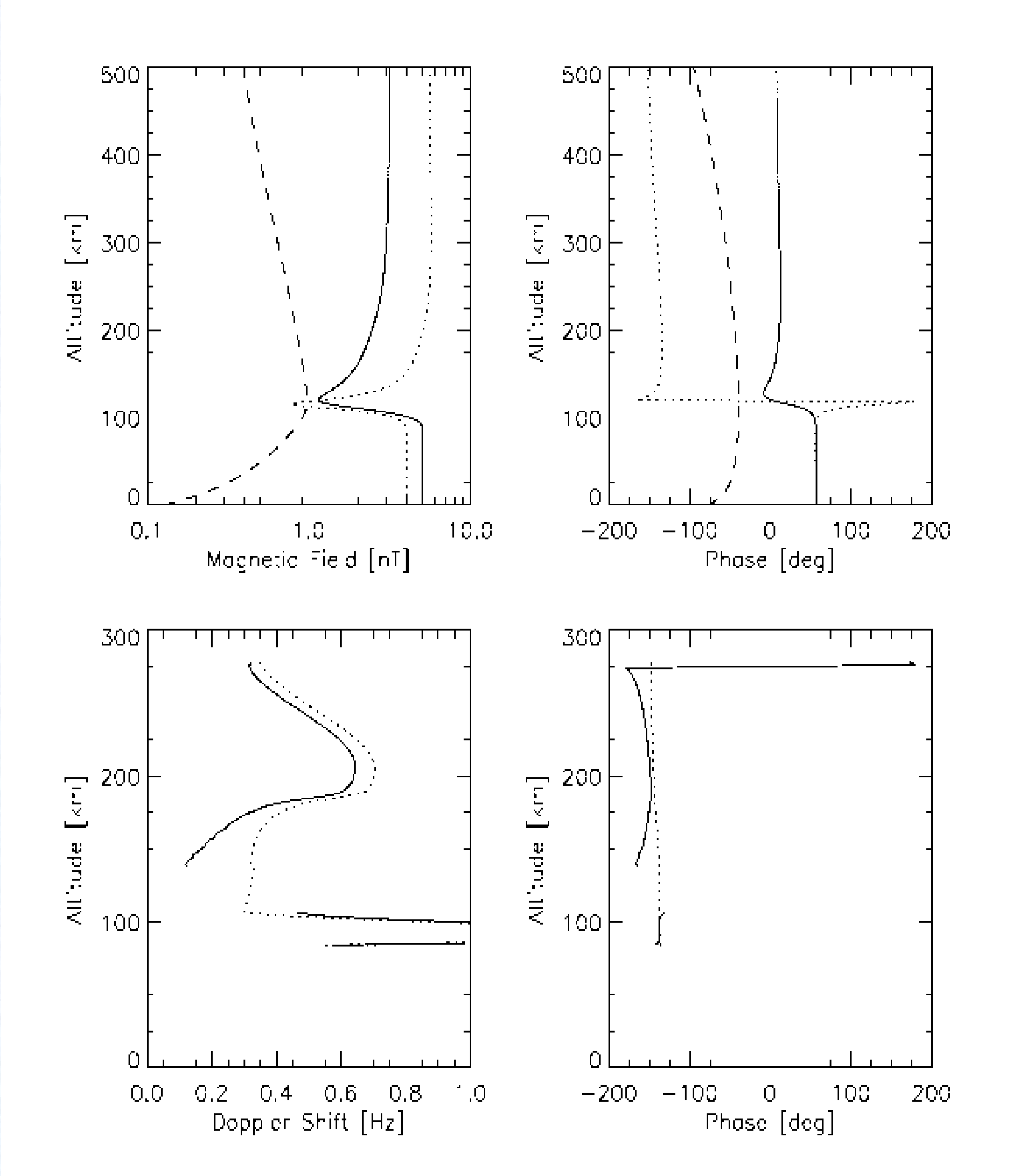
Example 2

Ionosphere-ground phase of ULF Doppler oscillations as a function of frequency and latitude; 12 Jan 1994.

Arrows indicate local field line resonance.

Modelling

- Used IRI-95 and MSIS-90 to represent ionospheric and atmospheric conditions, IGRF for the main magnetic field, and used measured B variations.
- Assumed incident ULF wave is 90 – 98% shear Alfven mode at 53 mHz (resonance), but becomes 100% fast mode (compressional) at 43 and 63 mHz.
  Set $k_y = 8 \times 10^{-7}\ m^{-1}$ and $k_x = 1 \times 10^{-6}\ m^{-1}$
- Then computed wave E and B altitude profiles, and Doppler shift of the radio signal due to changes in refractive index, advection, and compression by field-aligned component of B [Sutcliffe and Poole, *Planet. Space Sci.*, **38**, 1990; Sciffer et al., *Ann. Geophys.*, **23**, 2005].
- The main effect on ionospheric plasma is due to advection driven by electric field of downgoing ULF wave.

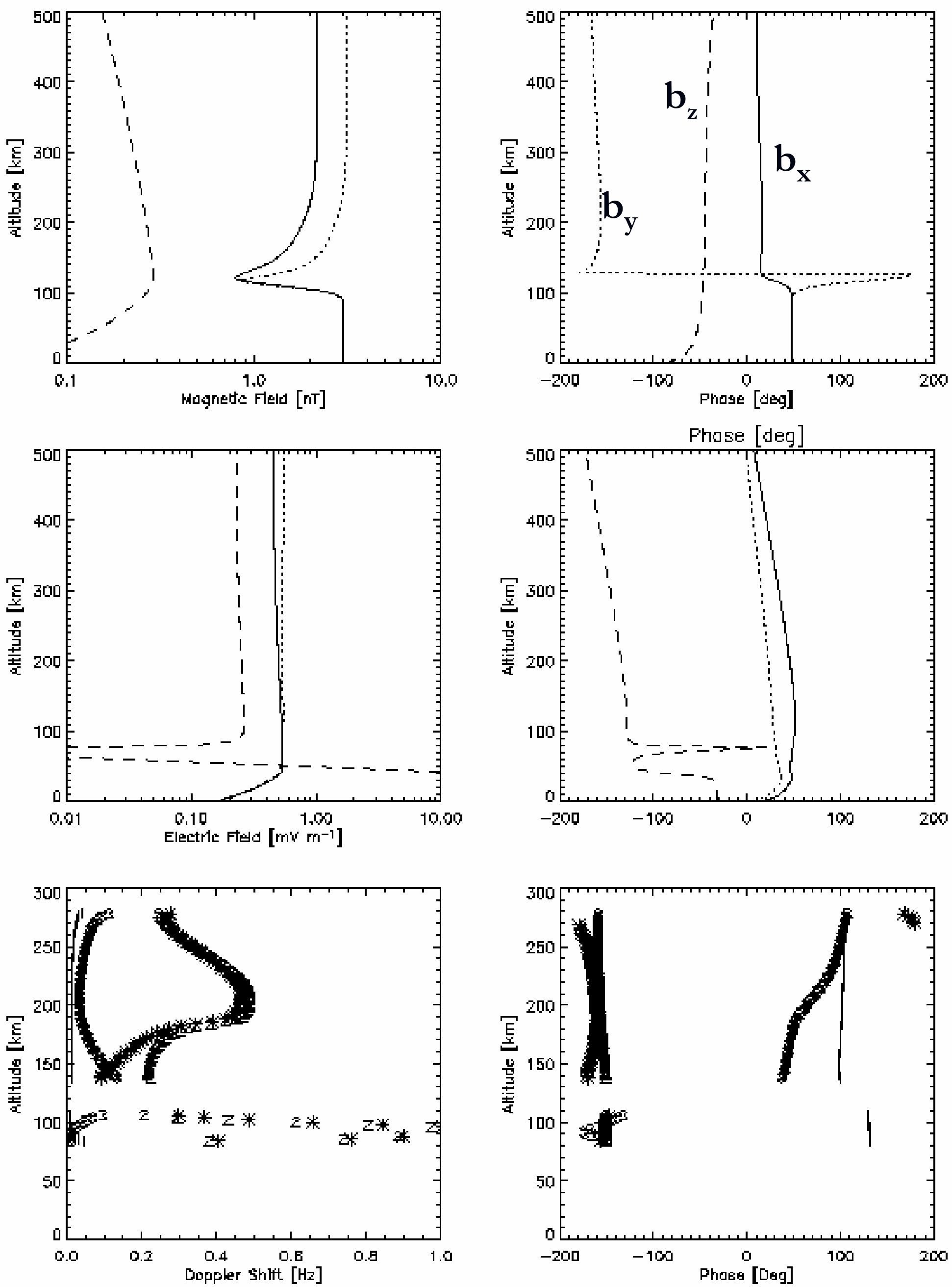


Model Results

B field and phase of downgoing ULF wave at 53 mHz, with 90% Alfven mode, 10% fast mode. b_x=solid line, b_y=dots, b_z=dashes.

Resultant Doppler shift amplitude and phase. Solid line = total of all mechanisms; dotted line = vertical motion (advection) alone.

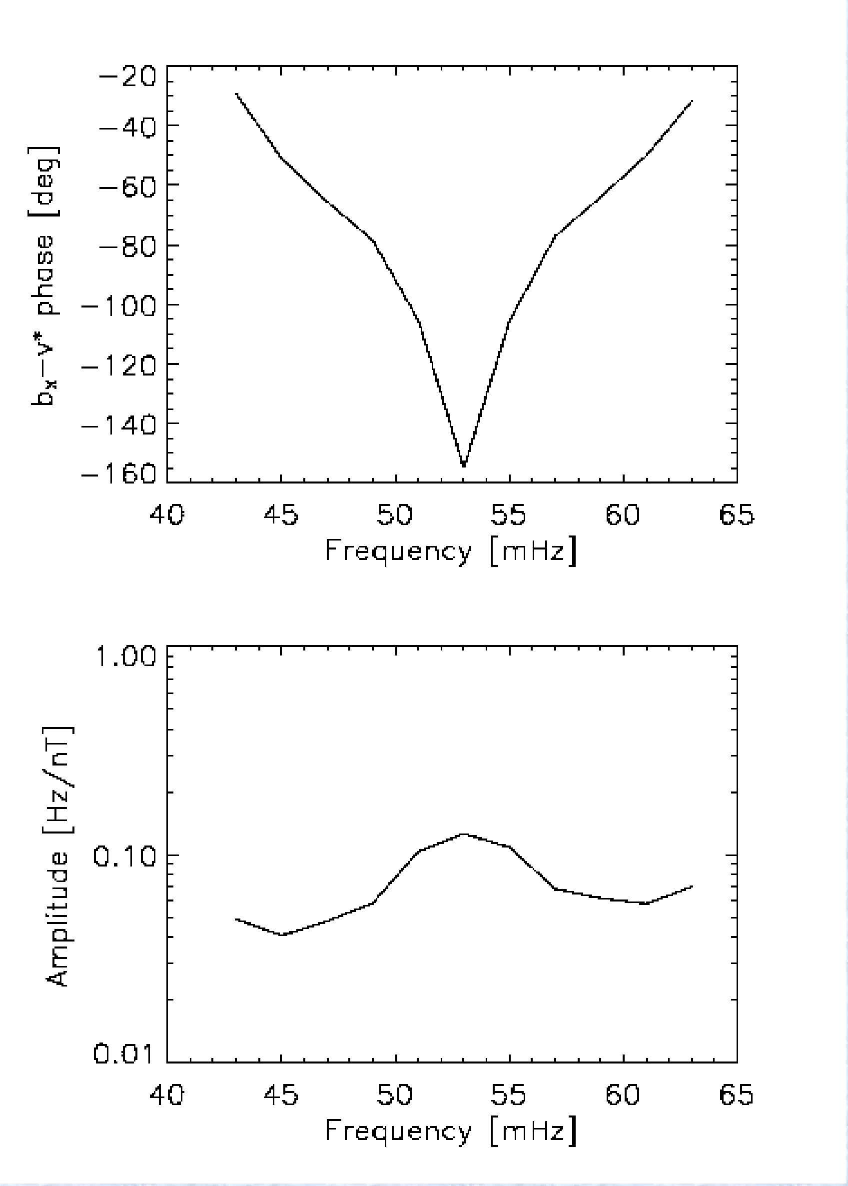
Previous Modelling



From Sutcliffe and Poole, *Planet. Space Sci.*, 38, 1581, 1990.

Amplitude and phase for shear Alfven wave at 50 mHz (upper panels).

Resultant Doppler shifts (bottom) for V1, V2, V3 and total mechanisms



Model Results

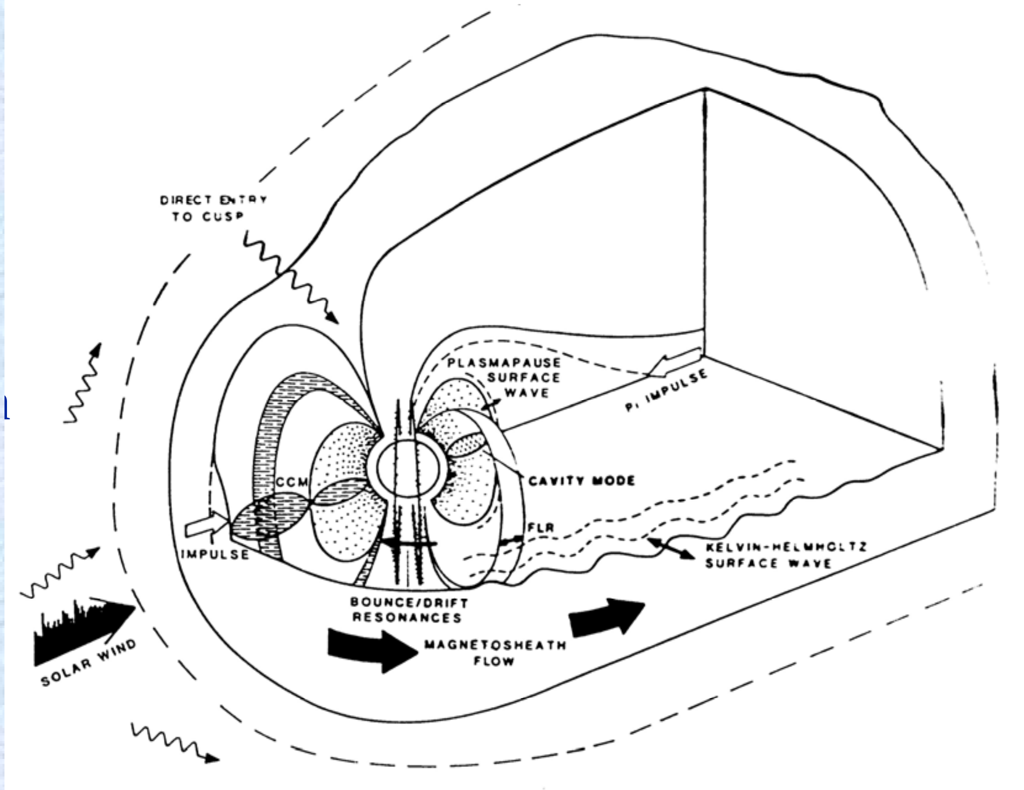
Resultant ionosphere-ground phase (top) and amplitude ratio.

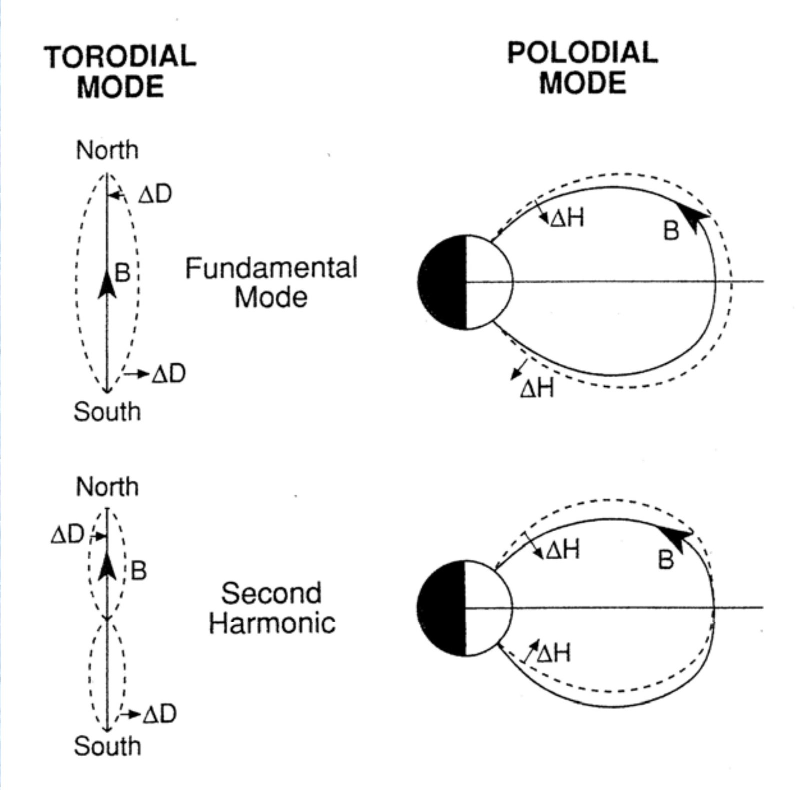
The incoming wave is assumed to comprise 98% Alfven mode at 53 mHz, changing to 100% fast mode at 43 and 63 mHz.

Conclusions

- In our low latitude study, almost every day when ionospheric Doppler oscillations were observable, they were synchronous with ULF waves recorded on the ground.
- Away from the resonant frequency the ionosphere-ground amplitude and phase are almost constant with frequency, around 0.05 Hz/nT and -30^{o}.
- At the local resonant frequency there is a peak in the amplitude ratio and a pronounced dip in the phase. Further peaks and dips identify resonance harmonics.
- Modelling shows these features are related to the admixture of downgoing fast and shear Alfven mode waves.

Incident Wave Modes





Instrumentation

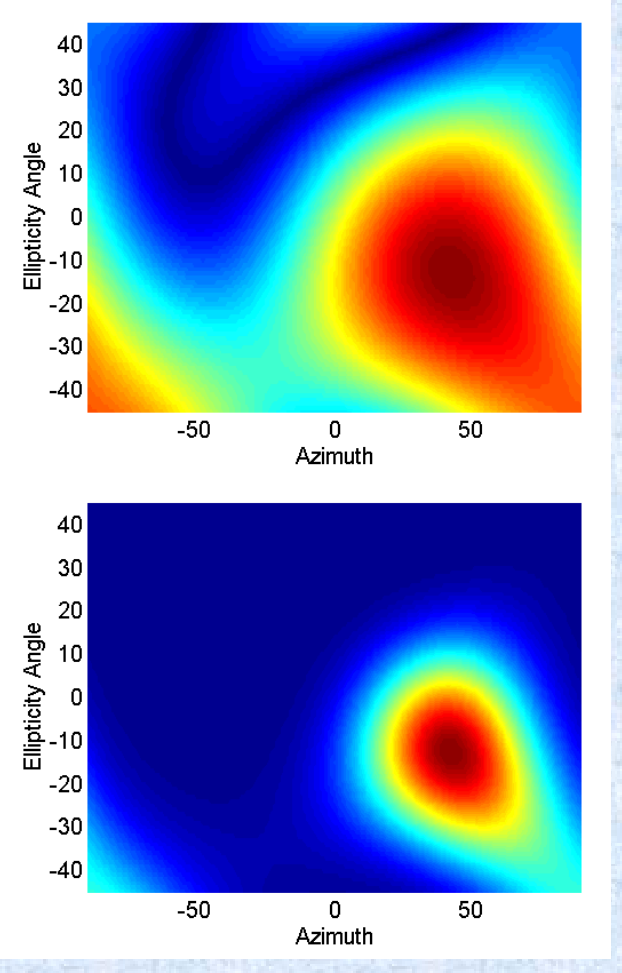
Magnetometers

- An array of up to 10 closely-spaced magnetometers recorded ULF pulsations at the ground.
- Cross-phase techniques were used to discriminate field line resonances from other wave modes.

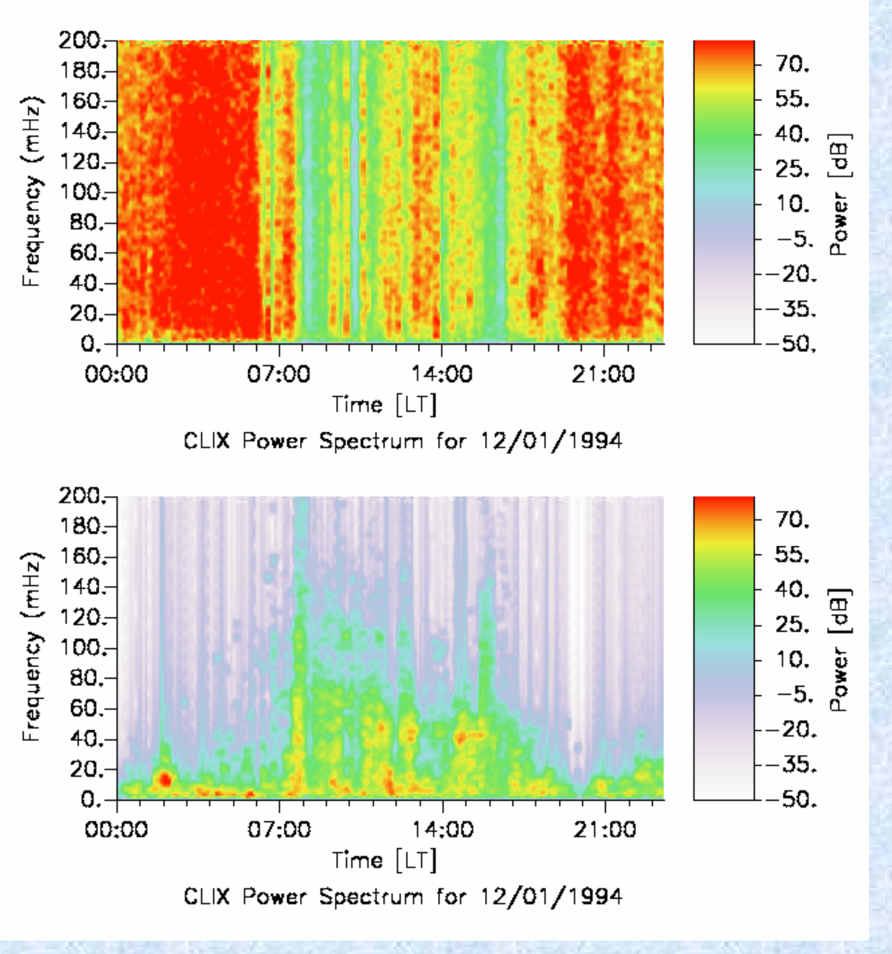
Doppler Sounders

- High stability HF transmitters at L=1.94 were monitored by an array of 5 HF Doppler receivers co-located with the magnetometers.
- Only the O-mode signal was recorded.
- Doppler sensitivity was ≤0.005 Hz over 1-140 mHz.

Doppler Analysis

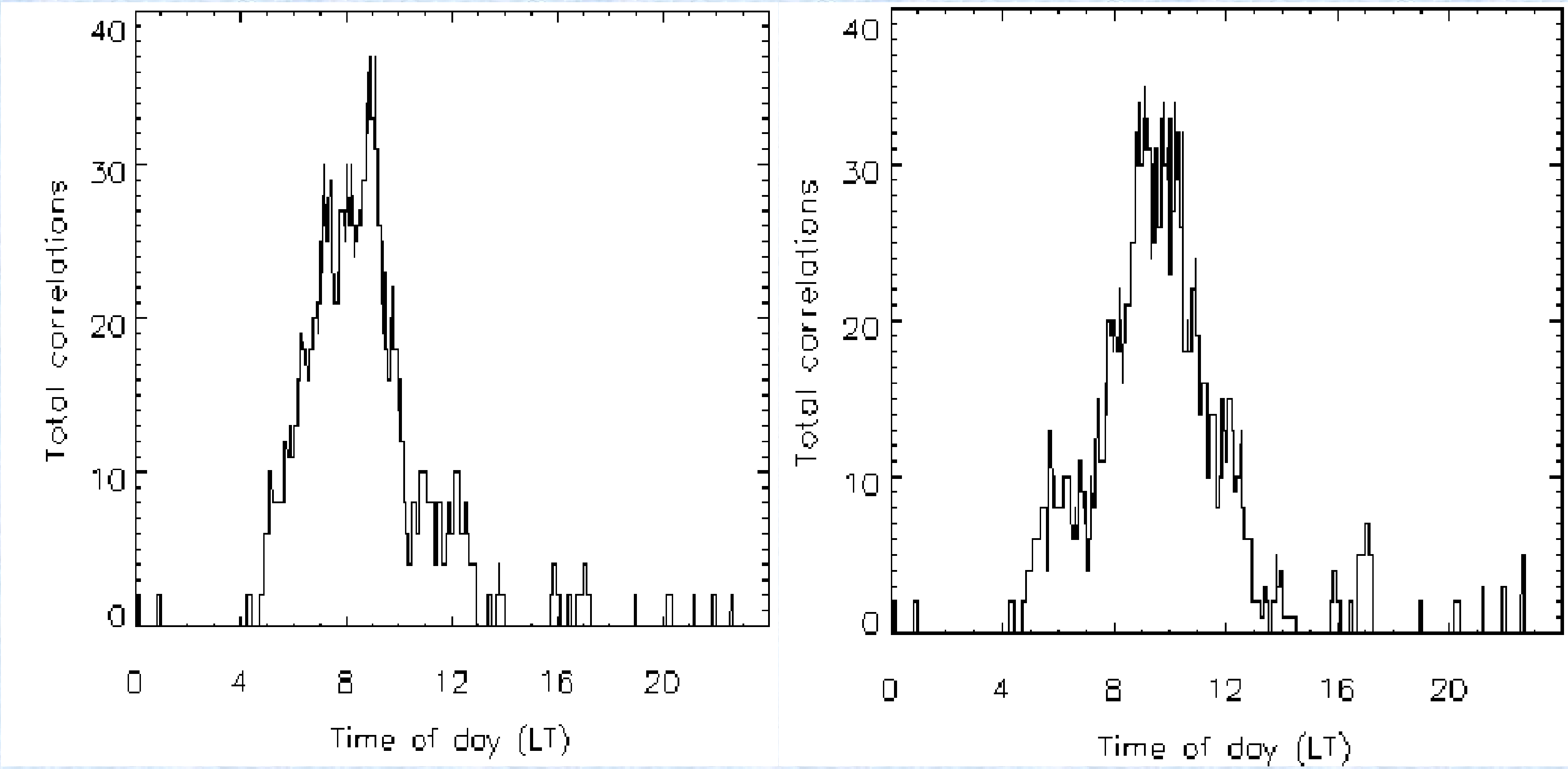


State vector response for Doppler data.



Unfiltered and filtered Doppler power spectra for 12 Jan 1994.

General Properties



Number of ULF events in the F-region and on ground NS (left) and EW (right) components over 32 days [30 min bins].