UNIVERSITY OF
SASKATCHEWAN

Incoherent versus coherent scatter radars (ISR’s vs CSR’s)

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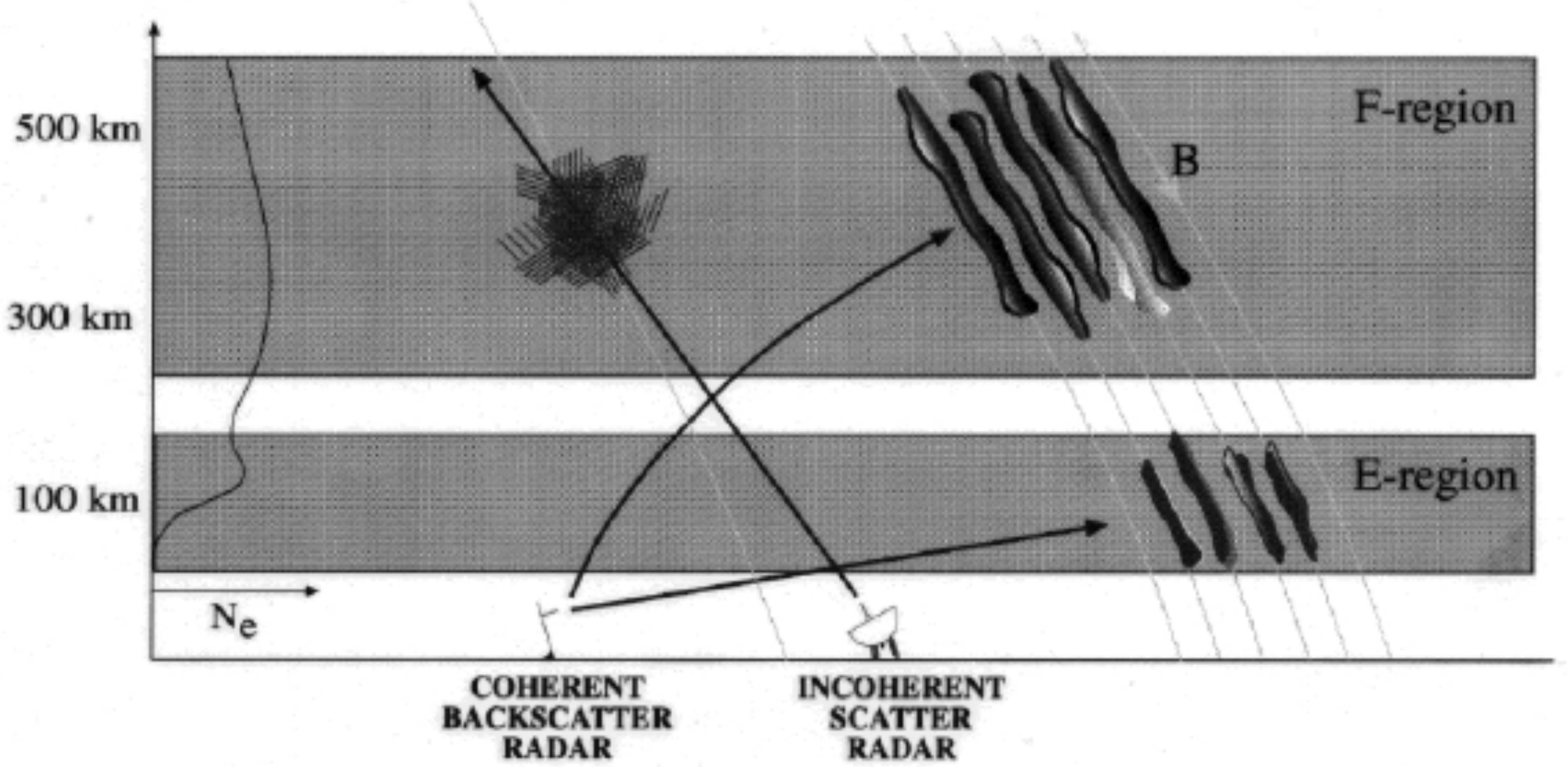
It’s really the same principle

- Echoes for both radars come from collective scattering, or plasma irregularities
- Or course, ISR have more power than CSR (Mw vs Kw)
- ISR tend to work at higher frequencies than CSR



ISR’s see weak ion-acoustic structures in any direction. CSR’s only see large amplitude structures aligned with the magnetic field. HF radars use refraction to bend the rays so as to hit perpendicularity to B in the F region.

It starts with the power radiated by individual electrons

$$\frac{dP_s}{d\Omega} = \frac{q^2}{4\pi c} \left| \mathbf{s} \times (\mathbf{s} \times \dot{\vec{\beta}}) \right|^2 \Big]_{ret}$$

We only consider the acceleration from the E field in the incident EM wave

$$\dot{\vec{\beta}} \approx \frac{q}{mc}\mathbf{E}_i = \frac{q}{mc}\mathbf{E}_{i0}\cos(\mathbf{k}_i \cdot \mathbf{r}(t') - \omega t')$$

The total power is from the vector sum of all the scattered E fields

$$\frac{dP_s}{d\Omega} = \frac{cR^2}{4\pi}\left(\sum_{j=1}^{N} \mathbf{E}_{js} \cdot \sum_{l=1}^{N} \mathbf{E}_{ls}\right)$$

The average power has a part from individual electrons and another from correlations between E fields

$$\frac{\overline{dP_s}}{d\Omega} = \frac{cR^2}{8\pi} N E_s^2 + \frac{cR^2}{4\pi}\frac{N(N-1)}{2}\overline{(\mathbf{E}_j \cdot \mathbf{E}_l)}_{j \neq l}$$

CSR’s rely entirely on the second term. ISR’s turn out to also rely on the second term to a very high degree as long as the probing wavelength exceeds the Debye length (required to boost the SNR)

ISR spectra are usually for near thermal equilibrium structures

It can “easily” be shown that the power from the sum of electric fields is related to the density structures as follows:

$$P_s(\mathbf{R},\omega_s) = \frac{cR^2}{4\pi}\frac{1}{2\pi}|E_s(\omega_s)|^2 = \frac{P_i r_0^2}{A2\pi}\left|\mathbf{s}\times(\mathbf{s}\times\hat{\mathbf{E}}_{i0})\right|^2\overline{|n_e(\Delta\mathbf{k},\Delta\omega)|^2}$$

To get the density fluctuations start with Vlasov (*Hello Phil*)

$$\frac{\partial f}{\partial t} + \mathbf{v}\cdot\nabla f + \mathbf{a}\cdot\nabla_{\mathbf{v}} f = 0$$

Structures are assumed to be small perturbations. Take a Laplace transform

$$f_{1e}(\mathbf{k},\omega) = \frac{e\mathbf{k}\phi_1(\mathbf{k},\omega)}{m_e}\cdot\frac{\nabla_{\mathbf{v}} f_{e0}}{\omega-\mathbf{k}\cdot\mathbf{v}} - \frac{iF_{1e}(\mathbf{k},\mathbf{v},0)}{\omega-\mathbf{k}\cdot\mathbf{v}}$$

Collective interactions

Individual contributions

Turn the crank a few turns and you obtain for the average spectral power

$$S(\mathbf{k},\omega) = \frac{2\pi}{k}\left|1 - \frac{G_e}{\epsilon}\right|^2 g_{e0}\left(\frac{\omega}{k}\right) + \frac{2\pi}{k}\left|\frac{G_e}{\epsilon}\right|^2 g_{i0}\left(\frac{\omega}{k}\right)$$

Where g is the one-dimensional velocity distribution along the line of sight and collective interactions come from the G functions:

$$G_\alpha(\mathbf{k},\omega) = \frac{\omega_{p\alpha}^2}{k^2}\int d^3\mathbf{v}\,\frac{\mathbf{k}\cdot\nabla_{\mathbf{v}} f_{\alpha 0}}{\omega - \mathbf{k}\cdot\mathbf{v}}$$

$$\omega_{p\alpha}^2 = \frac{4\pi n_0 e^2}{m_\alpha}$$

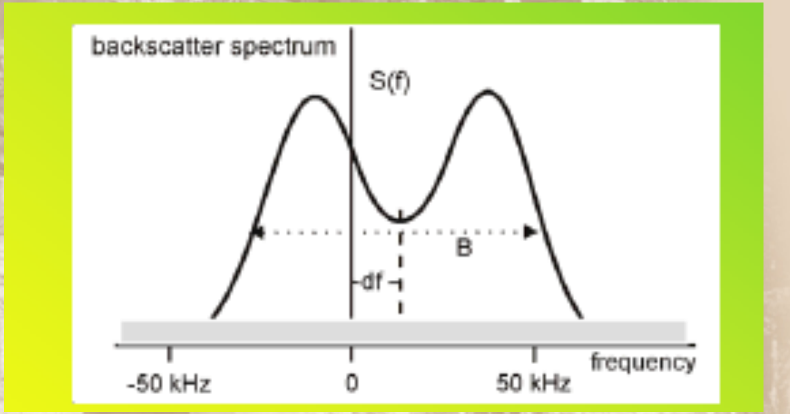
$$\epsilon = 1 + G_e(\mathbf{k},\omega) + G_i(\mathbf{k},\omega)$$

If we did not have Ge we would get the one-dimensional velocity distribution of electrons: Thompson scattering, or “incoherent” scattering

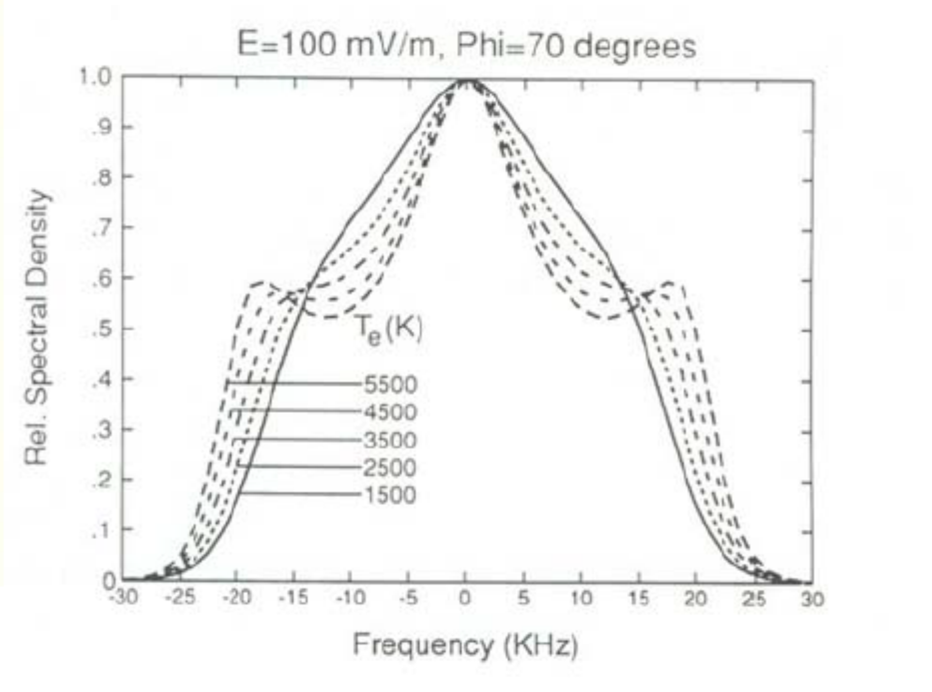
Bottom line: a recipe exists to calculate ISR spectra as long as the plasma is stable

The spectrum depends entirely on the velocity distribution of electrons and ions through:

$$G_\alpha(\mathbf{k},\omega) = \frac{\omega_{p\alpha}^2}{k^2}\int d^3\mathbf{v}\,\frac{\mathbf{k}\cdot\nabla_{\mathbf{v}} f_{\alpha 0}}{\omega - \mathbf{k}\cdot\mathbf{v}}$$



Standard case: Maxellian ions and electrons along the line of sight, Te>Ti, and reasonably large ion drift



Spectra obtained with "flat top distributions" observed at high latitudes for strong electric fields, in directions close to the perpendicular to the magnetic field.
(*Caveat: only valid as long as the plasma is stable*)

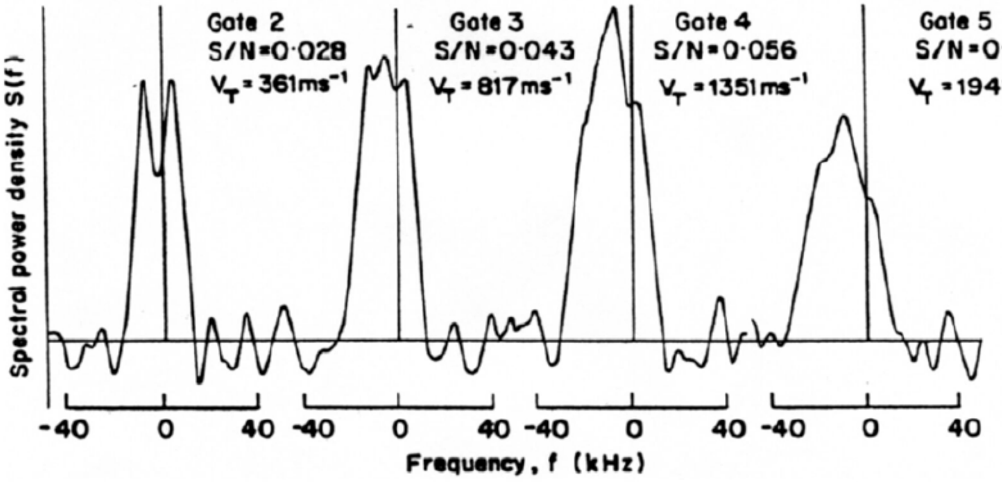


Figure 5. Ion line spectra observed when looking at a large aspect angle with the EISCAT UHF at Tromso. From *Lockwood et al.* [1987].

Spectral changes in a Maxwellian plasma as a function of electron drift for an O+ plasma and Te/Ti=4 (*the calculations cannot be valid past 140 km/s because the plasma is unstable beyond that point*)

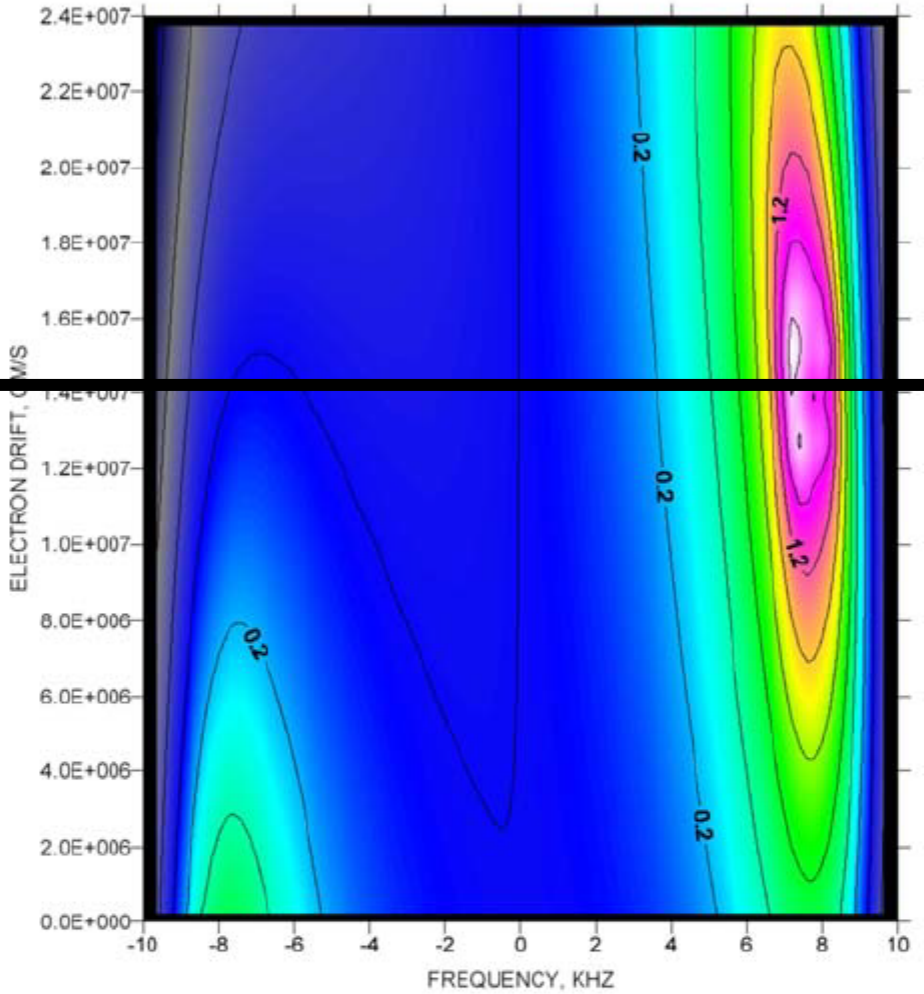
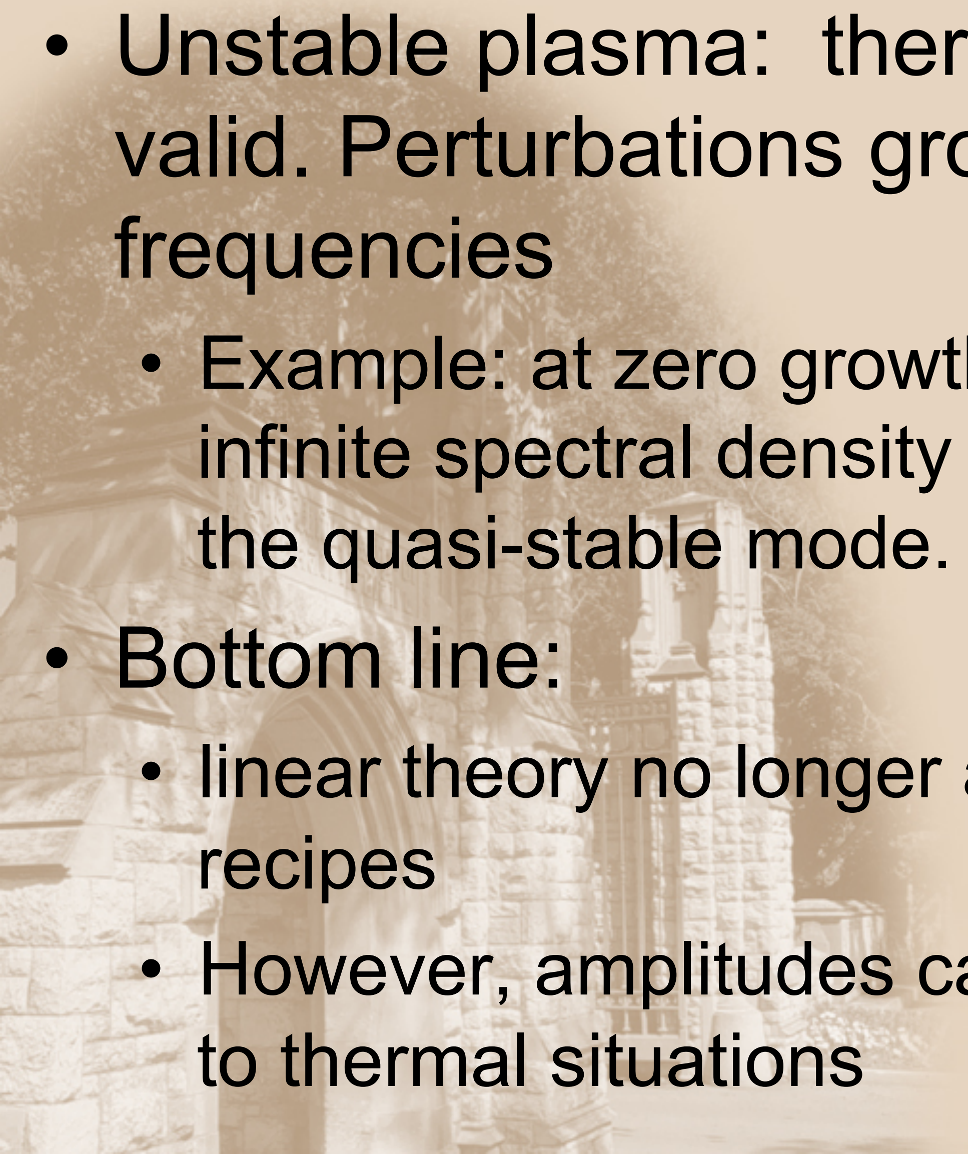


Figure 14. Logarithmic countours of the radar spectra obtained with spectral formula (1) for a 440 MHz radar and various electron drifts. Note that the plasma is actually unstable in this instance when the electron drift exceeds 140 km/s.

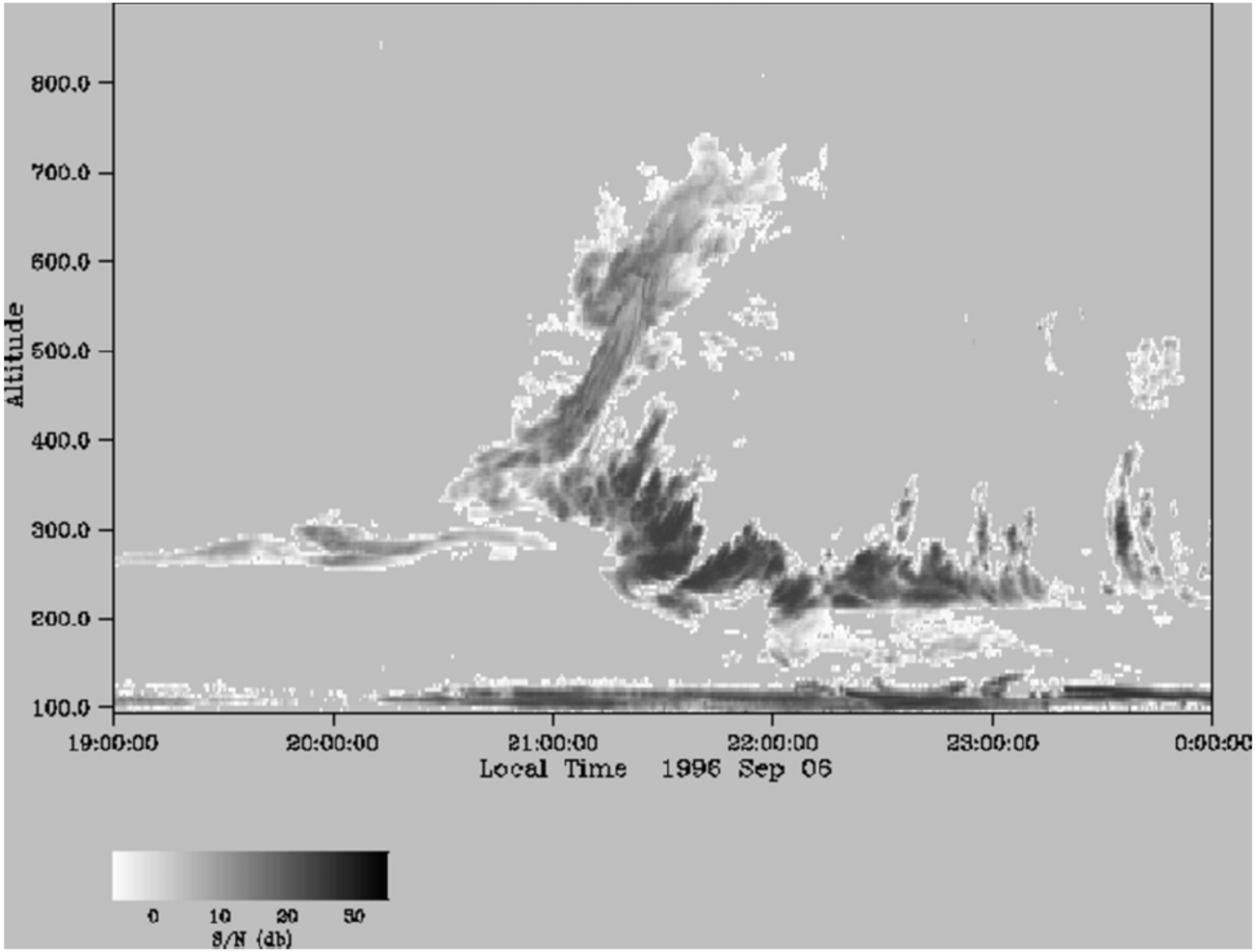
Game changer: unstable plasmas



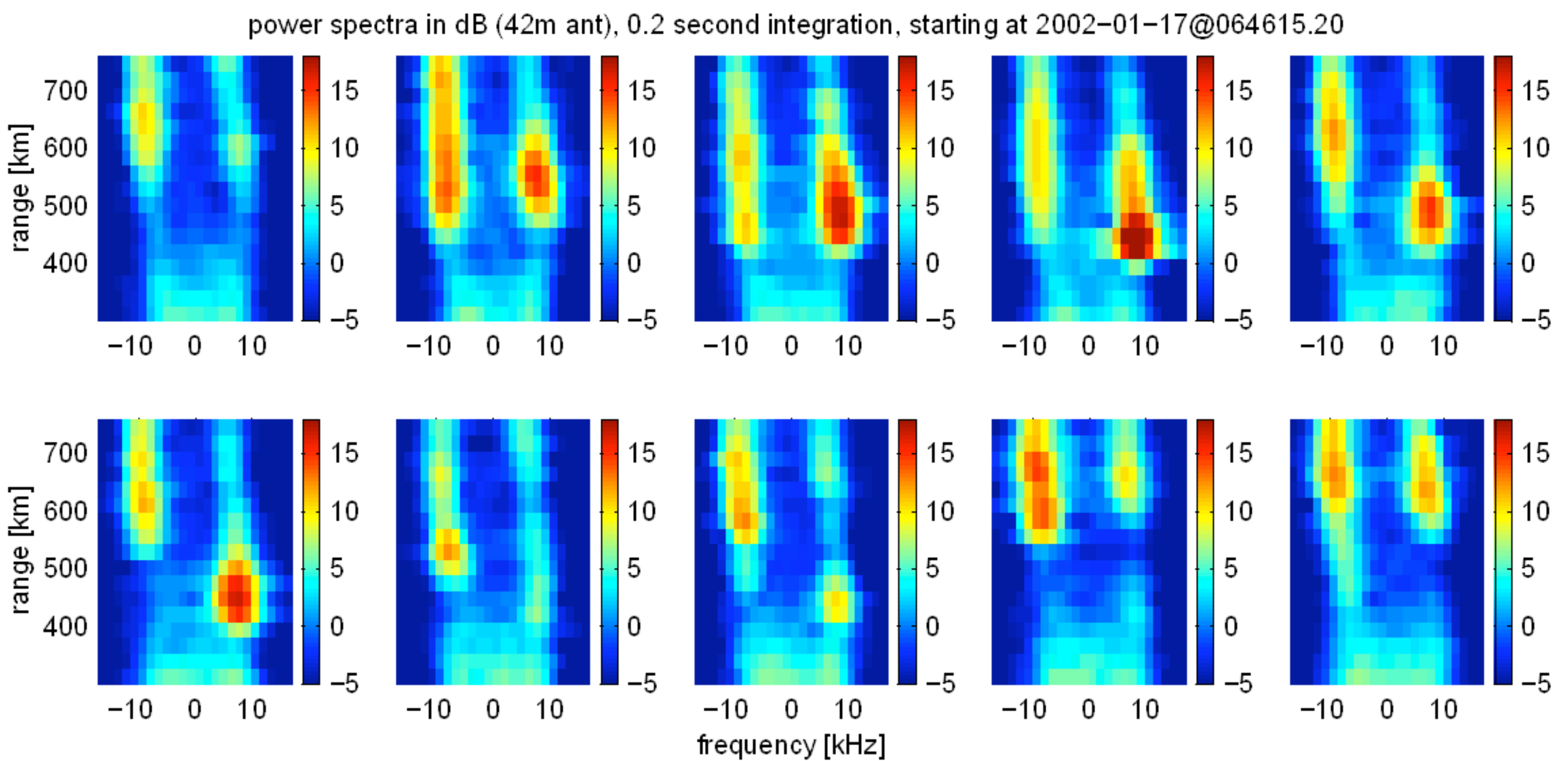
- Unstable plasma: thermal recipe no longer valid. Perturbations grow indefinitely at some frequencies
  - Example: at zero growth rate, the recipe gives an infinite spectral density at the eigenfrequency of the quasi-stable mode.
- Bottom line:
  - linear theory no longer applicable. No more recipes
  - However, amplitudes can become huge compared to thermal situations

ISR’s as high power CSR’s

- Power has been observed in the E region to be 90 Db above thermal. No need for Mw power: kw will do just fine.
- ISR’s can record non-thermal (‘coherent’) echoes but CSR’s don’t have the power to see thermal fluctuations.
- ISR’s examples:
  - Perpendicular to B: Farley-Buneman E region echoes and equatorial gradient-drift structures
  - Parallel to B: NEIAL’s



Pattern of 3 m irregularities detected by Jicamarca: the large amplitude structures are perpendicular to B and map out equatorial bubbles



Examples of a burst of NEIAL's shown by A Stromme in the 2007 EISCAT radar school

Note: there may well be several kinds of NEIAL's. Some of them just pop out at 200 km (Josh Semeter, private comm)

Question: CSR probably can't see NEAIL's because the are too short lived

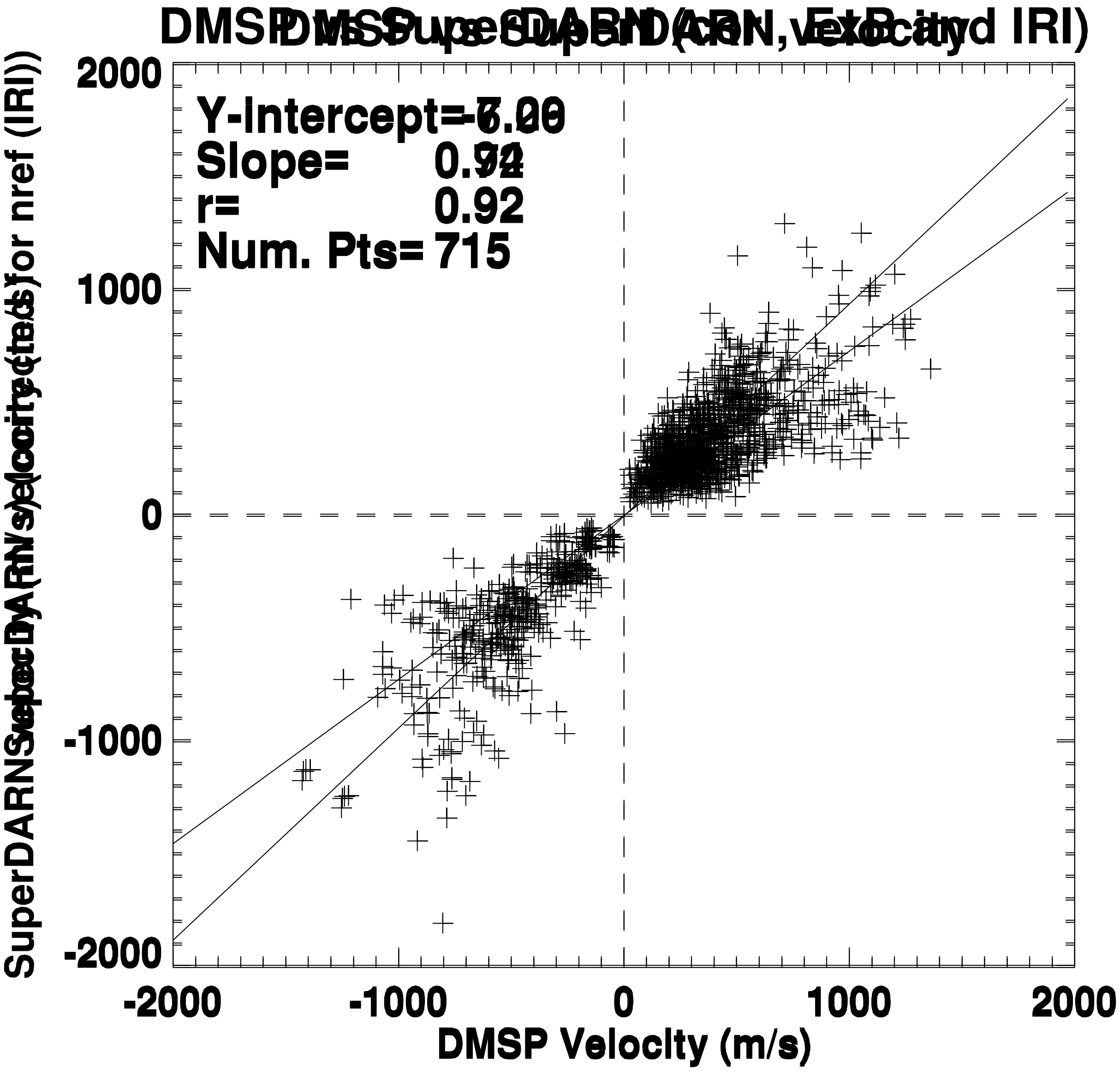
The properties of Non thermal spectra

- Beware: there is no recipe to derive spectra
- *Battle #1*: try to at least determine the origin of the instability. You may try
    - Associating the peak spectral frequency with an unstable eigenfrequency
    - Studying the circumstances behind the occurrence of the unstable events.
    - Praying for insight if the above fail (seems needed for certain types of echoes like so-called 150 km echoes)

Non thermal spectral properties

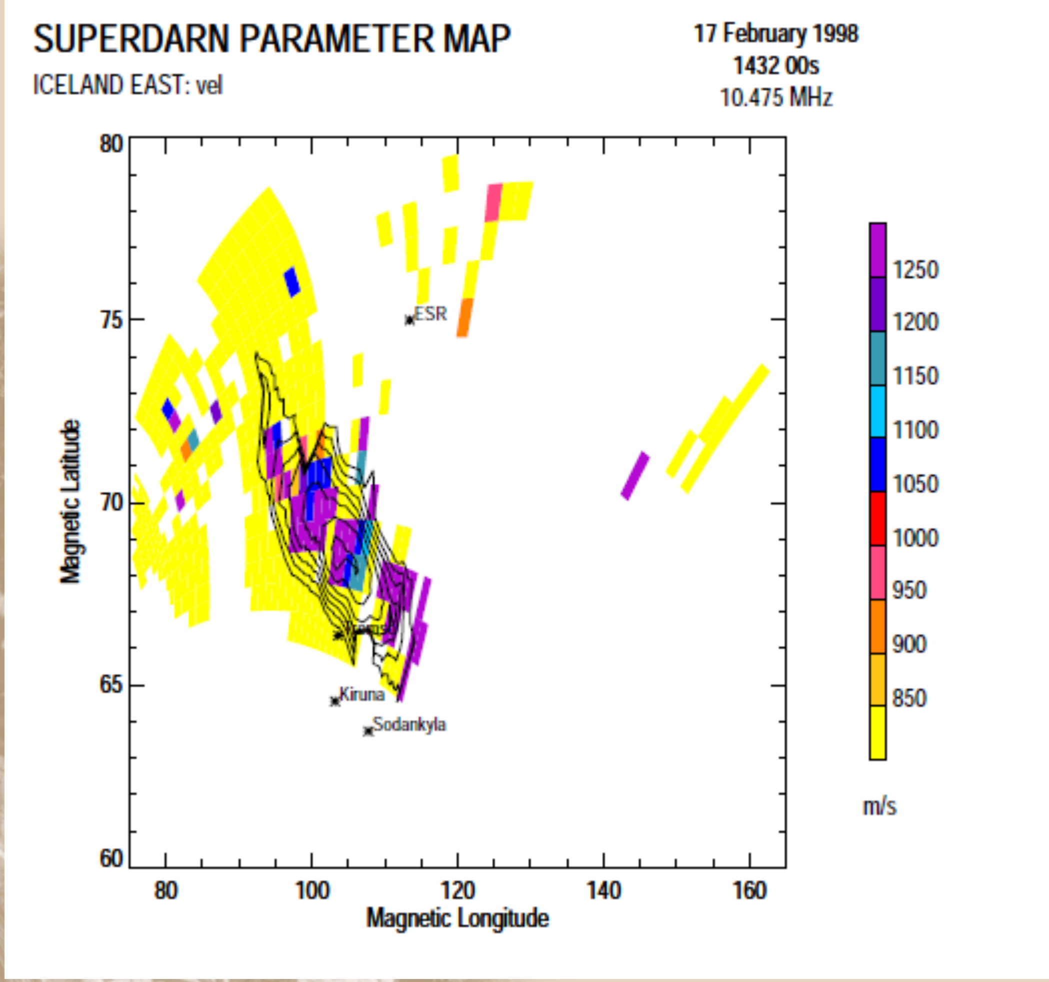
- **Doppler shift**:
  - F region magnetic field-aligned echoes should drift at ExB since ions and electrons both ExB drift
    - However, structures may have their own E fields, with higher densities having smaller E
  - Problems peculiar to HF radars
    - Index of refraction affects Doppler shift interpretation
    - Can have mixed echoes: ground and ionospheric
    - Bending to hit perpendicularity to B biases echoes to higher density regions which are by themselves slower than the average, at least in principle.

Co-located Radar & Satellite Velocities with and without index of refraction correction



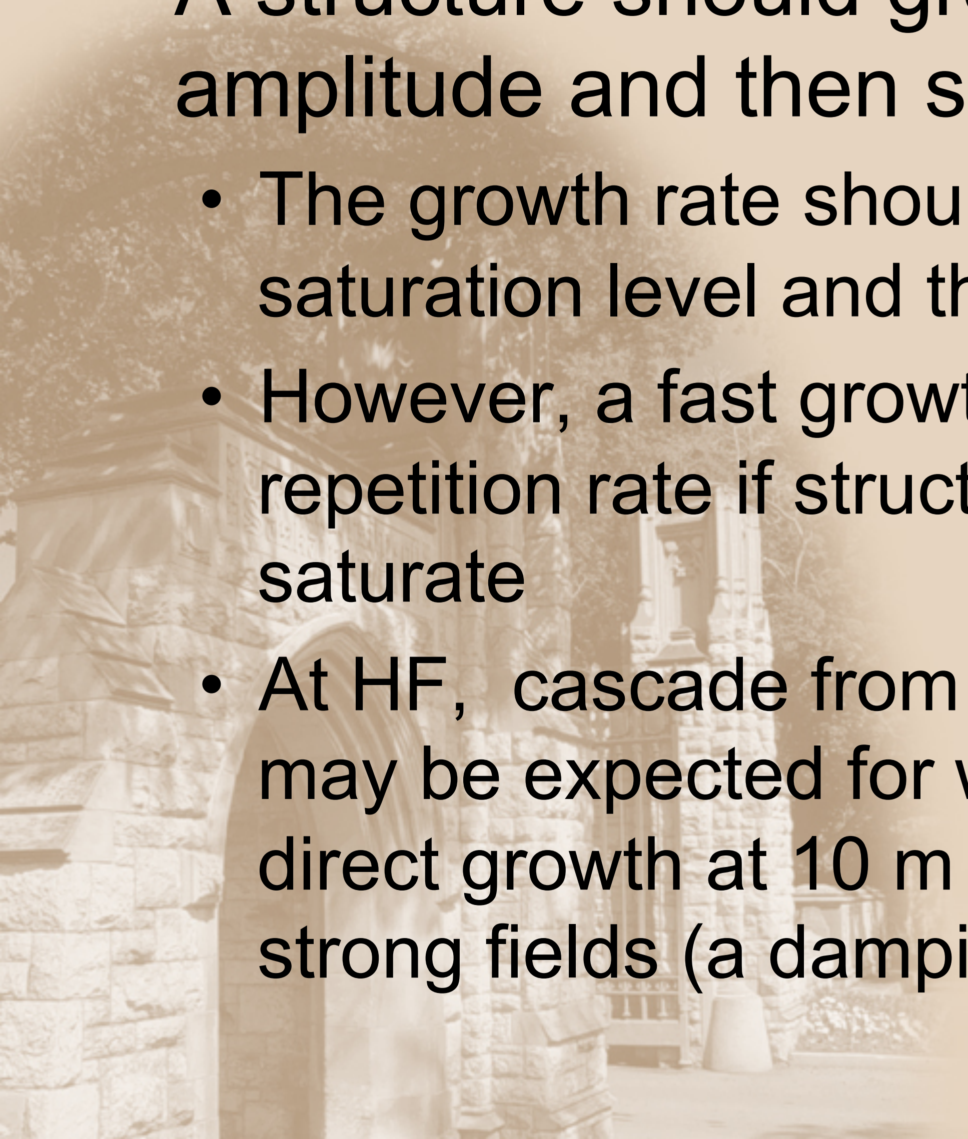
Non thermal spectral properties

- **Power**:
  - Problem: no beam filling as with thermal (ISR) echoes. How does power vary with range then?
  - Should power be associated with growth rate, and if so, why?
  - Should plane waves with relatively small amplitude (weak turbulence) produce more power than large non-plane wave structures (strong turbulence)?



Contours are the power of echoes in Hankasalmi while the colors are the Doppler shifts from Iceland East. Here, clearly, the increase in power is associated with stronger E fields.

The power vs growth rate dilemma



- A structure should grow to a certain amplitude and then saturate
    - The growth rate should not affect the saturation level and therefore the power
    - However, a fast growth might mean a faster repetition rate if structures crash after they saturate
    - At HF, cascade from larger size structures may be expected for weak E fields, whereas direct growth at 10 m would be allowed for strong fields (a damping-by-diffusion issue)

What do HF radars see anyway?

- Gradient-drift and Farley-Buneman are finger instabilities. This means 2 possible sources of echoes:
  1. ½ radar wavelength matches size of structures
  2. Radar Fourier-analyses the gradient along the wall of a finger (some would call that mode-coupling, or cascading).

For the Gradient-Drift instability in both the E and F region the "instability" is described by equations of the form

$$\frac{\partial n}{\partial t} + \mathbf{V} \cdot \nabla n = \frac{Dn}{Dt} = 0$$

This says that if there is a connection between **V** and n, fingers of plasma will develop, but n itself will not change.

However, while n does not change, **the ratio** $N_1 = \delta n / n_0$ can either grow or decay ($n = n_0 + \delta n$) if n_0 changes systematically with distance from the source. The equation that describes the growth/decay is

$$\left(\frac{\partial}{\partial t} + \mathbf{V}_0 \cdot \nabla \right) N_1 = \frac{DN_1}{Dt} = -N_1 \mathbf{b}.(\mathbf{k} \times \mathbf{K}) \frac{\mathbf{E}_0 \cdot \mathbf{k}}{B}$$

where

$$\mathbf{V}_0 = \frac{\mathbf{E_0} \times \mathbf{B}}{B^2}$$

$$\mathbf{k} = \nabla \ln \delta n \ \ || \ \ \mathbf{E}_1$$

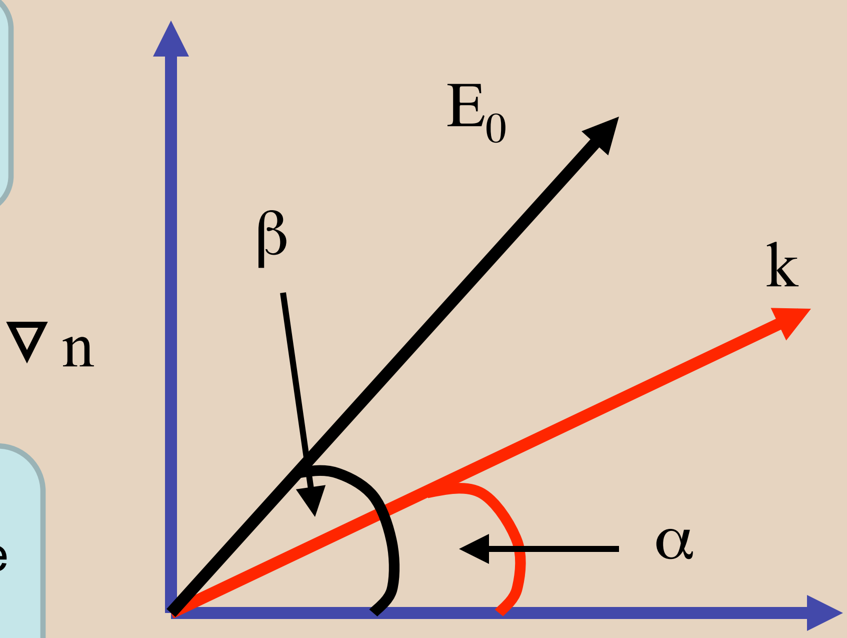
$$\mathbf{K} = \nabla \ln(n_0)$$

$$\left[\frac{\partial}{\partial t} + \mathbf{V}_0 \cdot \nabla\right] N_1 = -N_1 \mathbf{b} \cdot \left[\hat{\mathbf{k}} \times \mathbf{K}\right] \hat{\mathbf{k}} \cdot \frac{\mathbf{E}_0}{B}$$

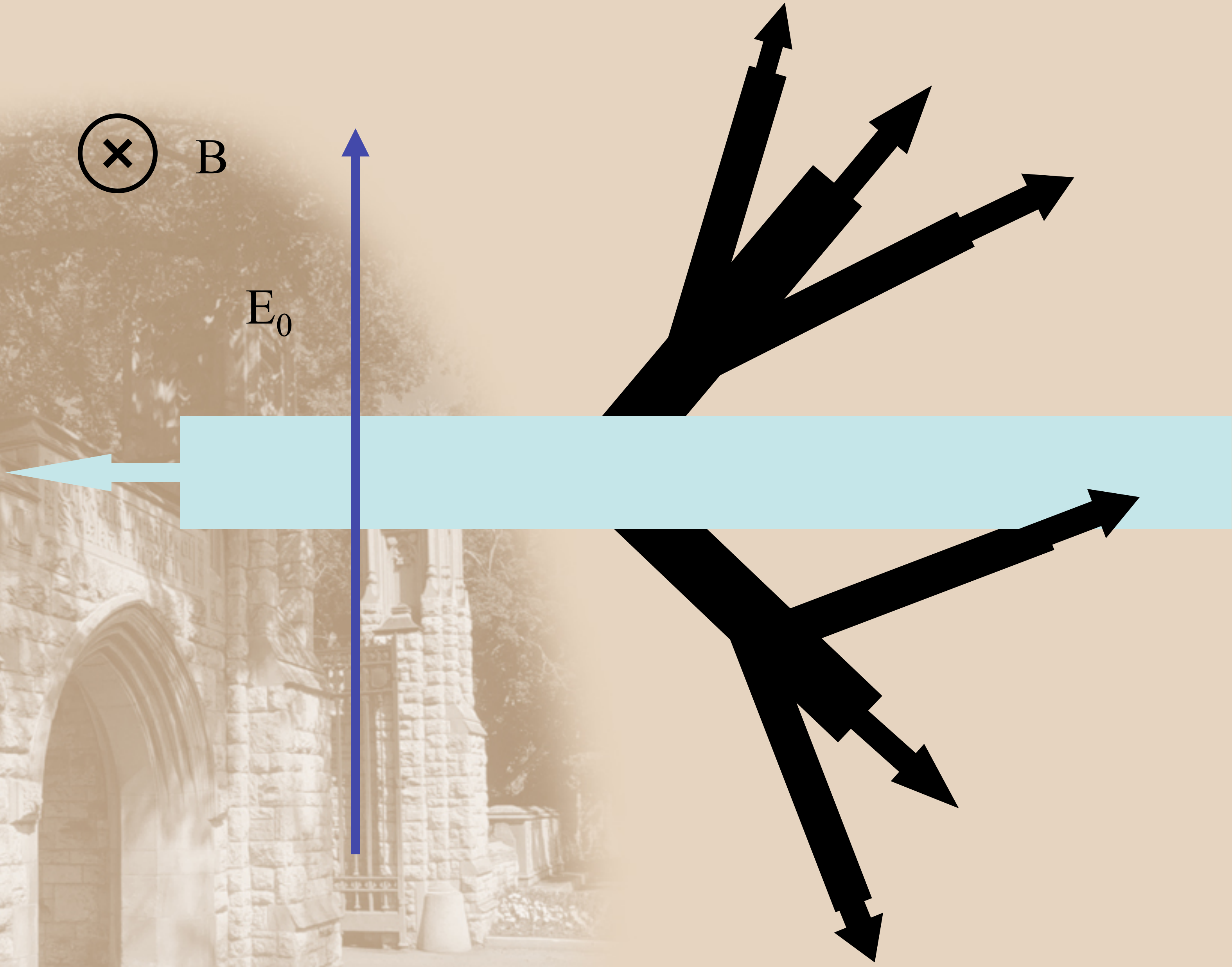
This was presented by *Keskinen and Ossakow, 1982*, in the form

$$\gamma = -\cos(\alpha)\frac{1}{L}\frac{cE_0}{B}\cos(\alpha - \beta)$$

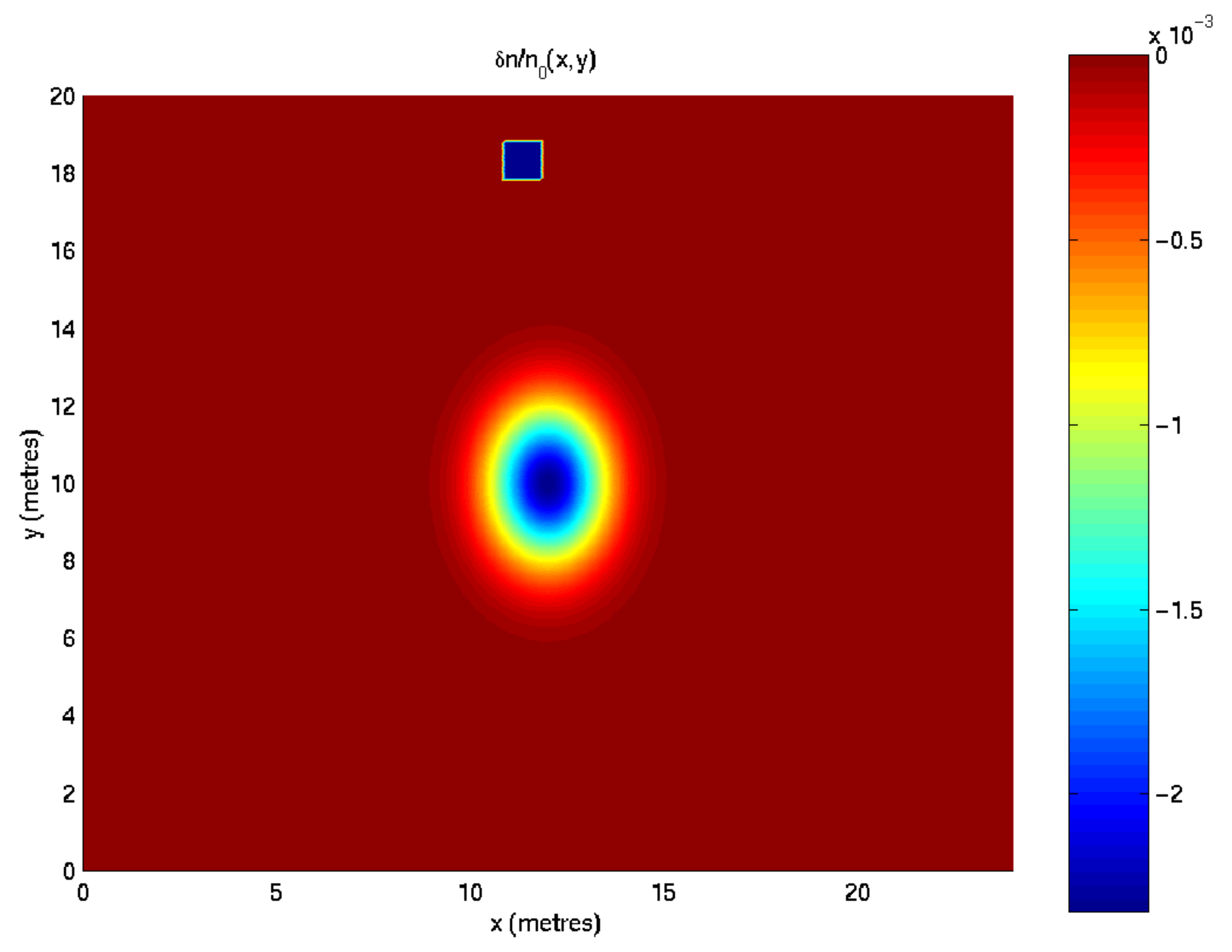
There is no Fourier decomposition here, just a steepening wall that can be Fourier analyzed after the fact. Call the steepening “cascading” if you want.



Primary and Secondary Growth structure



E region Farley-Buneman are also finger instabilities, and the structures quickly reach the size of the wavelength



Non thermal spectral properties

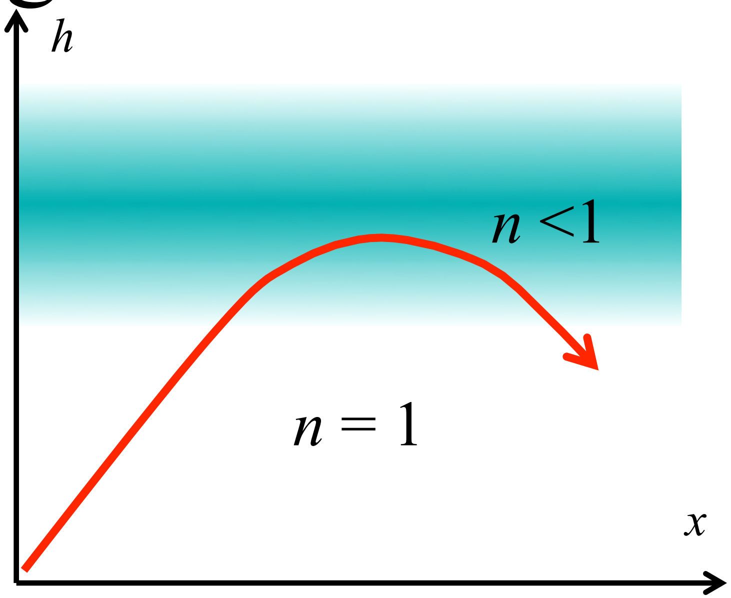
- **Spectral width**:
  - HF radars often get ground “hard target” echoes
  - Mixed ground and ionospheric scatter problems
  - The narrower the spectrum, the less turbulent the plasma has to be
  - Width describes a lifetime, except for E region?

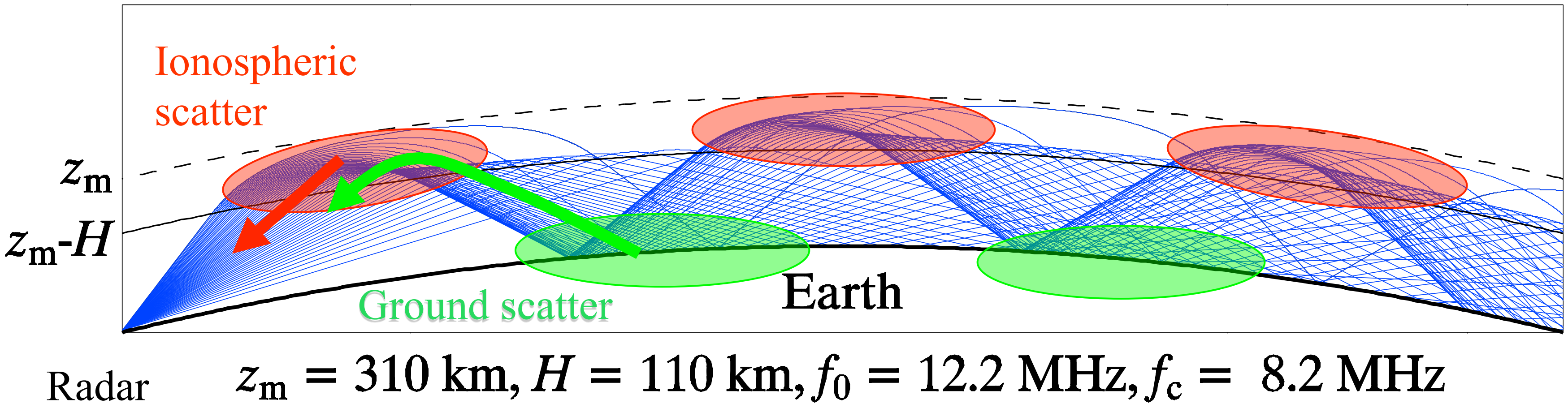
HF Propagation

f_0=10-20 MHz

$$n^2 = 1 - \frac{f_N^2}{f_0^2}, \quad f_N \propto \sqrt{N_e}$$

HF: $f_N \sim f_0$





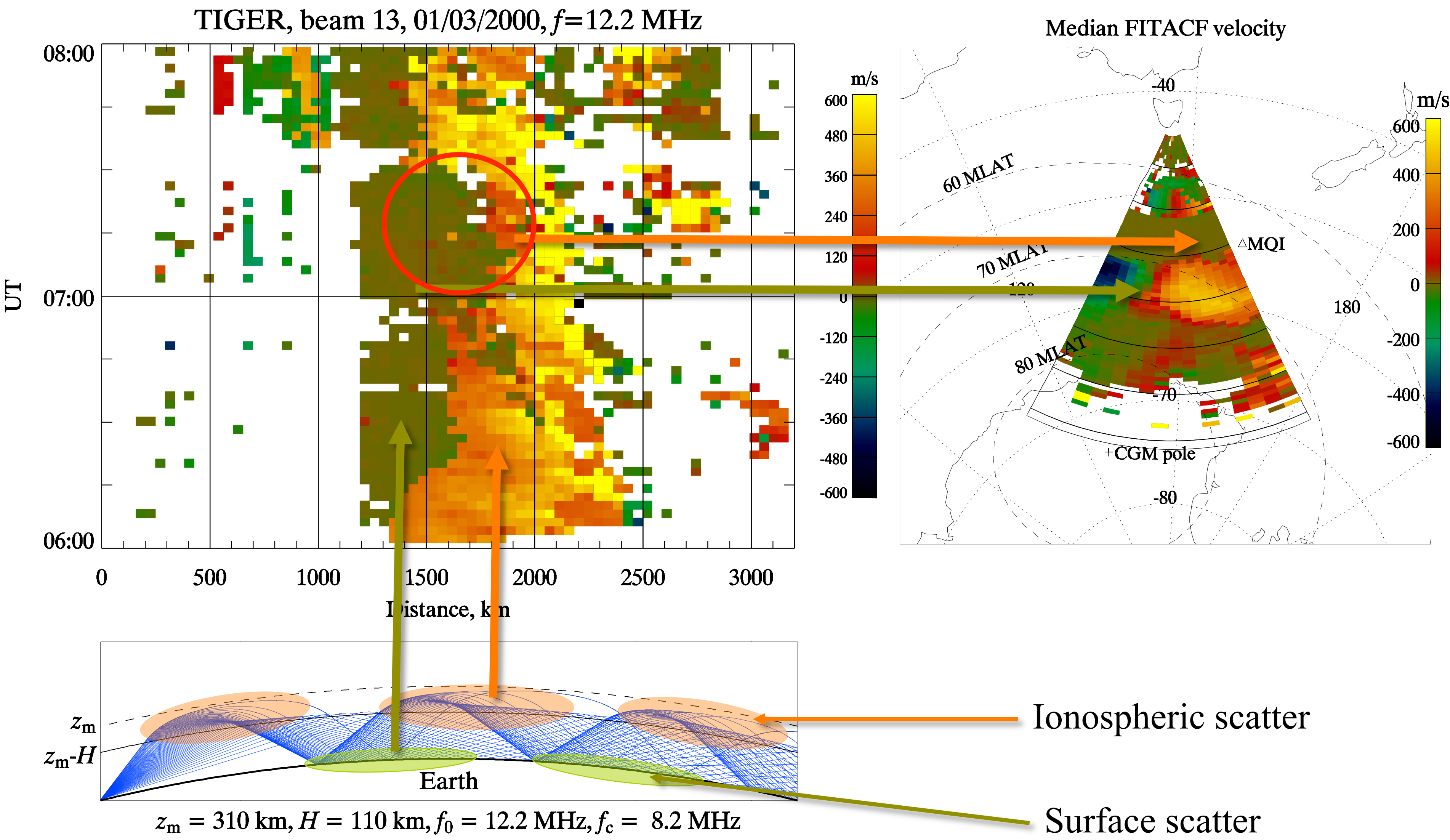
z_m = 310 km, H = 110 km, f_0 = 12.2 MHz, f_c = 8.2 MHz

Ground scatter

Problem:

Ground scatter often interferes with ionospheric scatter and distorts drift velocity estimates

Ground scatter interference

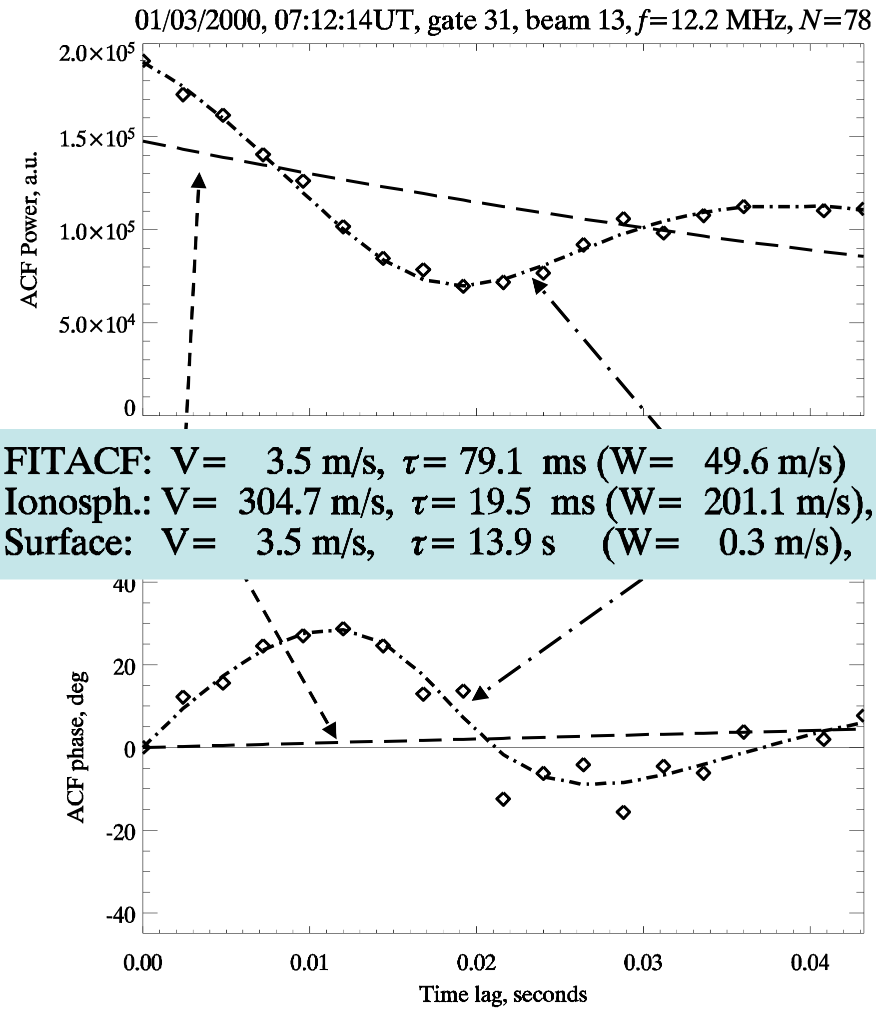


z_m = 310 km, H = 110 km, f_0 = 12.2 MHz, f_c = 8.2 MHz

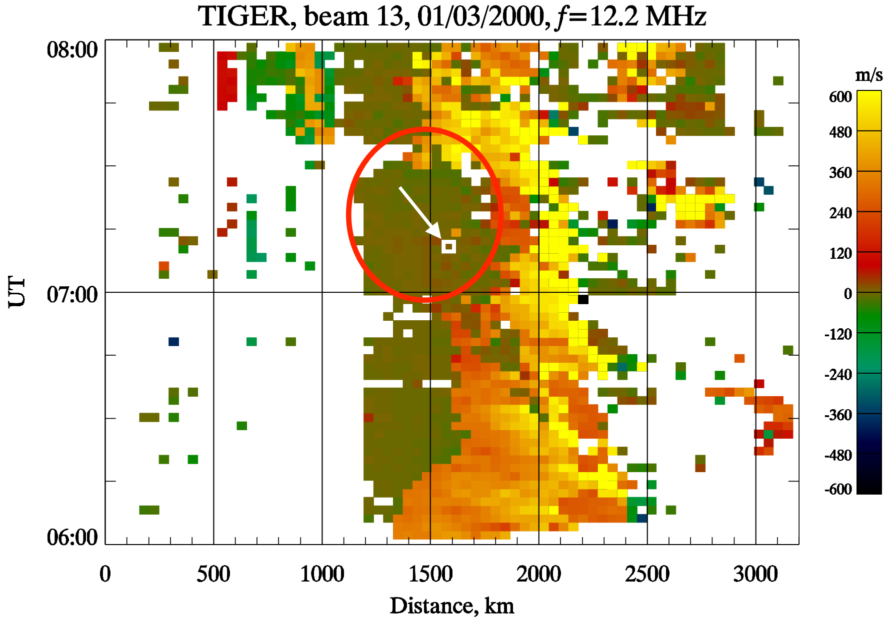
Ionospheric scatter

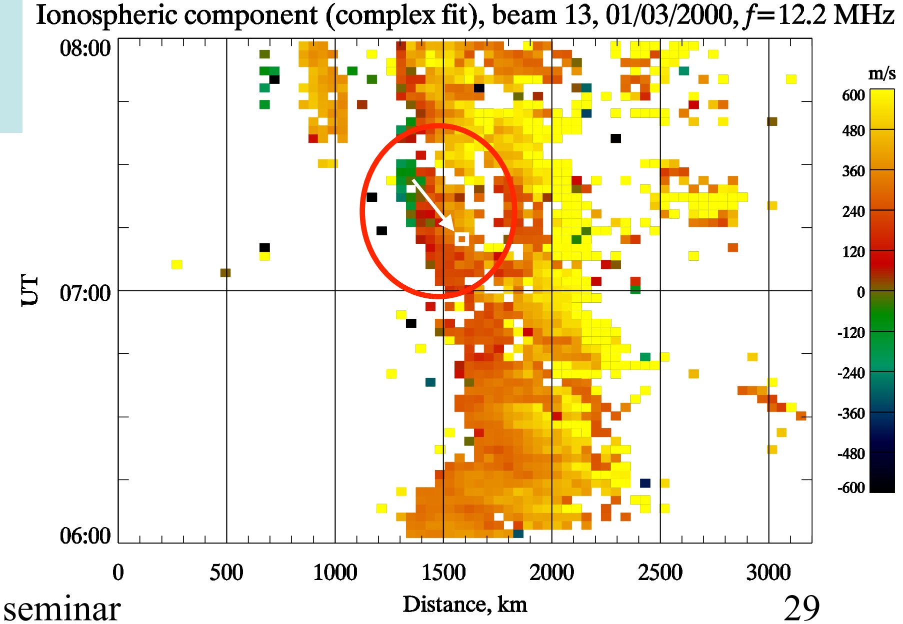
Surface scatter

Implementation

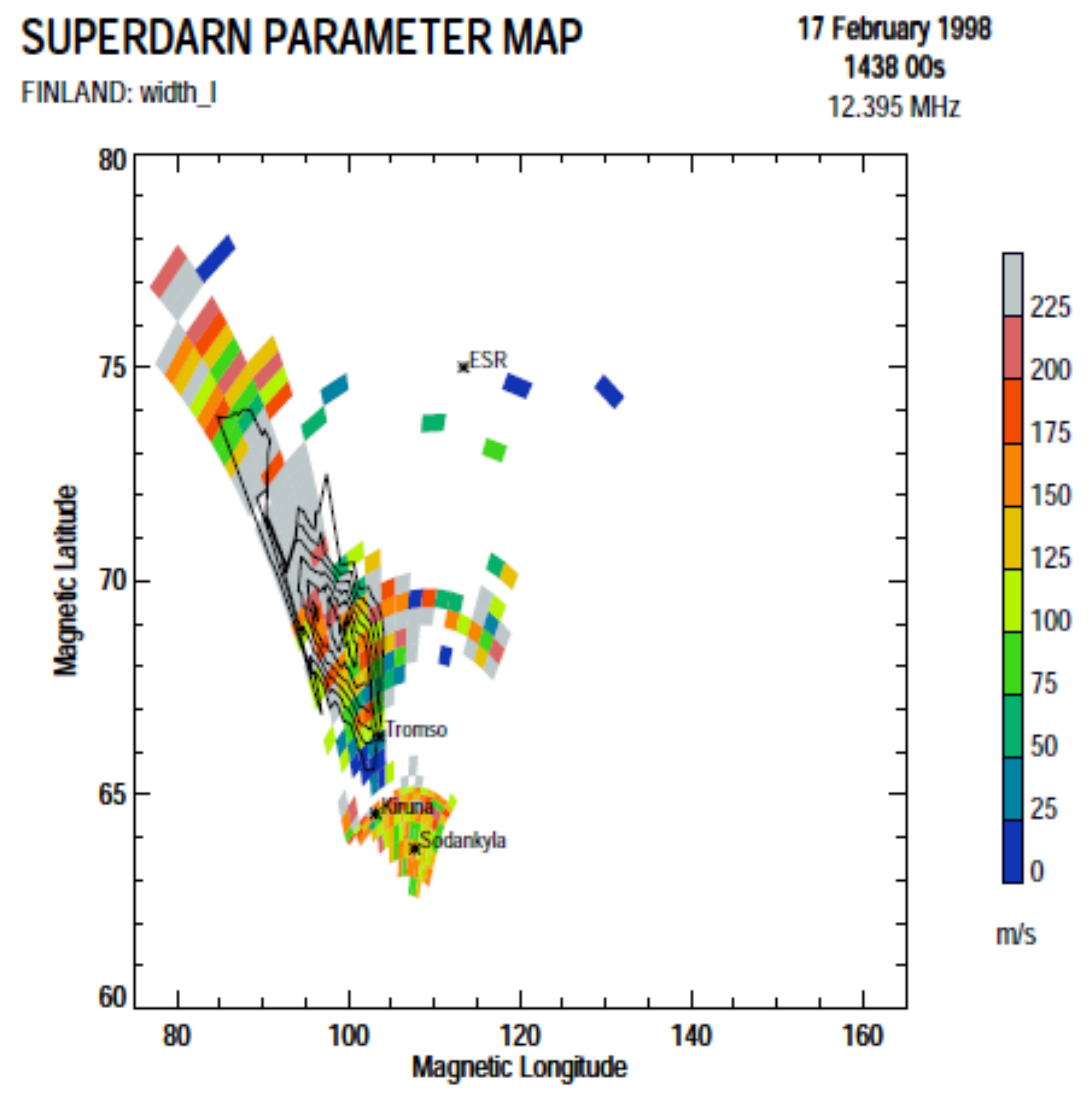


FITACF: V= 3.5 m/s, τ= 79.1 ms (W= 49.6 m/s)
Ionosph.: V= 304.7 m/s, τ= 19.5 ms (W= 201.1 m/s), 46%
Surface: V= 3.5 m/s, τ= 13.9 s (W= 0.3 m/s), 54%



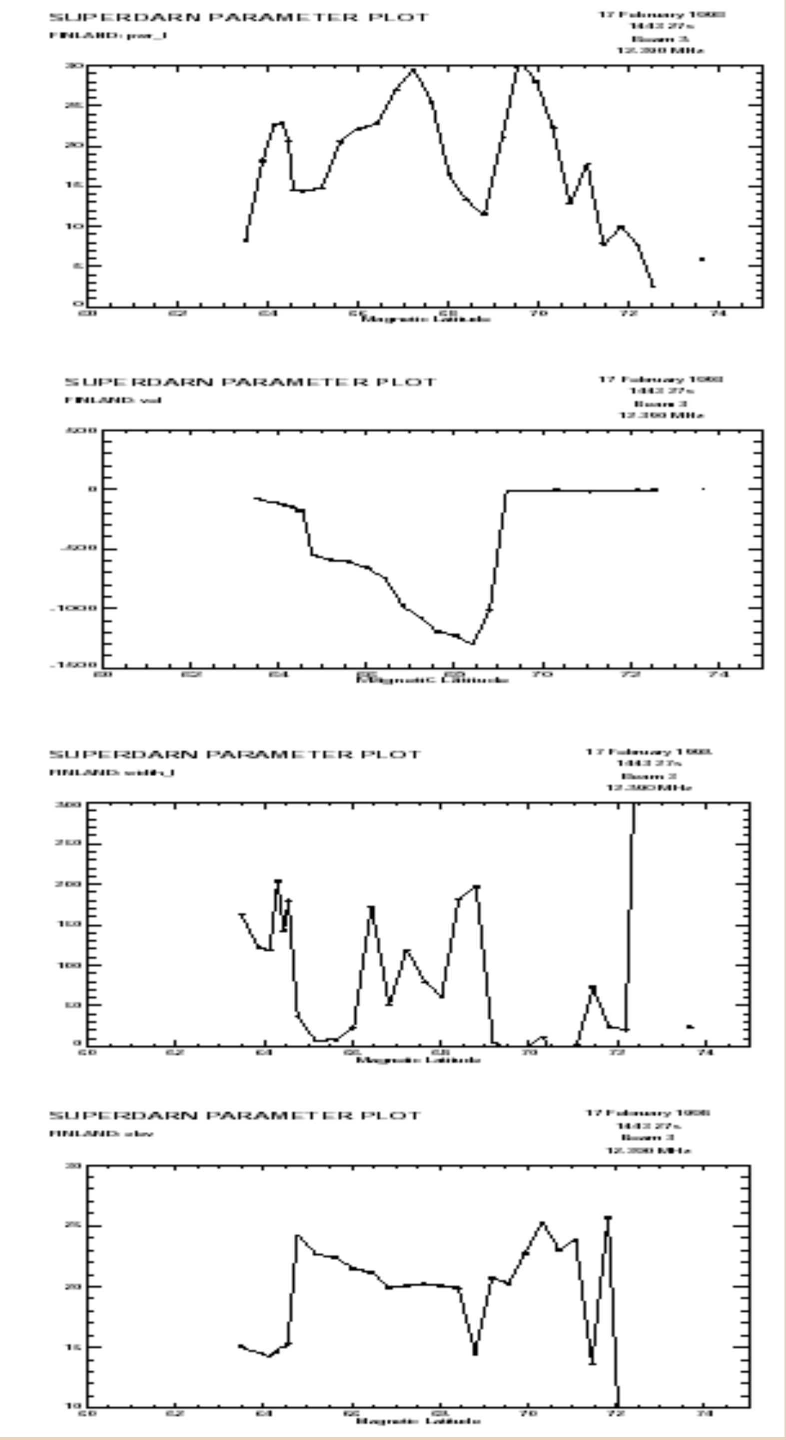


An event with extremely narrow echoes: a different instability mechanism?



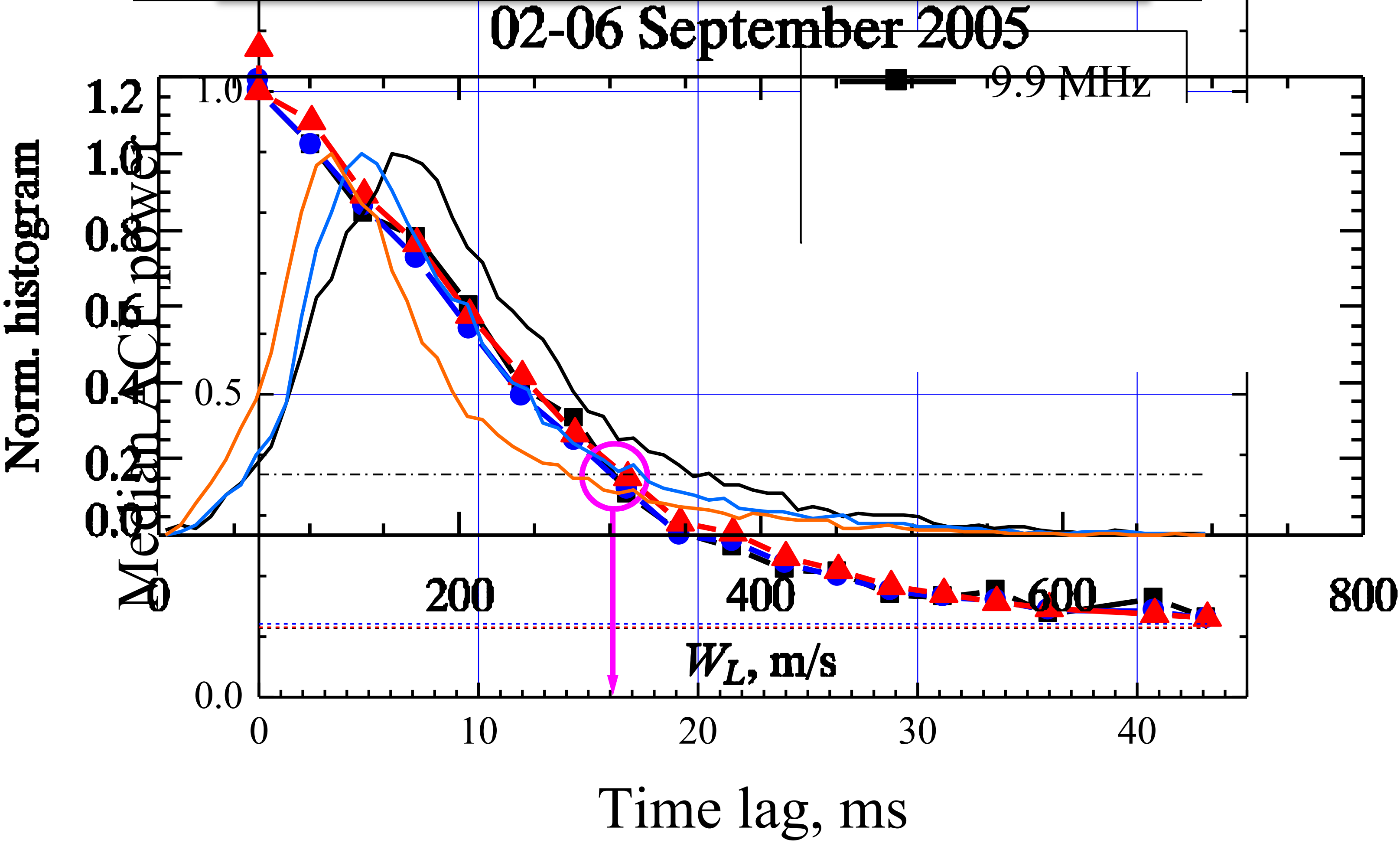
The narrow echoes:

1. Are the first F region echoes
2. Are at higher elevation angles than other F region echoes
3. Are inside of very near a region of strong shears
4. Are on the edge of more powerful F region echoes
5. Are very clean highly coherent features

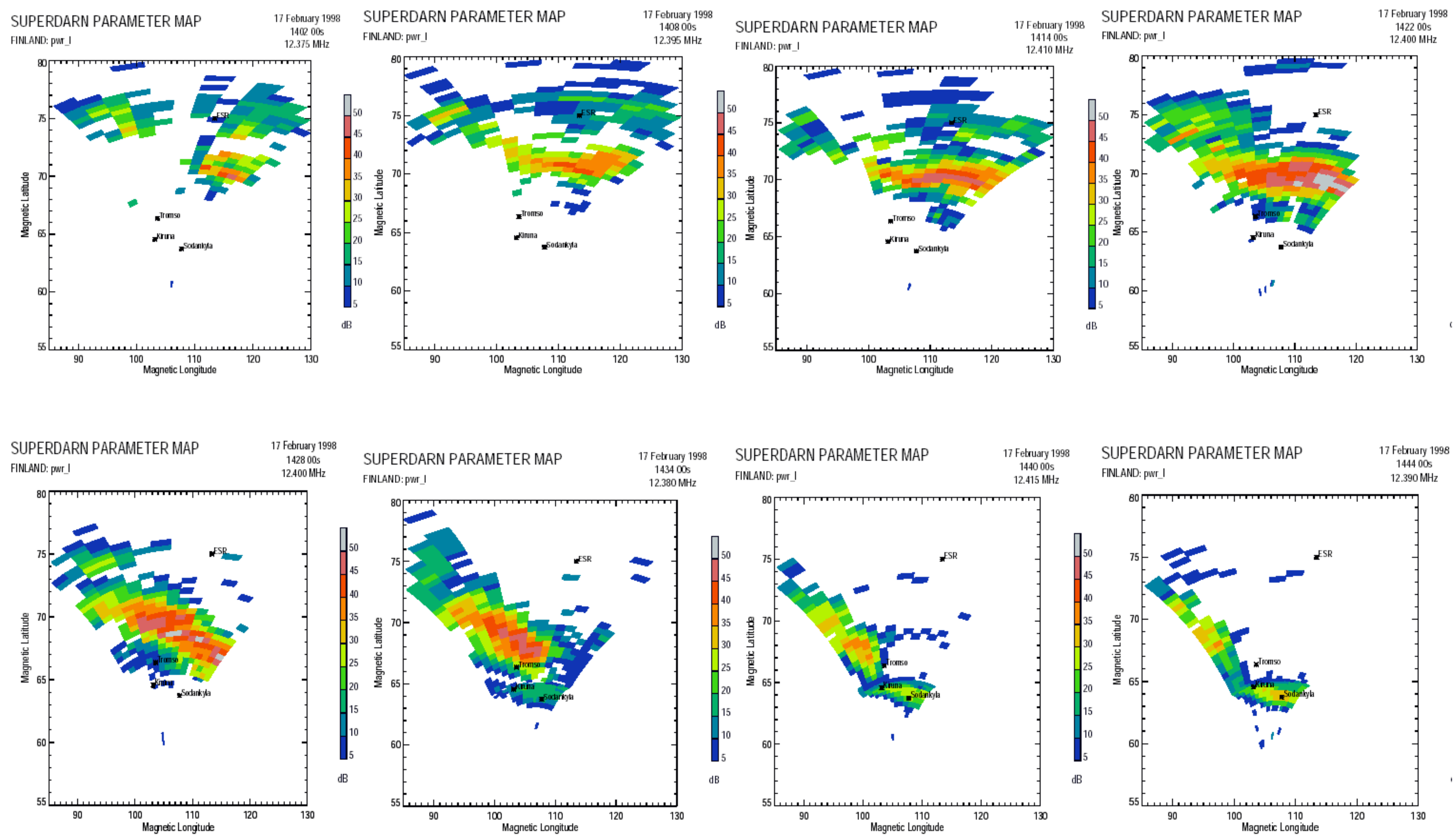


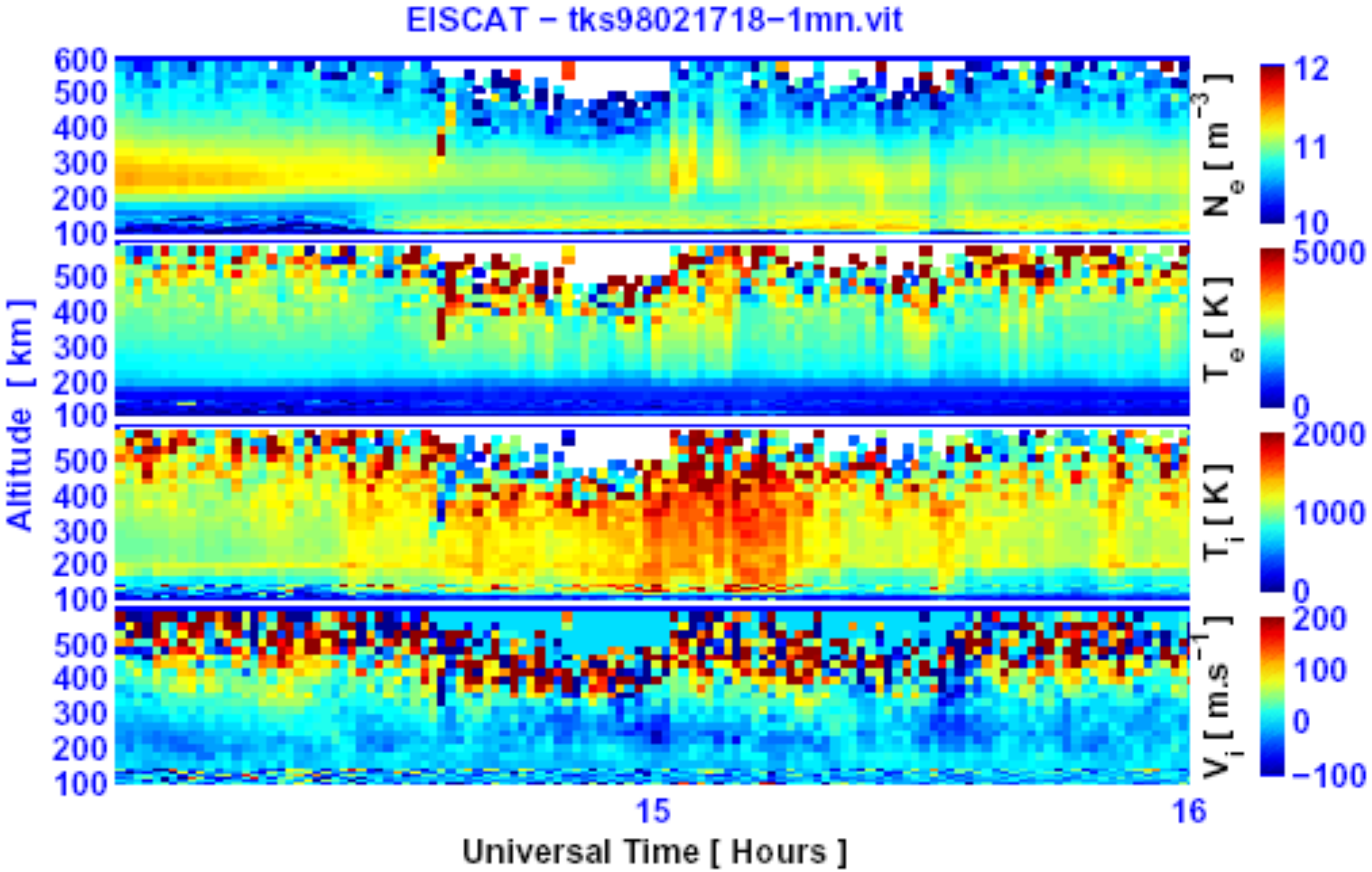
Width vs frequency

Look at the primary parameter – τ_c



Using coherent and incoherent radars together in a substorm onset study




EISCAT – tks98021718–1mn.vit
Altitude [km]
600
500
400
300
200
100
N_e [m^{-3}]
12
11
10
T_e [K]
5000
0
T_i [K]
2000
1000
0
V_i [$m.s^{-1}$]
200
100
0
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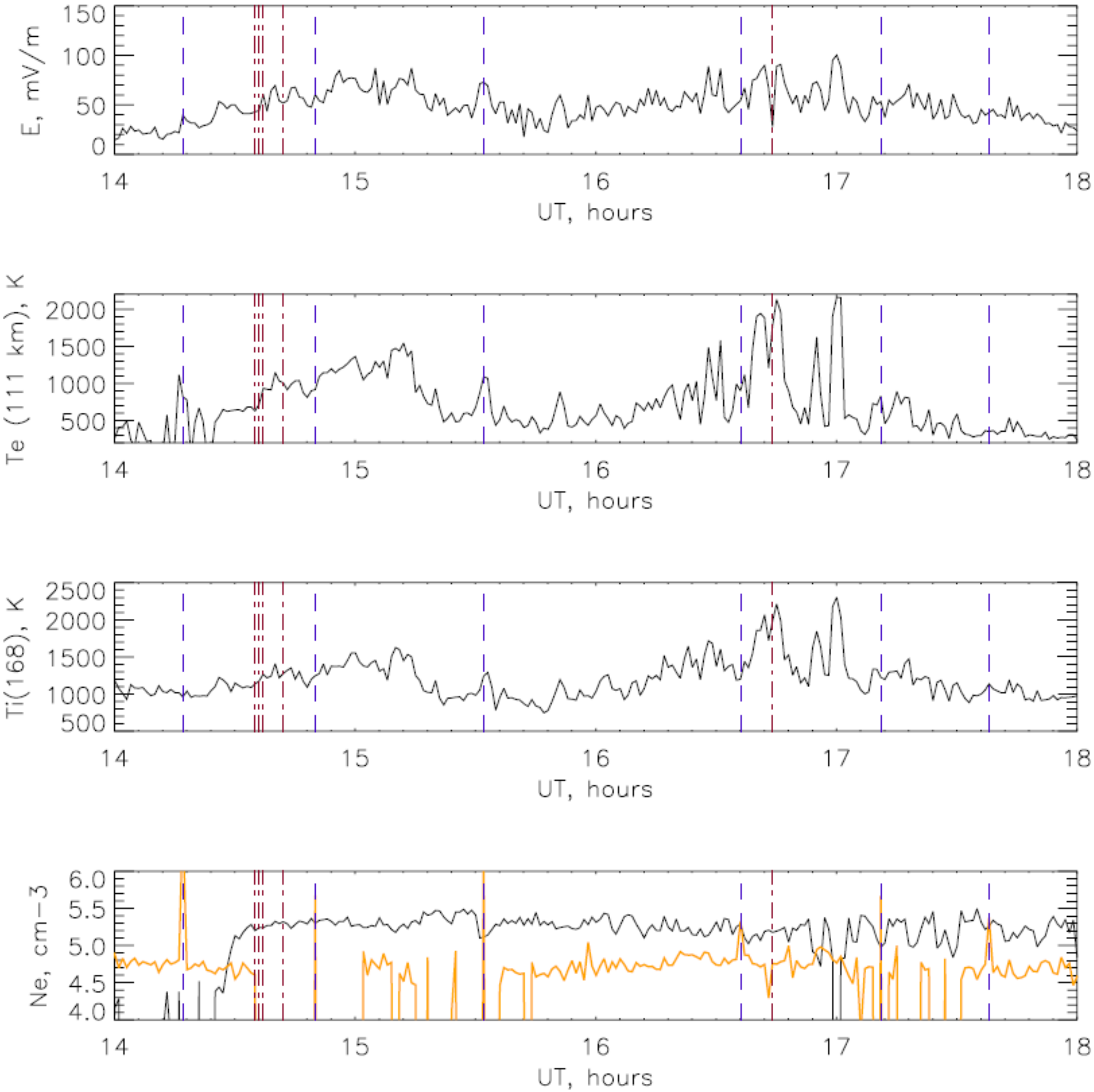
15
16
Universal Time [Hours]


E, mV/m
150
100
50
0
Te (111 km), K
2000
1500
1000
500
Ti(168), K
2500
2000
1500
1000
500
Ne, cm−3
6.0
5.5
5.0
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4.0
14
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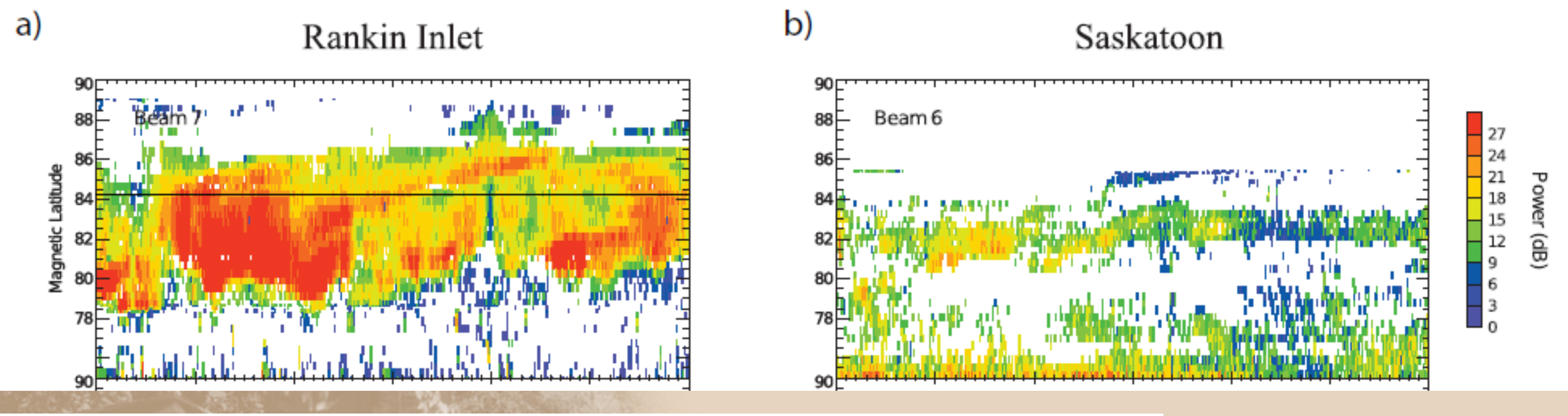
UT, hours

Using ISR and CSR in a patch study



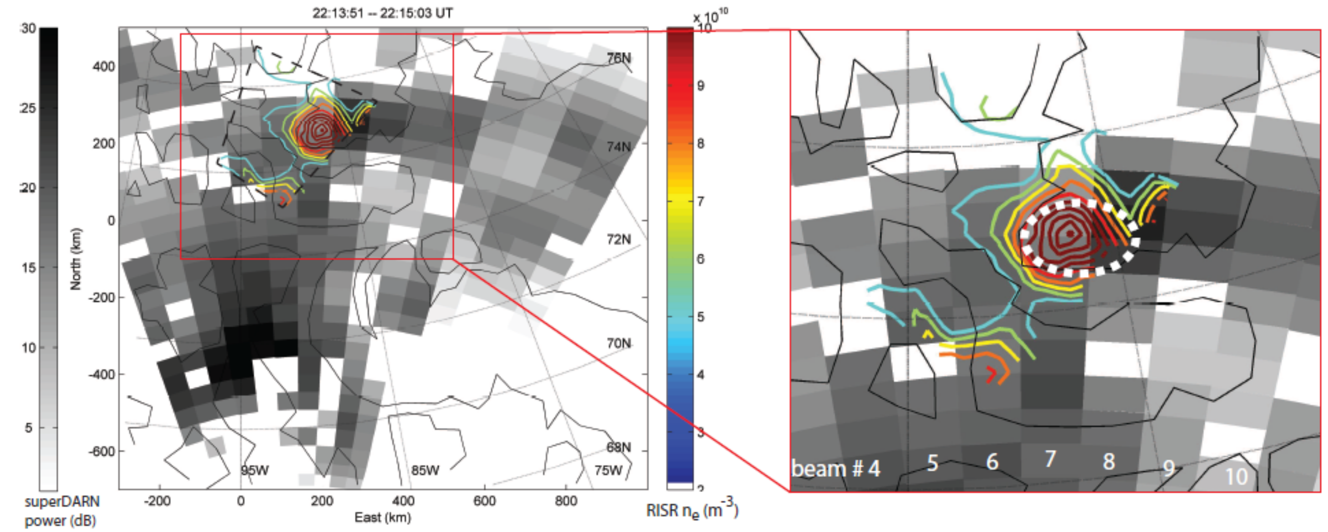
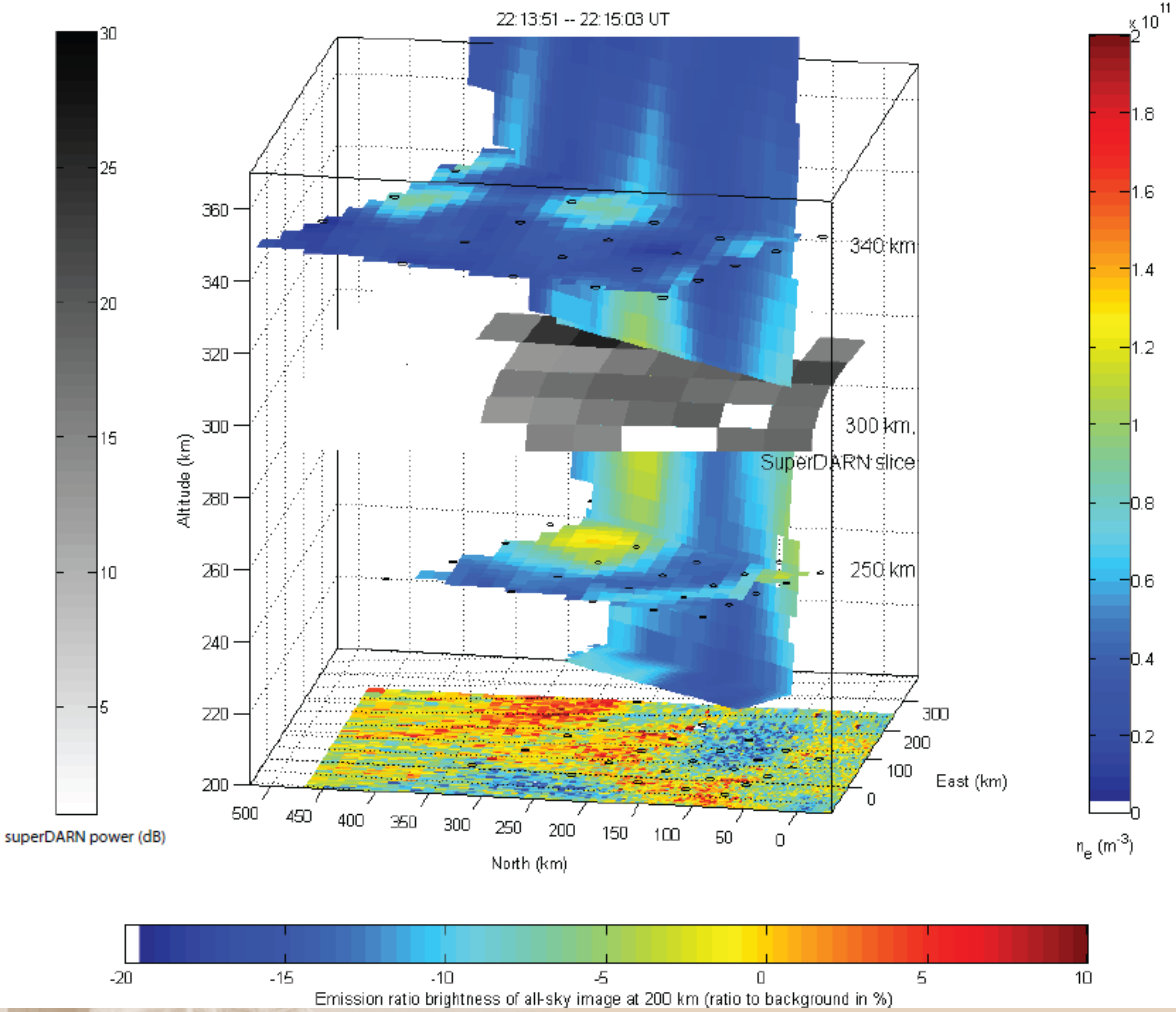


Figure 3. RISR-N electron density contour is plotted in color on top of gray scale SuperDARN echoes. The FOV of RISR-N is outlined by a dashed black line.

From Dahlgren et al, JGR, 2012


22:13:51 -- 22:15:03 UT
30
25
20
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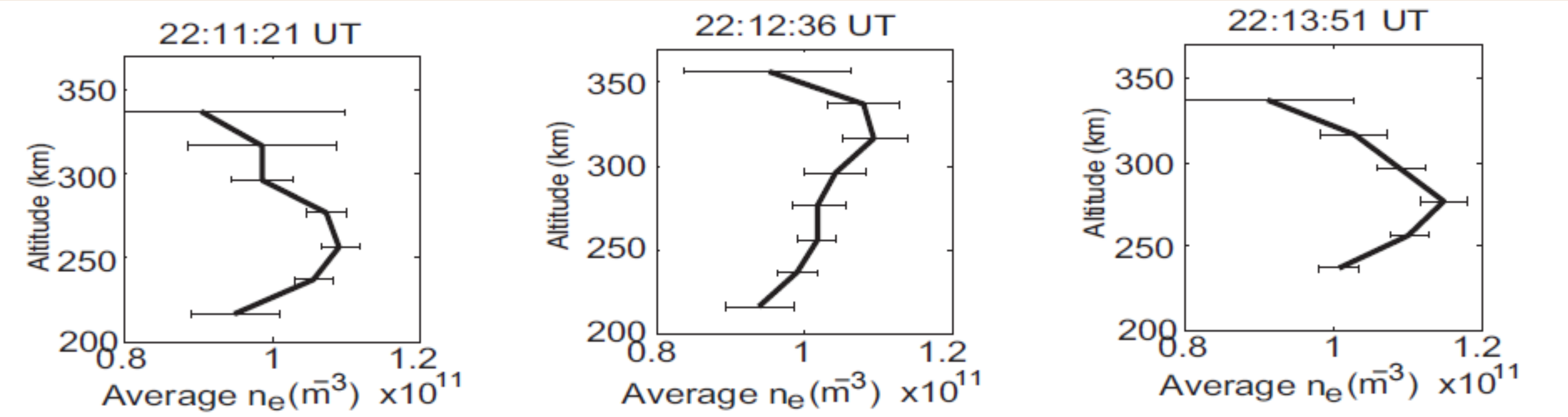
10
5
superDARN power (dB)
Altitude (km)
360
340
320
300
280
260
240
220
200
340 km
300 km,
SuperDARN slice
250 km
500
450
400
350
300
250
200
150
100
50
0
North (km)
300
200
100
0
East (km)
x 10^11
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
n_e (m^-3)
-20
-15
-10
-5
0
5
10
Emission ratio brightness of all-sky image at 200 km (ratio to background in %)



Very fast changes in average density of patch. Could it be a set of a few field-aligned patches? Would this be consistent with SuperDARN detection?

Possible interpretation of the radar data

Summary

- ISR’s see weak thermal structures but can also become CSR’s in the presence of large amplitude structures in their line of sight
- CSR’s can only see unstable structures
- ISR spectra can be derived only as long as the plasma is shown to be stable
- CSR spectra cannot be derived on first principles and their origin and features are often not understood.
- CSR’s produce very useful Doppler shift information and are used to identify morphological signatures on global scales
- ISR’s and CSR’s complement each other well because of the context they provide for one another

Announcing the next SuperDARN workshop and school: all are welcome

- The next International SuperDARN workshop will be held in Machoire d’Orignal (Moose Jaw), Saskatchewan
- DATE: May 26-31, 2013
- PLACE: Temple Gardens Mineral Spa, Moose Jaw, Canada
- We are planning a few days school for graduate students and other interested parties in Saskatoon in the days leading up to the workshop.


INFORMATION