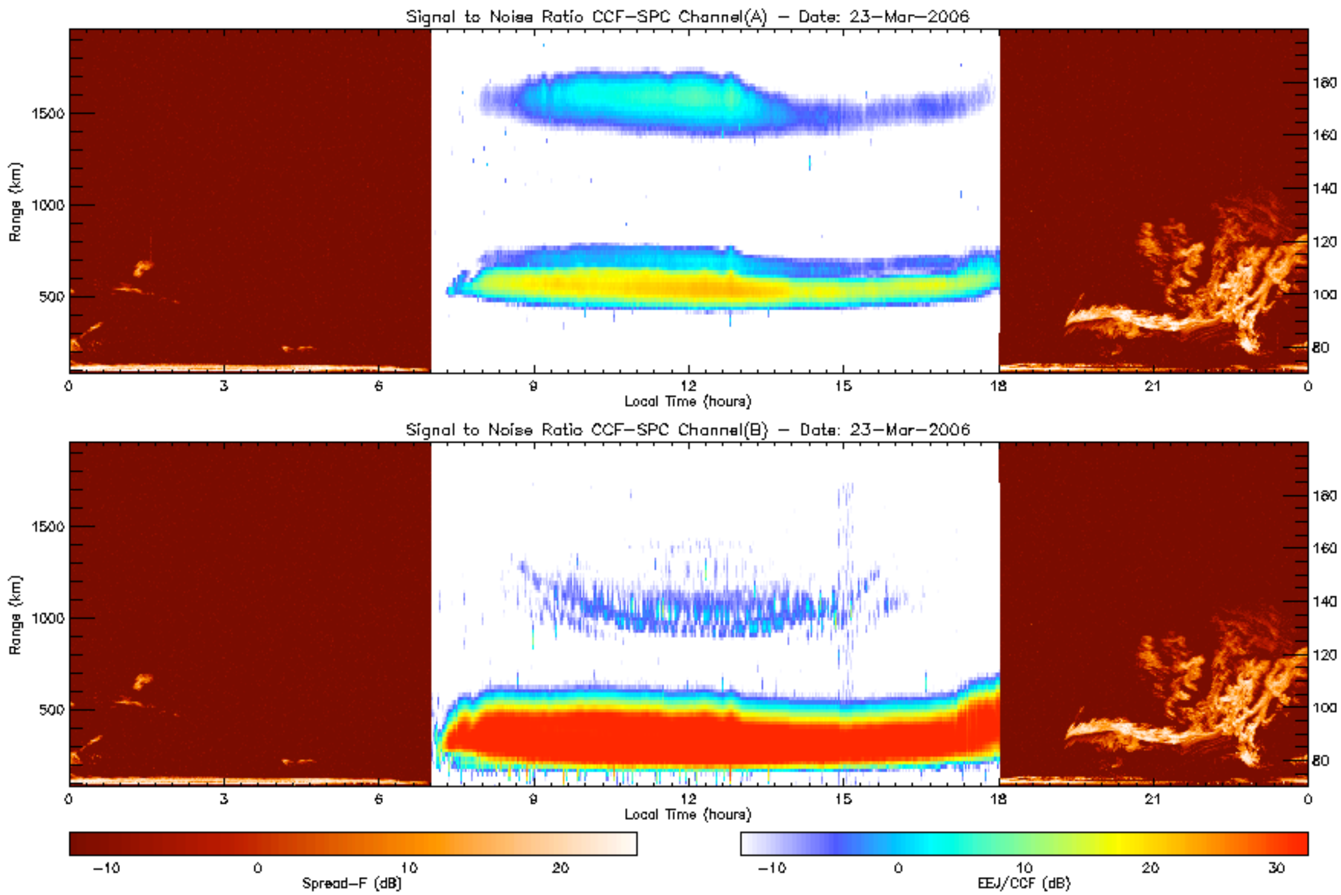
Equatorial Ionospheric Plasma Irregularities: What have we learned from radar studies?



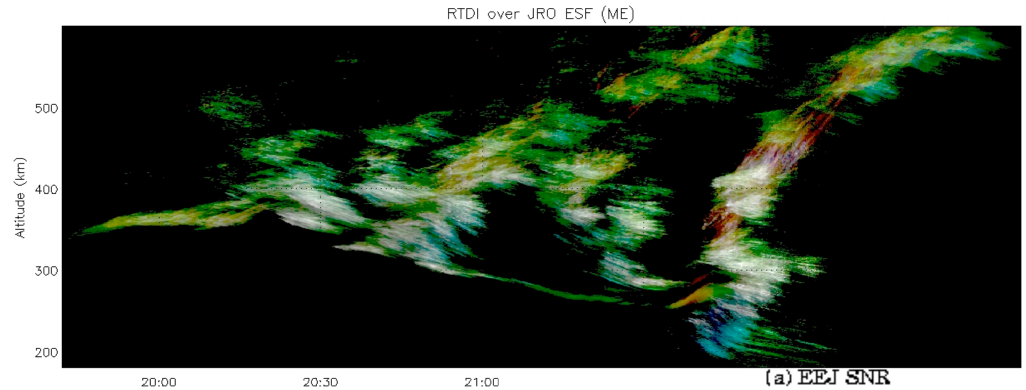
J. L. Chau et al.
Radio Observatorio de Jicamarca, Instituto Geofísico del Perú, Lima

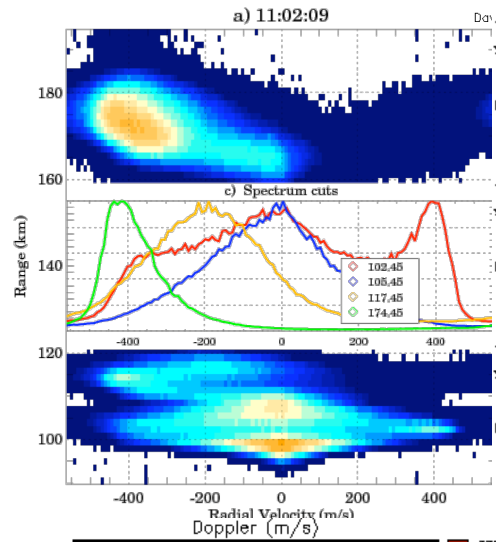
Clemson University – Jan 24, 2008

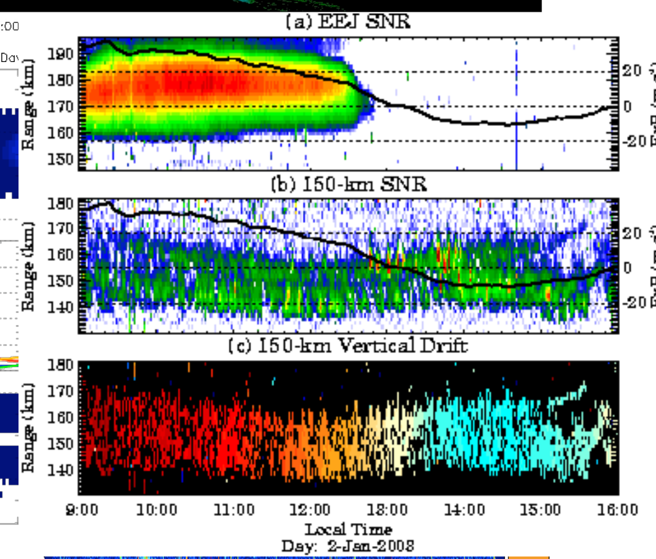
Outline

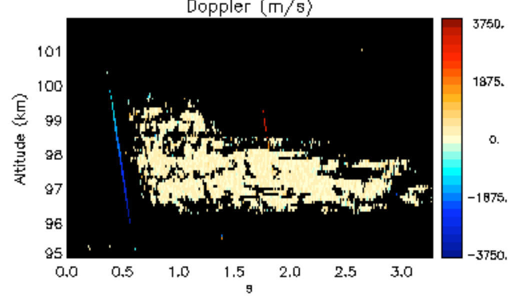
Radio Observatorio de JICAMARCA Radio Observatory

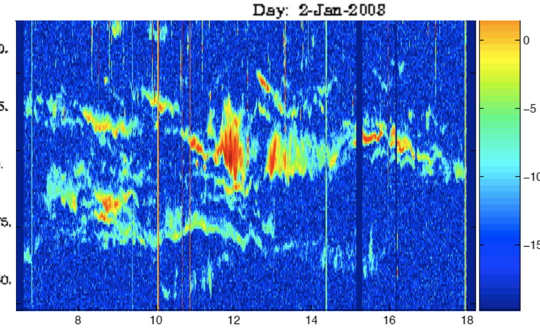
- The Equatorial ionosphere
- The Jicamarca Radio Observatory
- Equatorial ionospheric plasma irregularities: What we know from radar studies?
  - Equatorial spread F (ESF) echoes
  - 150-km echoes
  - Equatorial electrojet (EEJ) echoes
  - Meteor head and trail echoes
  - Perennial Equatorial Mesospheric Echoes (PEME).
- 150-km recent findings





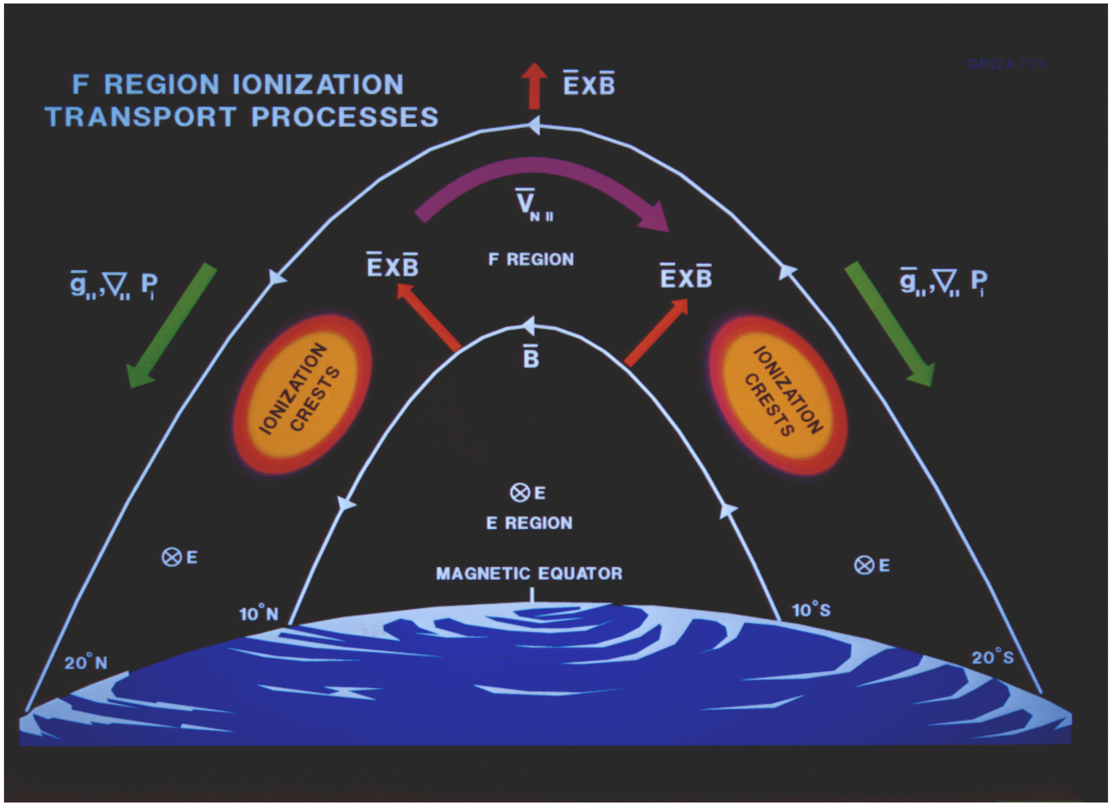


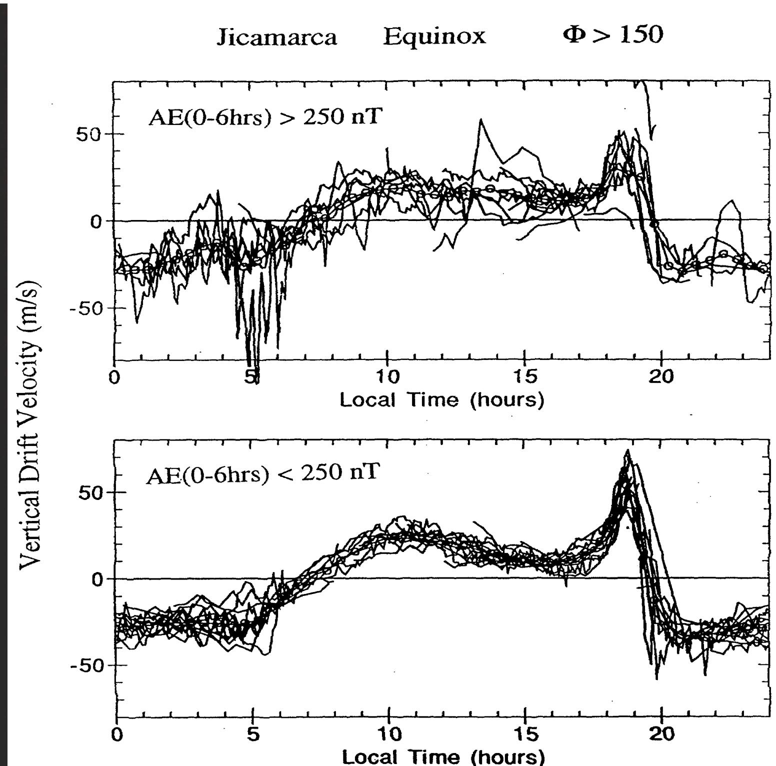




Equatorial Ionosphere

Radio Observatorio de JICAMARCA Radio Observatory

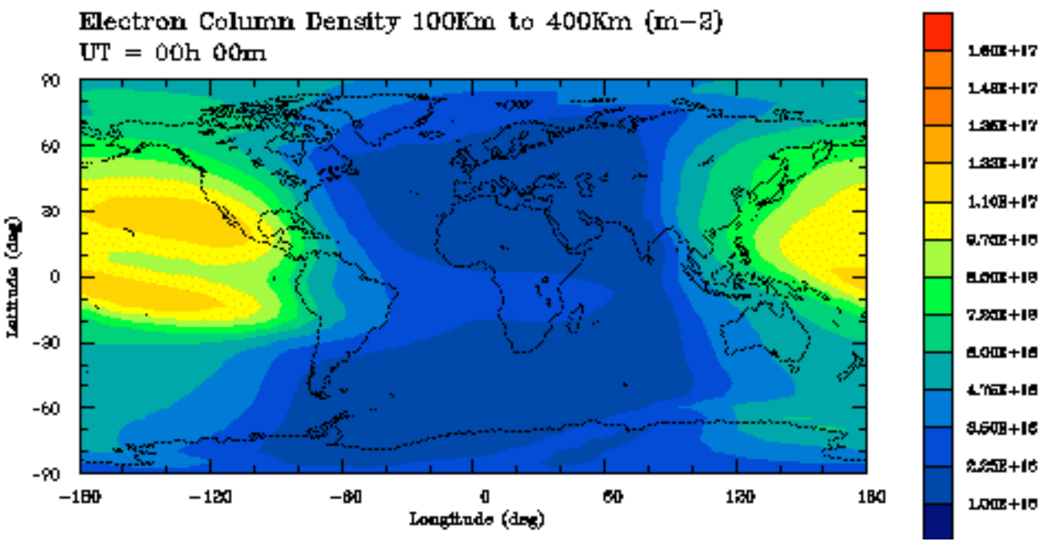




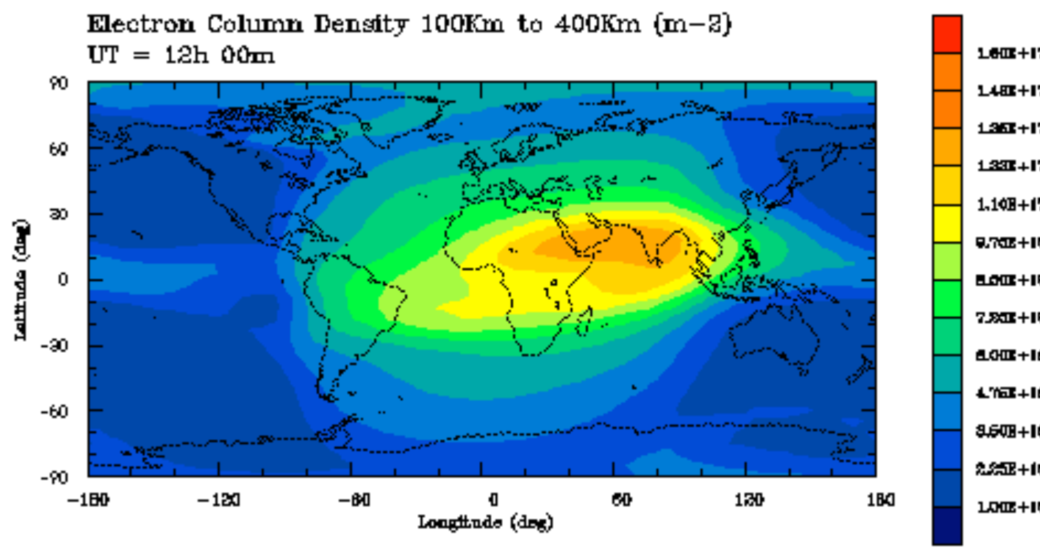
[from *Fejer et al*, 1999]

- **B** field is nearly horizontal
- Daytime:
  - *E*-region E is eastward
  - Off-equatorial E maps to F above mag. Equator -> Upward ExB
  - Formation of Appleton Anomaly
- Around sunset, *F* region dynamo develops and competes with *E*, generates PRE and ExB goes downward (E westward)
- At night upward density gradient is opposite in direction to g, Rayleigh-Taylor unstable, allowing plasma density irregularities to form.

Ionosphere Total Electron Content: Quiet Vs. Disturbed Conditions

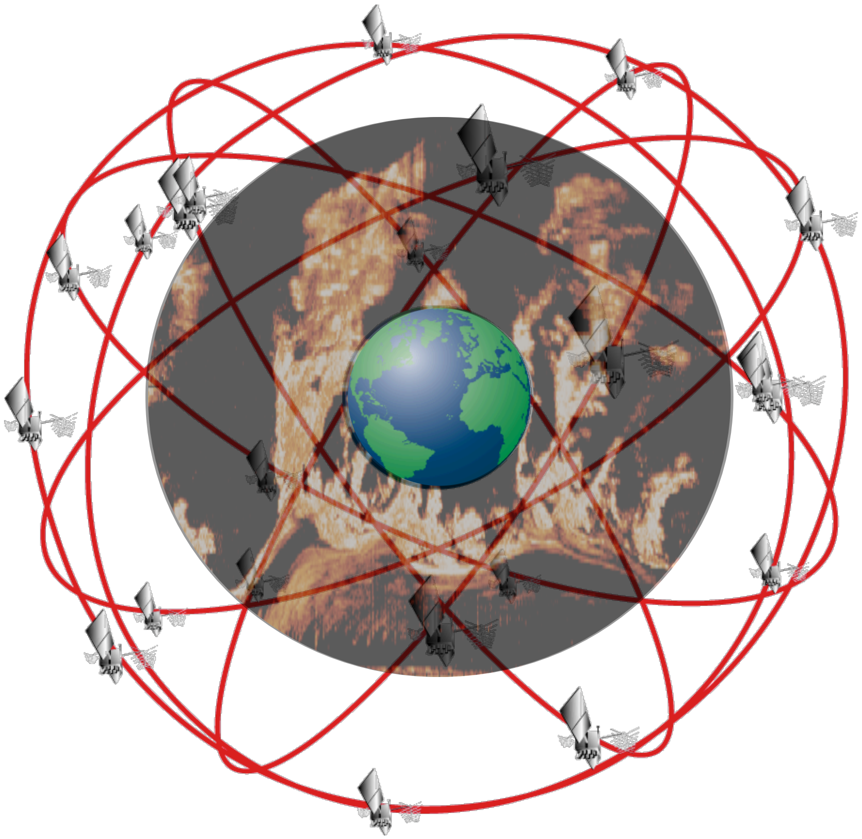


Ionospheric Storm UT = 12h 00m



GPS System

Radio Observatorio de JICAMARCA Radio Observatory



- 24 GPS satellites
- Orbits at 20,000 kms altitude and 6 orbital planes
- Each satellite completes an orbit every 12 hours

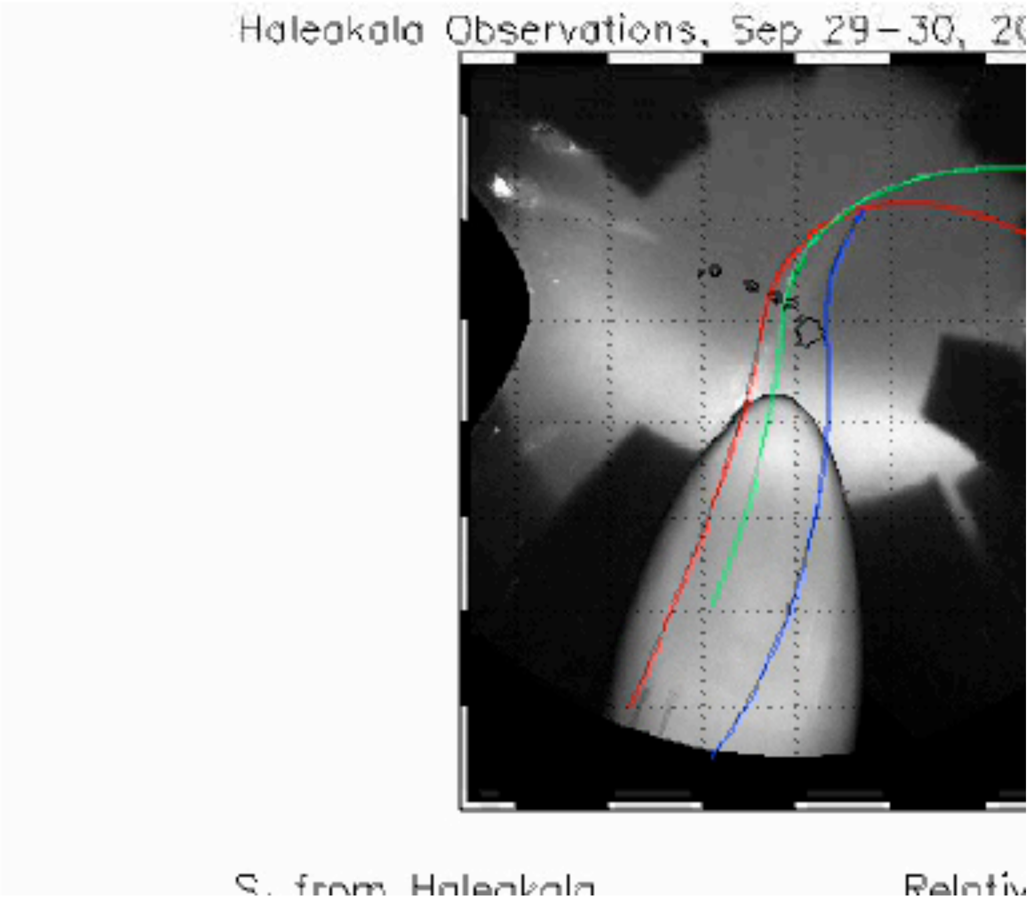
Applications

- Civil, military
- Scientific: Geodesy, Meteorology, Aeronomy

Equatorial Ionosphere: Ionospheric irregularities and GPS signals

Radio Observatorio de JICAMARCA Radio Observatory

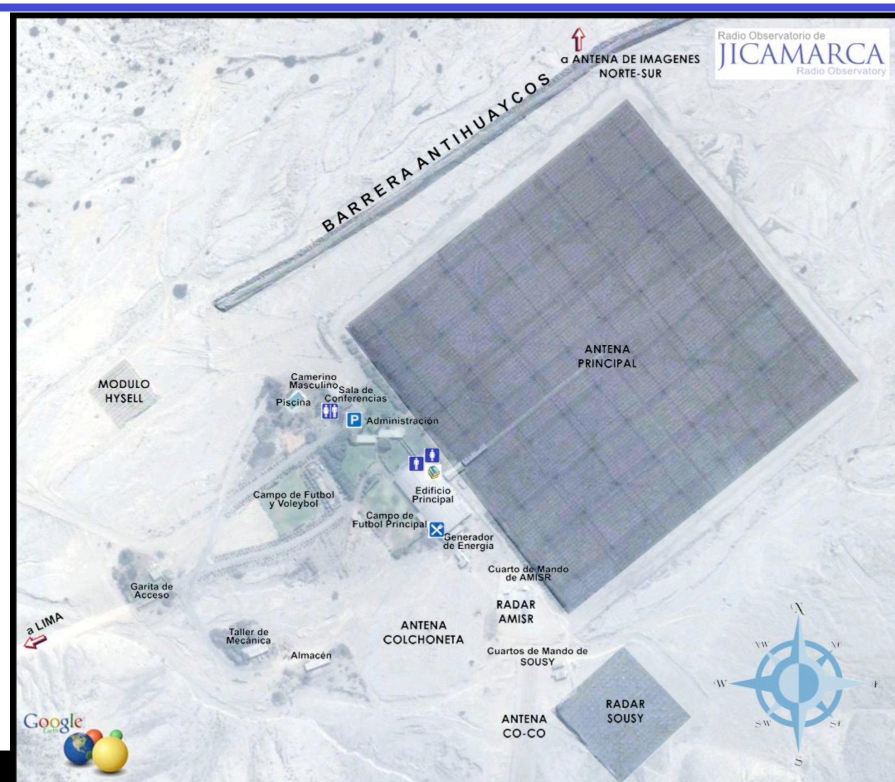
[*Courtesy of J. Makela*]

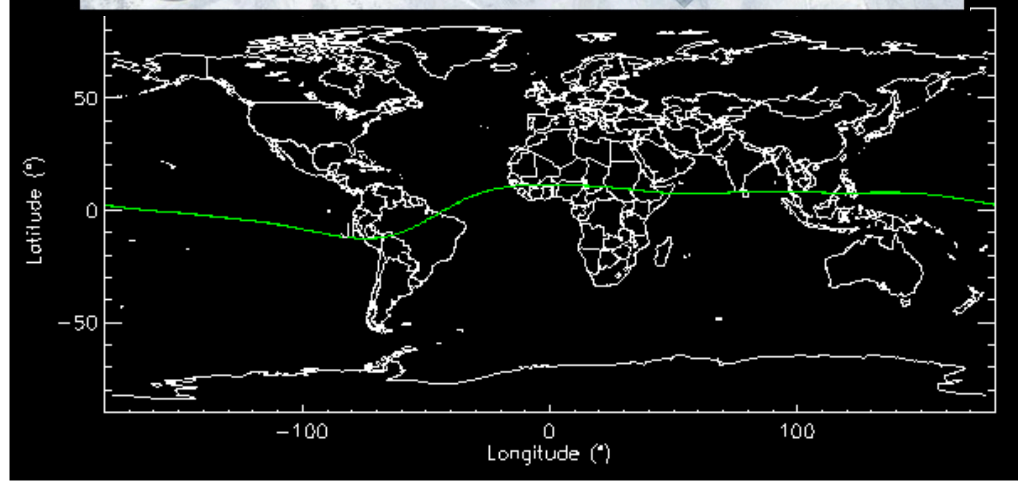


The Jicamarca Radio Observatory

Radio Observatorio de JICAMARCA Radio Observatory

- Built in 1961 by the US NBS and then donated to IGP in 1969.
- Operating frequency: 50 MHz
- Antenna type: array of 18,432 dipoles, organized in 8x8 cross-polarized modules.
- Pointing directions: within 3 degrees from on-axis. Phase changes are currently done manually.
- Transmitters: 3 x 1.5 MW peak-power with 5% duty cycle.
- Located "under" the magnetic equator (dip 1º).

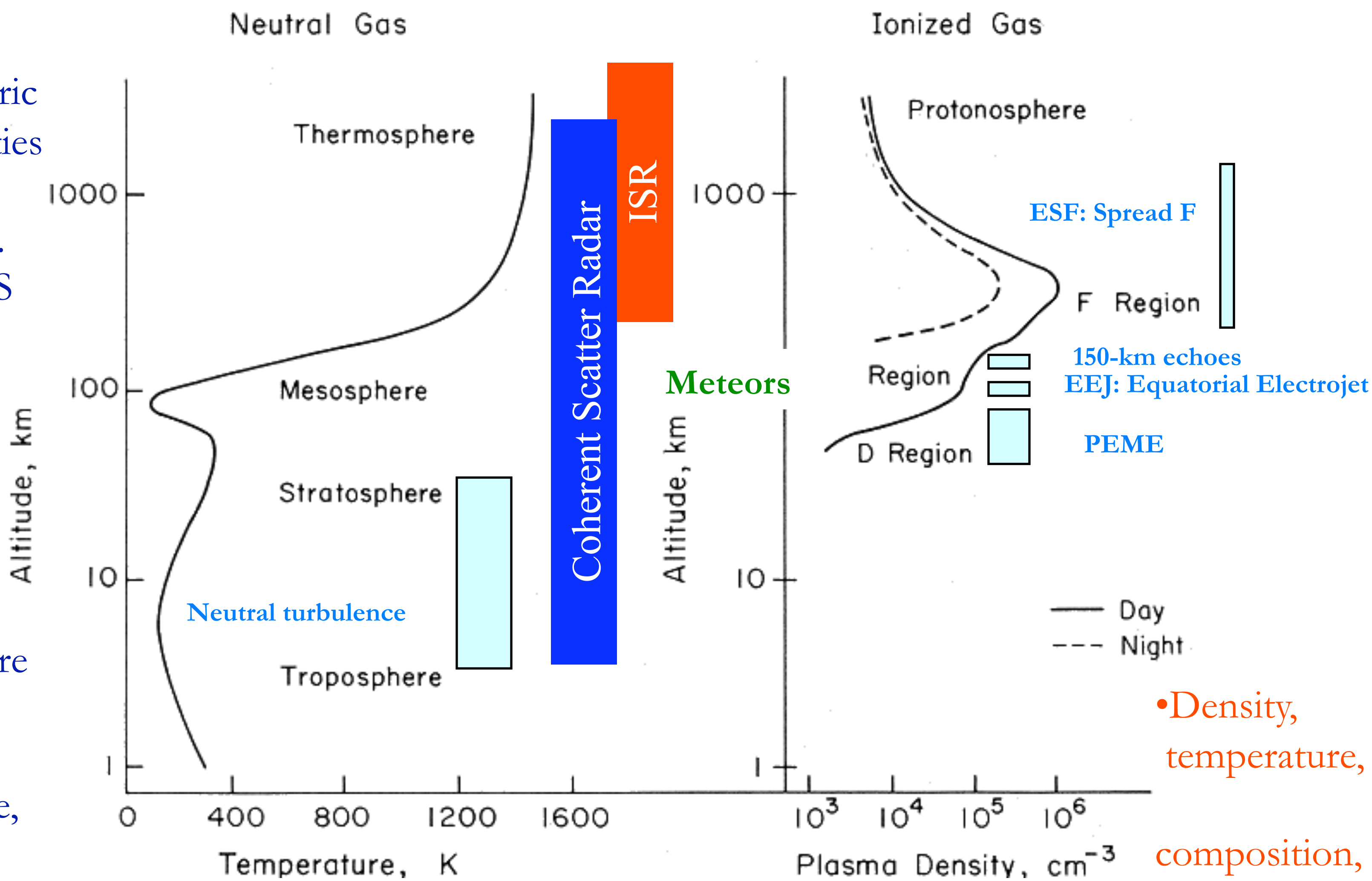




¿What do we study at Jicamarca?

Radio Observatorio de JICAMARCA Radio Observatory

- Ionospheric Irregularities (EEJ, 150 -km, ESF).
- SAR, GPS



- Neutral atmosphere dynamics (winds, turbulence, vertical velocities)
- Meteorology, aviation.

- Density, temperature, composition, electric fields
- Modeling, space weather

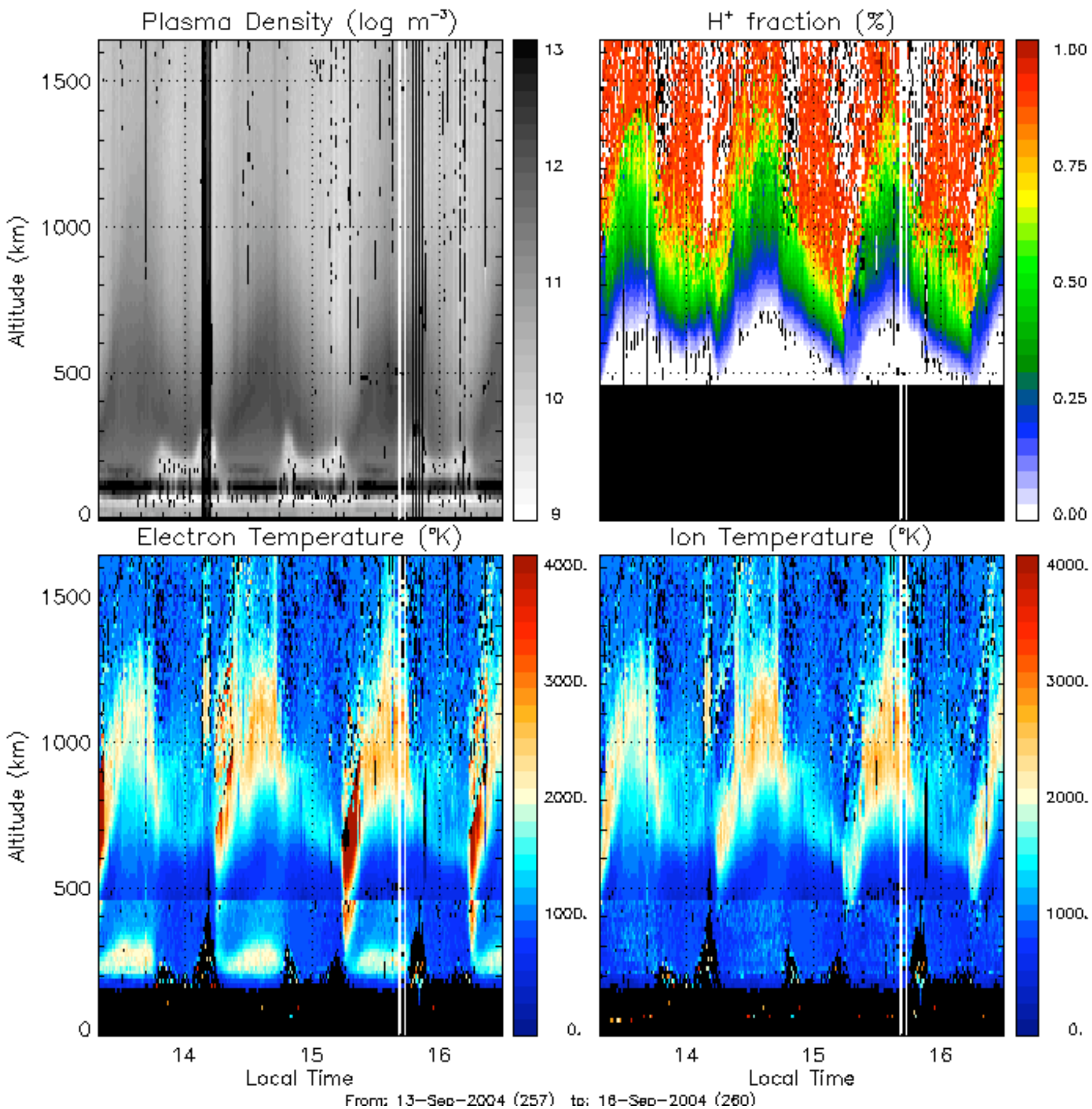
Jicamarca Themes (Stable Ionosphere)

Radio Observatorio de JICAMARCA Radio Observatory

- **Understanding the stable ionosphere**
  - Topside: What controls the light ion distribution? Why are the equatorial profiles so different from those at Arecibo? What is the storm time response of the topside?
  - *F* region: Do current theories fully explain electron and ion thermal balance? Do we understand the electron collision effects on ISR theory now? What is the effect of *F*-region dynamics near sunset on the generation of ESF plumes? What are the effects of N-S winds on inter-hemispheric transport?
  - *E* region: What are the basic background parameters in the equatorial *E* region? What is the morphology of the density profiles in this difficult to probe region? How does this morphology affect the *E*-region dynamo?
  - *D* region: What effects do meteor ablation and mesospheric mixing have on the composition in this region?

Oblique ISR Examples

Radio Observatorio de
JICAMARCA
Radio Observatory



•This modes combines the Faraday Double Pulse mode with a long pulse mode, allowing the use of the available duty cycle.

•It provides:

-Absolute electron density (from Faraday rotation) and temperatures below 500 km.

-Density, temperatures and composition above 500 km.

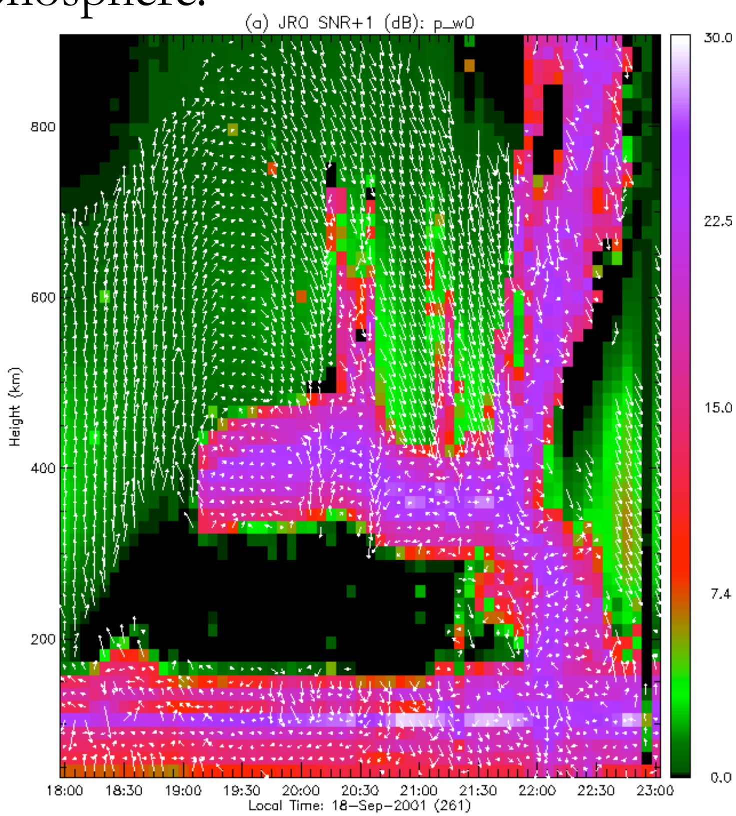
•Preliminary results [*Hysell et al.* 2008].

-Good for Topside work and sunrise observations.

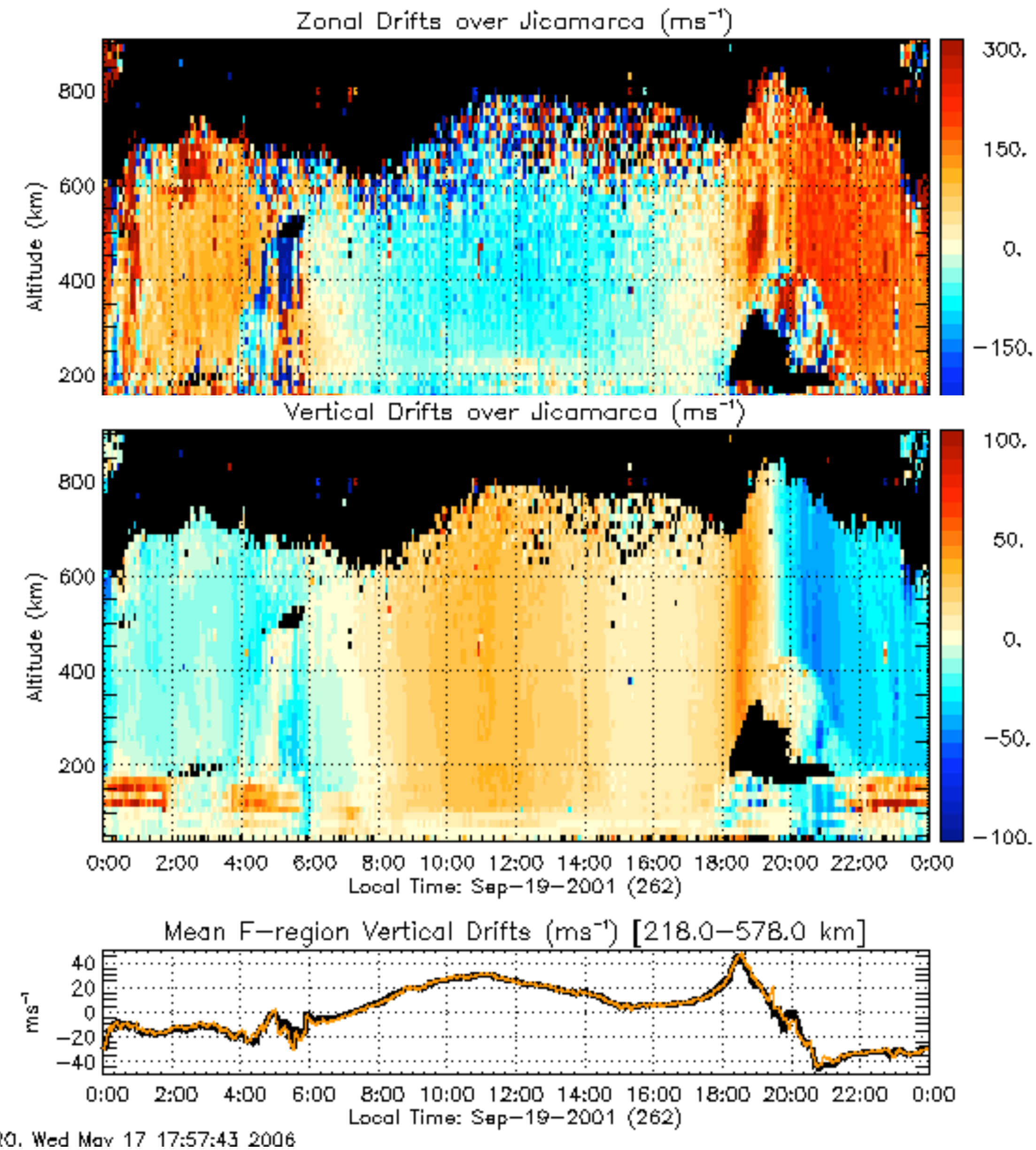
Perpendicular ISR Examples

Radio Observatorio de JICAMARCA Radio Observatory

- Simultaneous measurements of vertical and zonal drifts, with 15 km and 5 min resolutions.
- JRO provides the most precise electric field measurements in the ionosphere.



[from *Kudeki and Batthacharyya*, 1999]



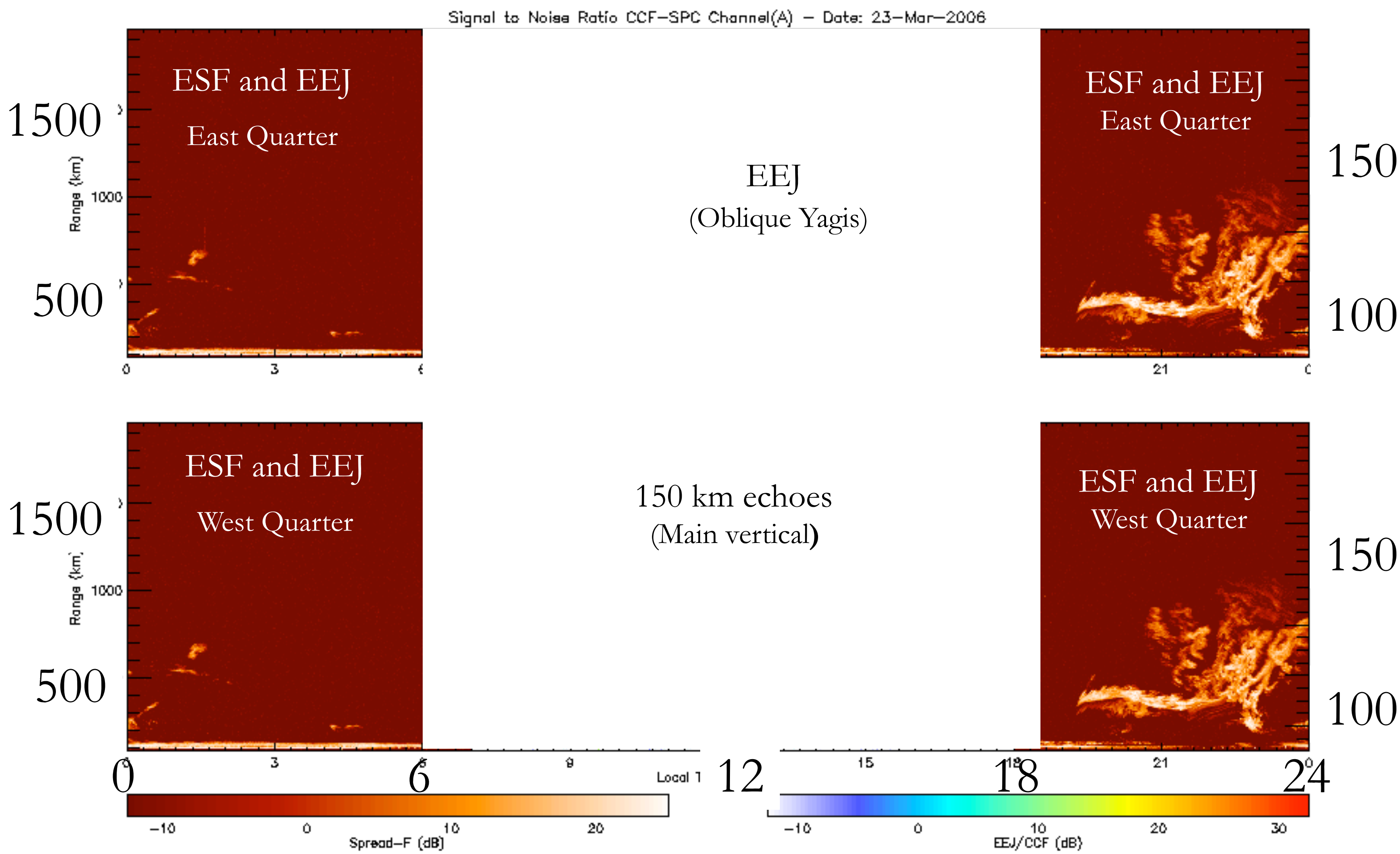
Plasma irregularities: What do we know from traditional radar studies?

Radio Observatorio de JICAMARCA Radio Observatory

- Coherent echoes are typically 2-6 orders of magnitude stronger than ISR echoes.
- Range-time distributions (Intensity=RTI, Velocities)
  - Day-to-day and seasonal variability
  - Time periodicities (Gravity waves, tides)
- Spectral characteristics
  - Spectral shape (Gaussian, Lorentzian, more than one Gaussian)
  - Mean Doppler and Spectral width
- Multi-beam observations
  - Spatial Characteristics
  - 3D velocity vector
- Interferometry
  - Zonal velocity
  - Aspect Sensitivity (scale lengths)
- Imaging
  - Resolve space-time ambiguities

Coherent echoes over Jicamarca (1)
RTIs above 100 km

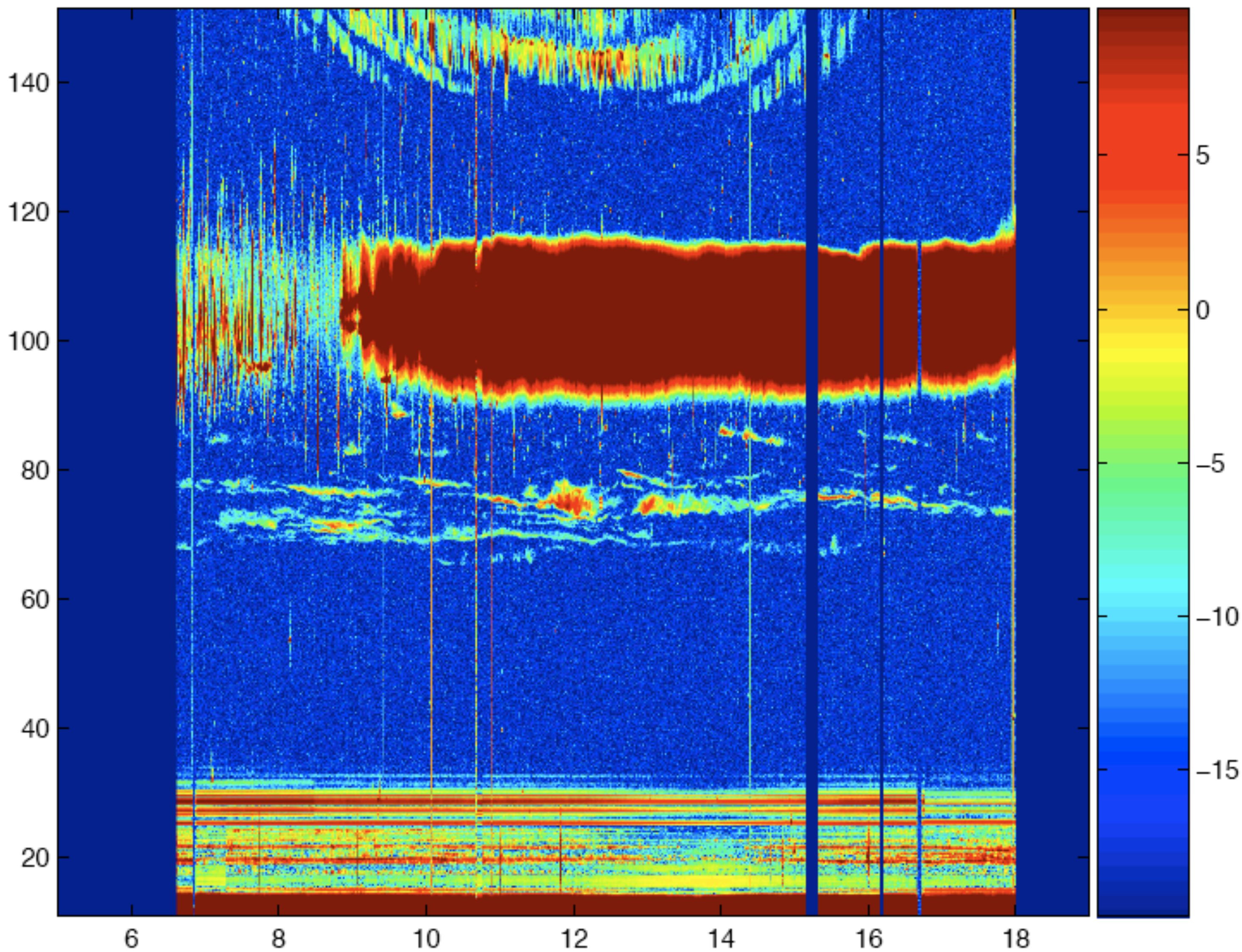
Radio Observatorio de JICAMARCA Radio Observatory



ESF: Equatorial Spread F (nighttime) **150-km echoes**: Daytime

EEJ: Equatorial Electrojet (all day)

Coherent echoes over Jicamarca (2)
RTI below 200 km



150-km echoes
Daytime

EEJ echoes
All Day
(Daytime stronger)

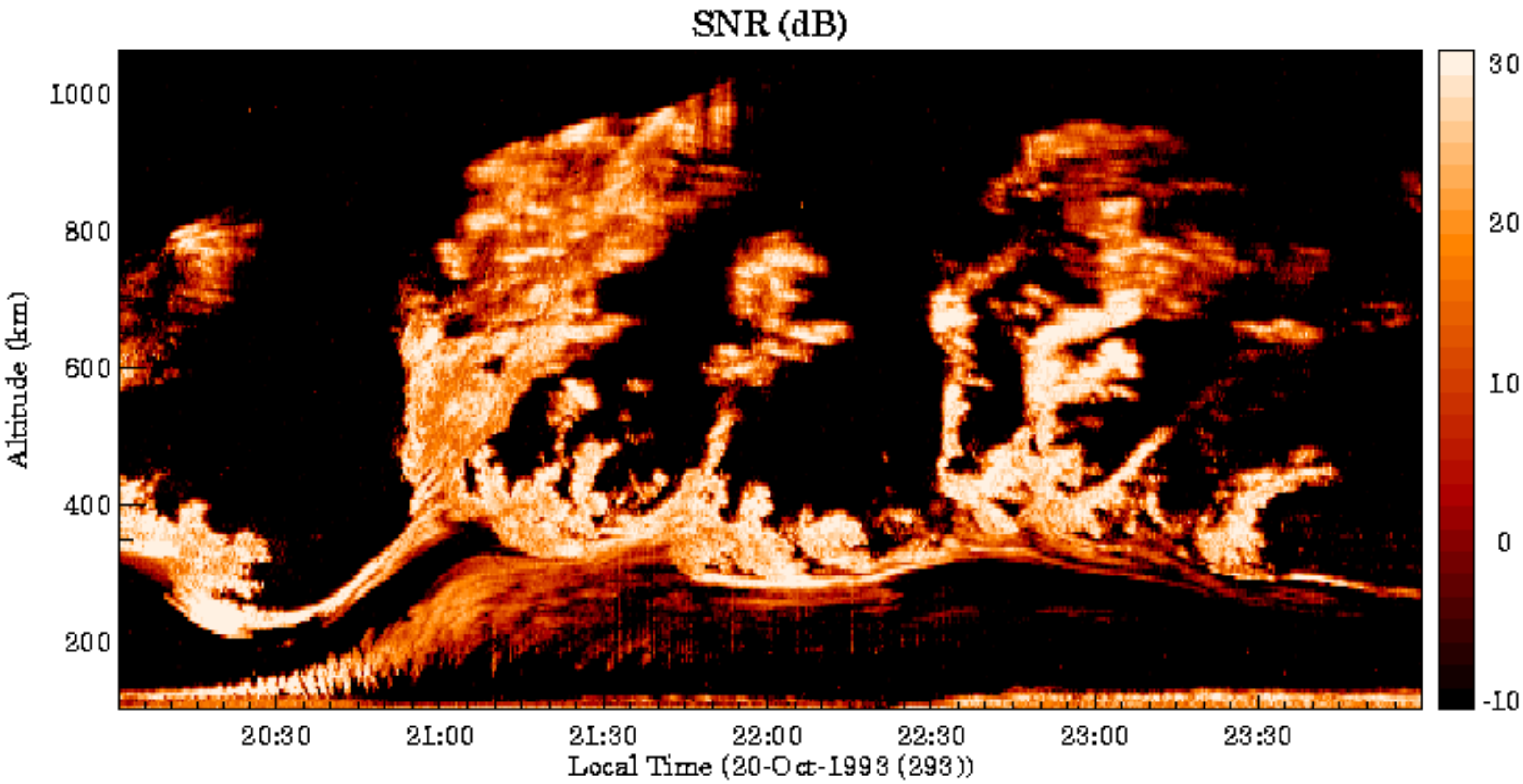
Meteor echoes
All Day
(head, non-specular and specular trails)

Mesospheric echoes
Daytime

Stratospheric and Tropospheric echoes
All Day

ESF: RTI maps

Radio Observatorio de JICAMARCA Radio Observatory



ESF: Instability at work

Radio Observatorio de
JICAMARCA
Radio Observatory

5464 WOODMAN AND LA HOZ: RAD

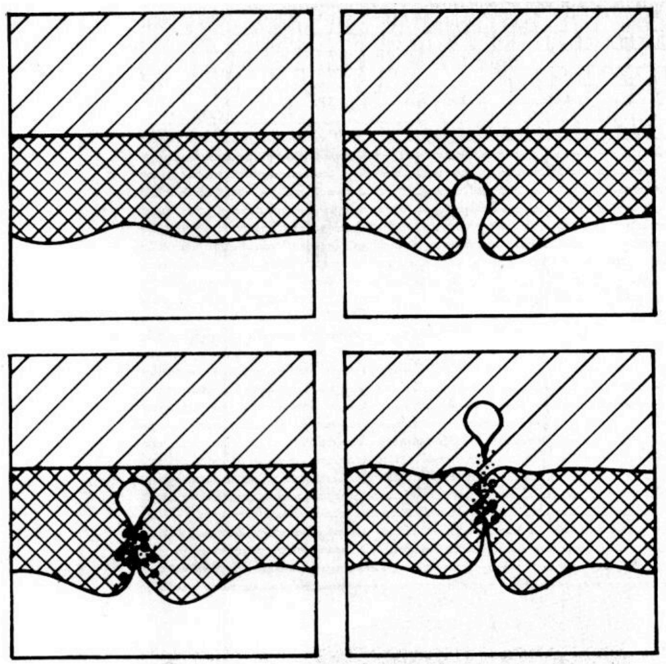


Fig. 9. Schematic representation of a three-density model of the ionosphere showing the formation of a bubble of low electron density and its propagation to the gravitationally stable top. The middle fluid is heavier than the top, and the top fluid heavier than the bottom.

$$\gamma_W = (U \sin\alpha)/L \qquad (4)$$

winds, an example of which is shown in Fig. 4, has

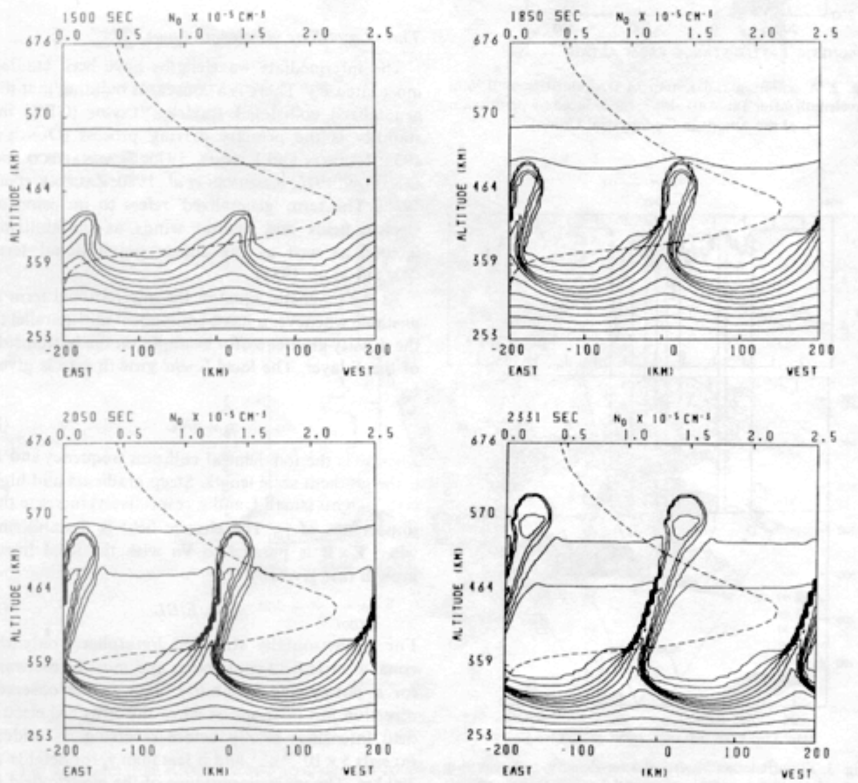


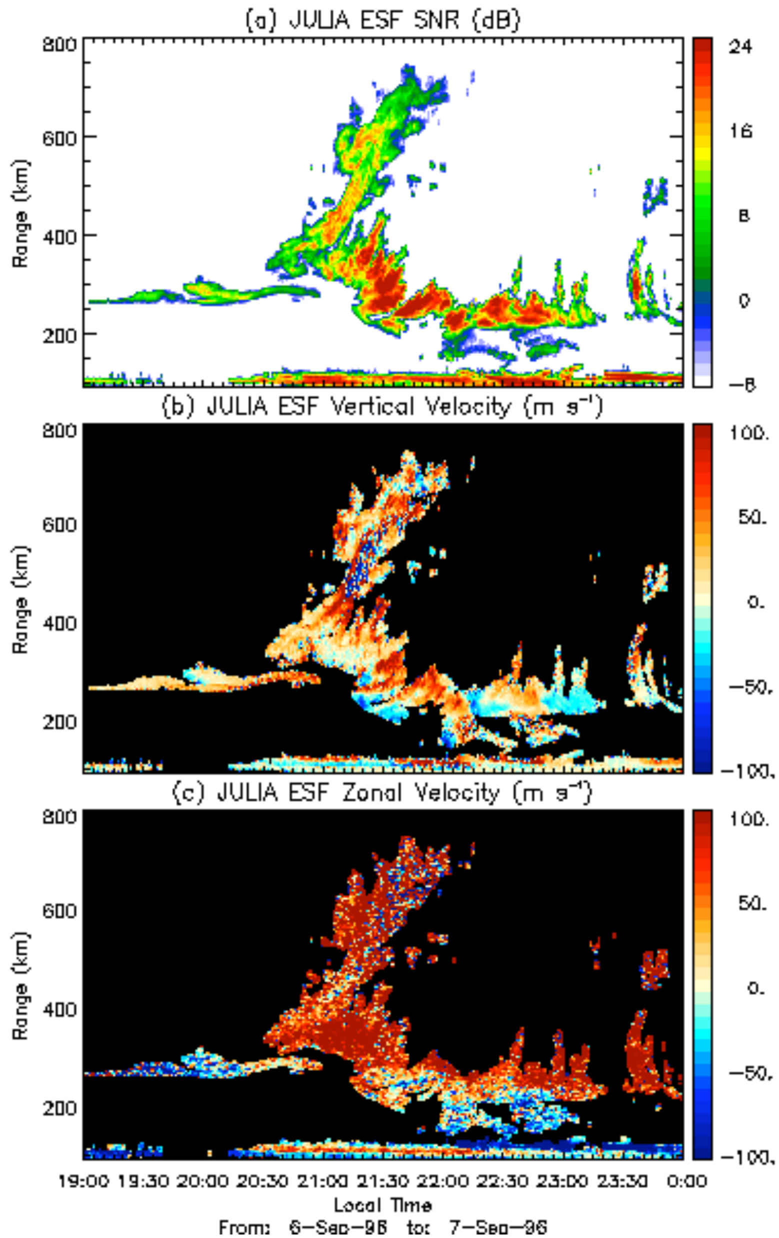
Fig. 4. Results of a numerical simulation of equator spread-*F*, including background winds and finite *E*-region conductivity (after ZALESAK *et al.*, 1982; reproduced by permission of the American Geophysical Union).

[from *Woodman and La Hoz, 1976*]

[from *Zalensak et al.*, 1982]

ESF: Type of echoes

Radio Observatorio de JICAMARCA Radio Observatory

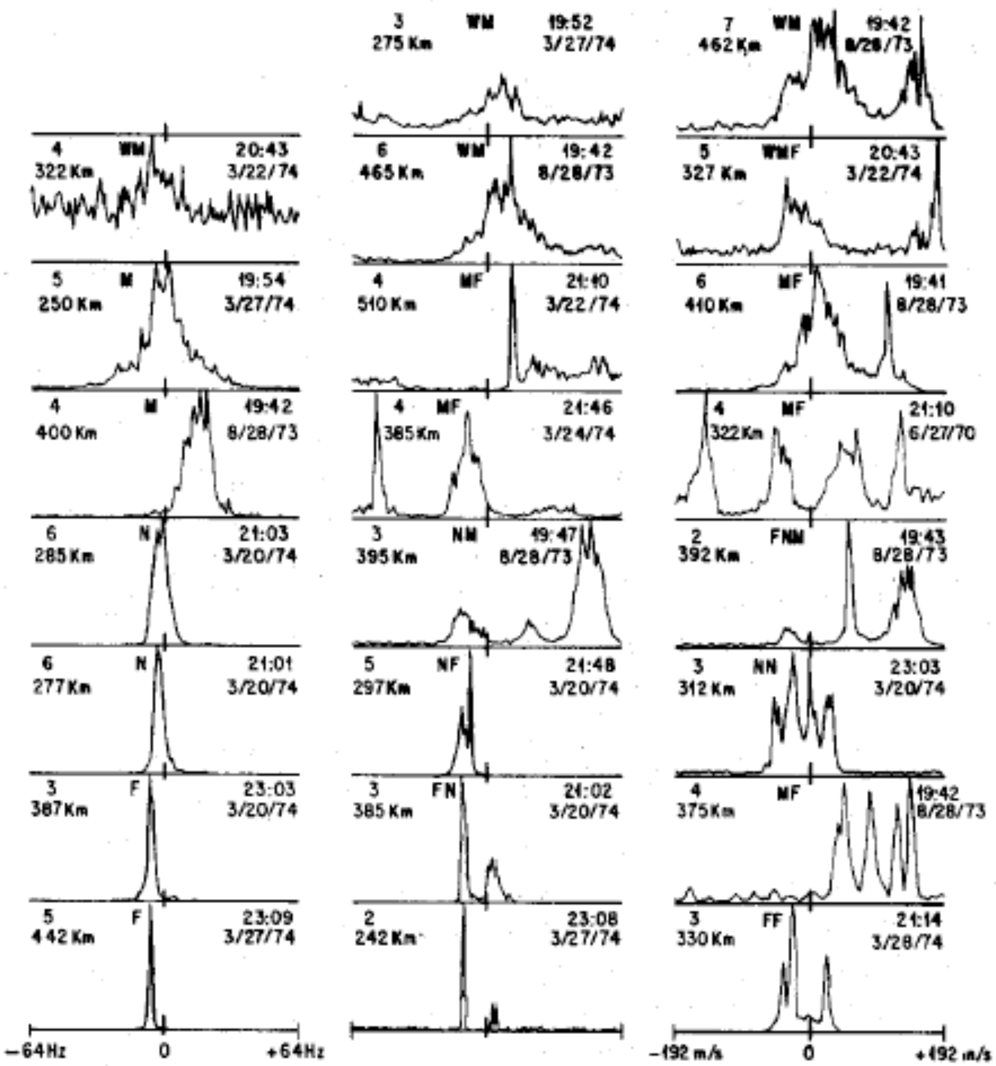


- Nighttime
- Main type (interchange or generalized Rayleigh-Taylor instabilities)
  - Bottomtype layers
    - Composed of kilometer scale waves
    - Drift westward
  - Bottomside
    - Drift eastward
    - Greater vertical displacement
  - Topside (Plumes)
    - Drift eastward and upward
    - A variety of spectra shapes
  - Valley-type

[from *Hysell and Burcham,* 1998 and *Hysell* 2000]

ESF spectra: Do we understand all of them?

Radio Observatorio de JICAMARCA Radio Observatory



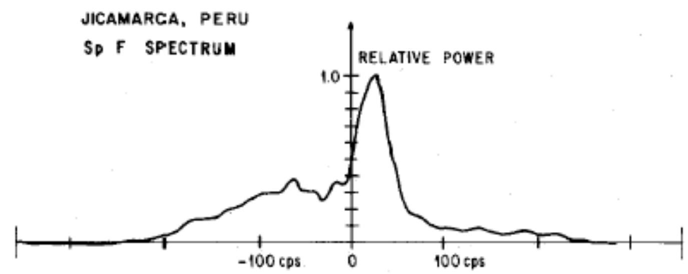


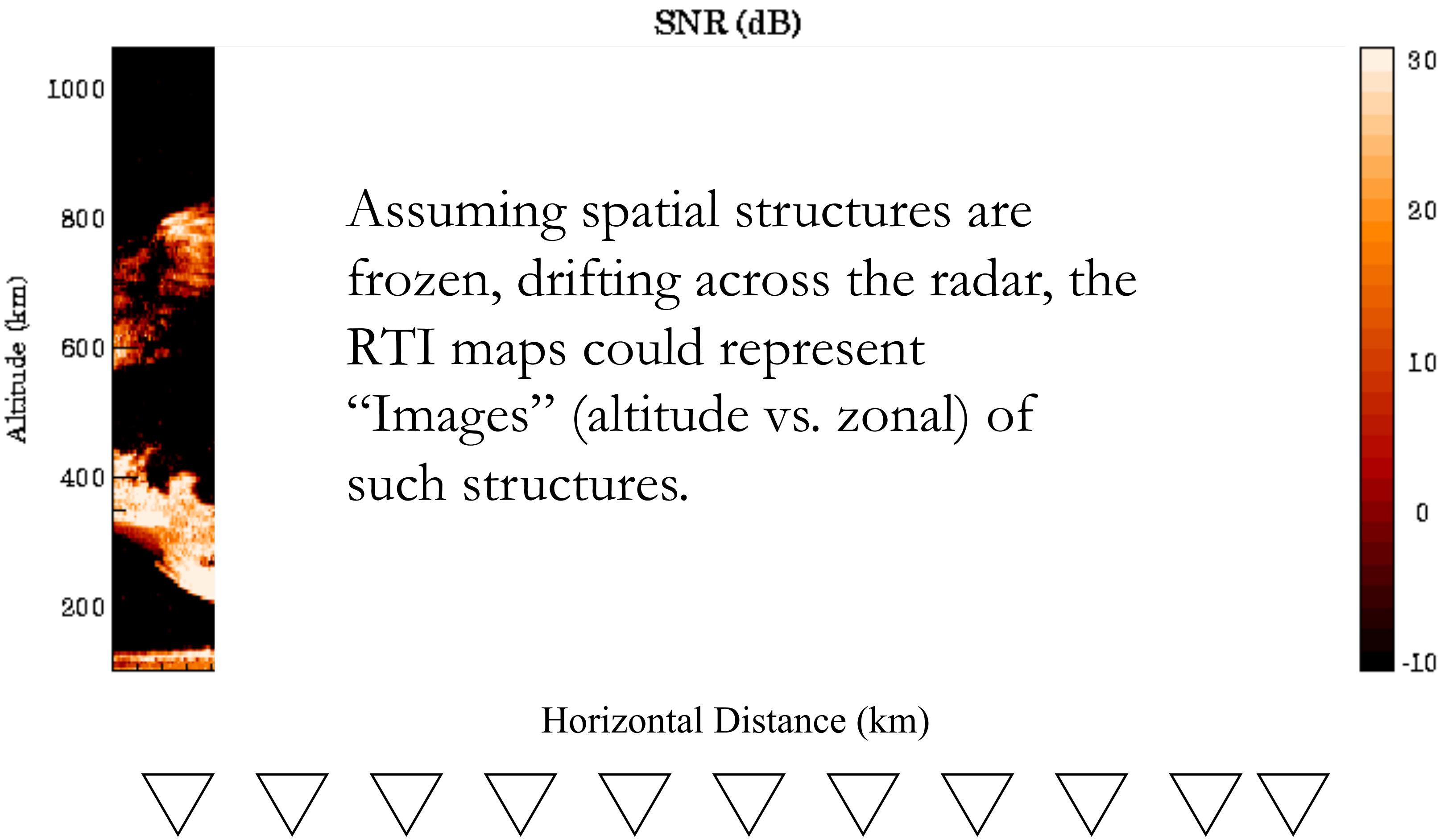
Fig. 5. Sampling record showing the WM type spectrum without frequency aliasing.

- Bottomtype: Very narrow single-peak spectra.
- Bottomside and Topside: Narrow, wide, multi-peak spectra.

[from *Woodman and La Hoz*, 1976]

RTI maps as "images": Slit camera interpretation

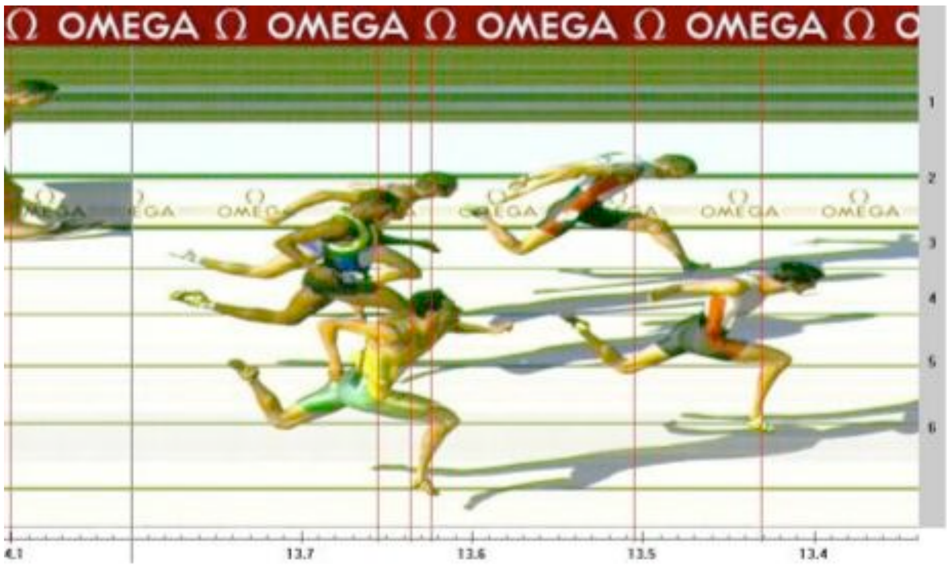
Radio Observatorio de JICAMARCA Radio Observatory



Assuming spatial structures are frozen, drifting across the radar, the RTI maps could represent "Images" (altitude vs. zonal) of such structures.

Slit-camera analogy and problems

Radio Observatorio de JICAMARCA Radio Observatory

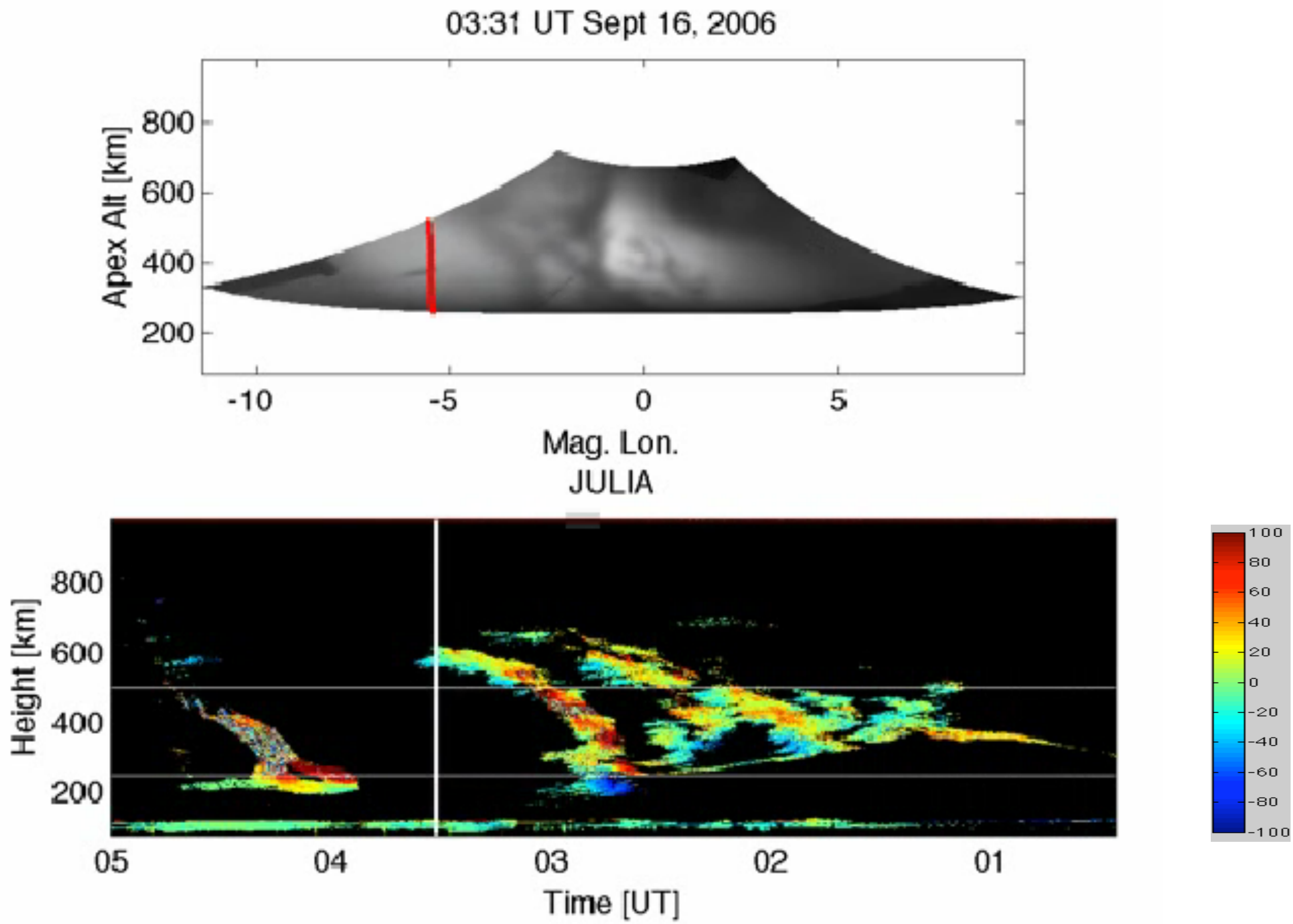


- In some applications like races it is useful
- In many other applications it provides misleading results:
  - Slow structures are stretch out
  - Fast-moving structures are compressed.
- In general, it is difficult to discriminate space-time features.

used with permission ©Tom Dahlin

Radar "Slit" Camera vs. Optical "Airglow" Camera

Radio Observatorio de JICAMARCA Radio Observatory



[*Courtesy of J. Makela*]

JRO as Video RF Camera

Radio Observatorio de
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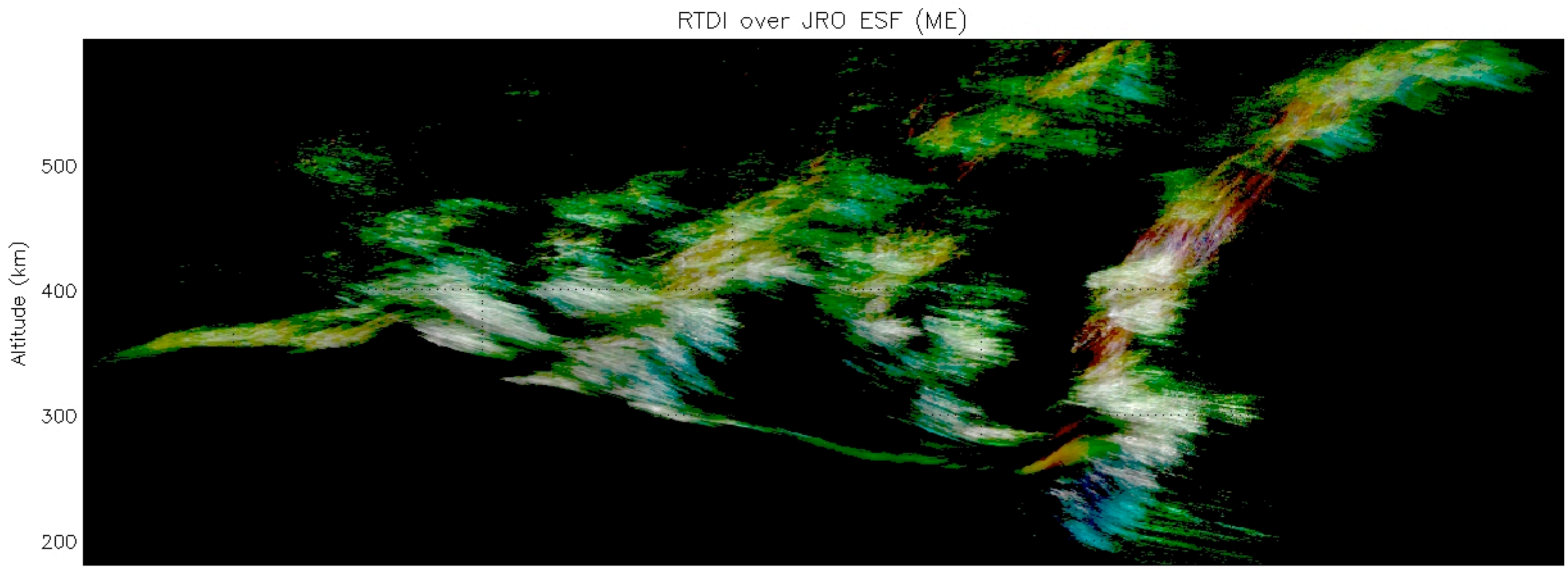
Radio Observatory

ESF RTDI: Slit camera interpretation

Radio Observatorio de JICAMARCA Radio Observatory



East (km) West

- Typical RTI maps are shown with "false" colors (colors from a pre-defined color table are associated to the signal intensity).
- Here we use Doppler for color. True 24-bit color range time intensity (RTI) plot using Doppler information (RTDI). RTI map is obtained for three Doppler regions centered around: -ve (Red), zero (Green), and +ve (Blue) Doppler velocities.
- It allows, for example, identification of regions and times where there is a depletion channel pinching off, Doppler aliasing, Doppler widening, etc.

ESF RTDI + Imaging (1)

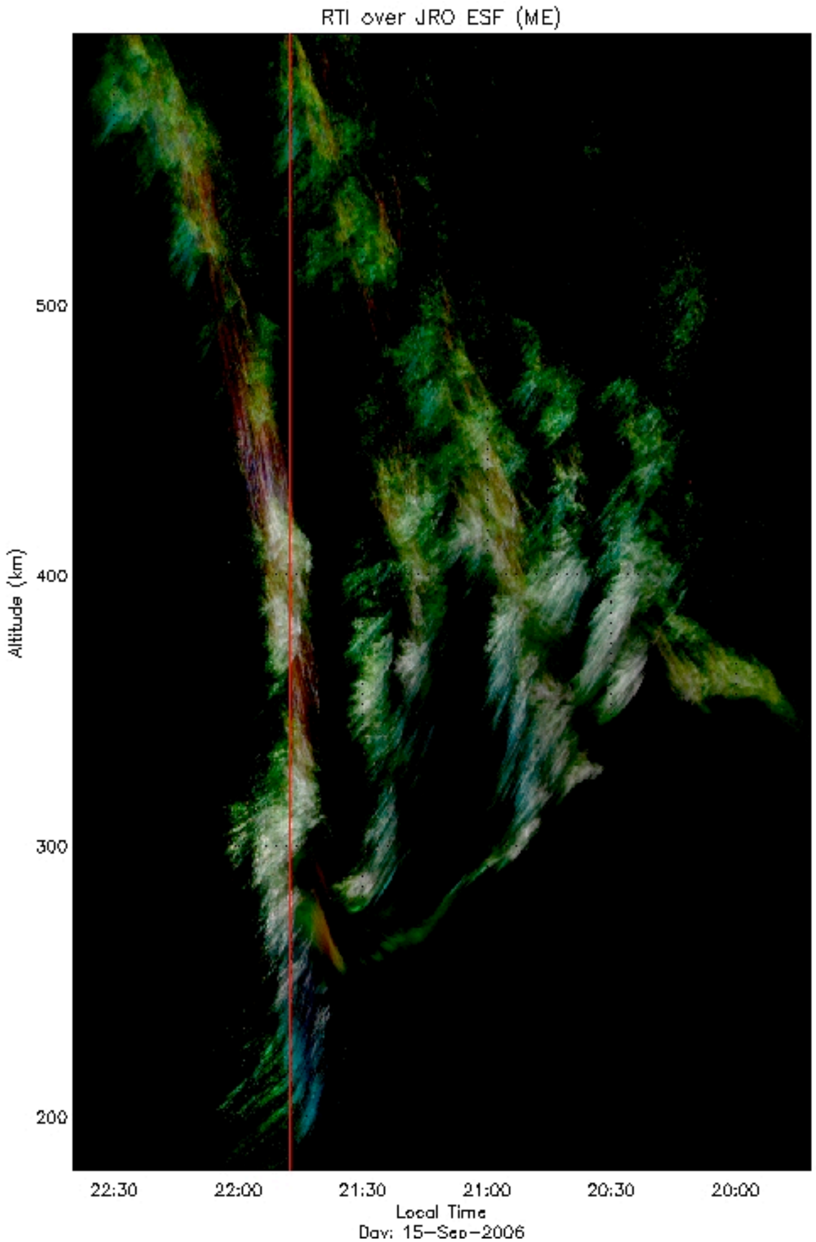
Radio Observatorio de JICAMARCA Radio Observatory

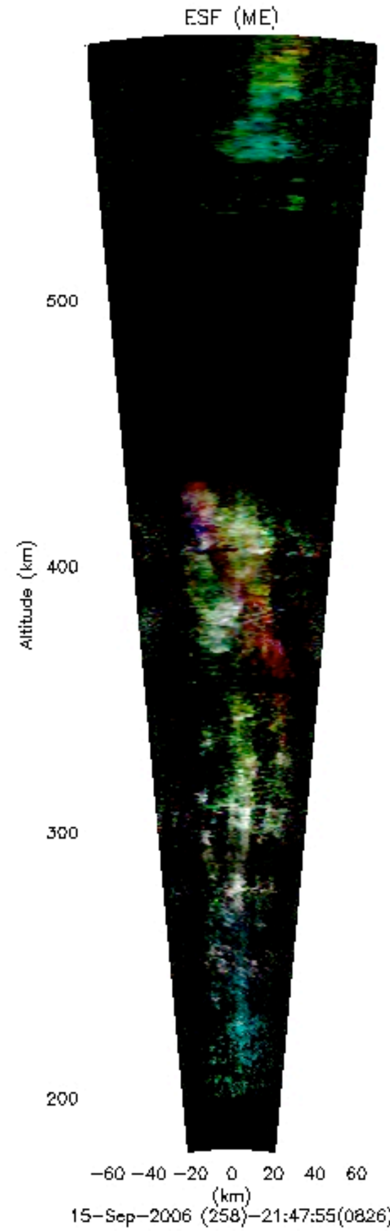
500

400

300

200





- Space and time ambiguities are avoided.
- New structures are identified and characterized, e.g.,
  - Bifurcations
  - Pinch-off of bottom irregularities
  - Vortices in the narrow bottomtype layers

ESF Imaging experiment with IPP=600: Frequency aliased spectra

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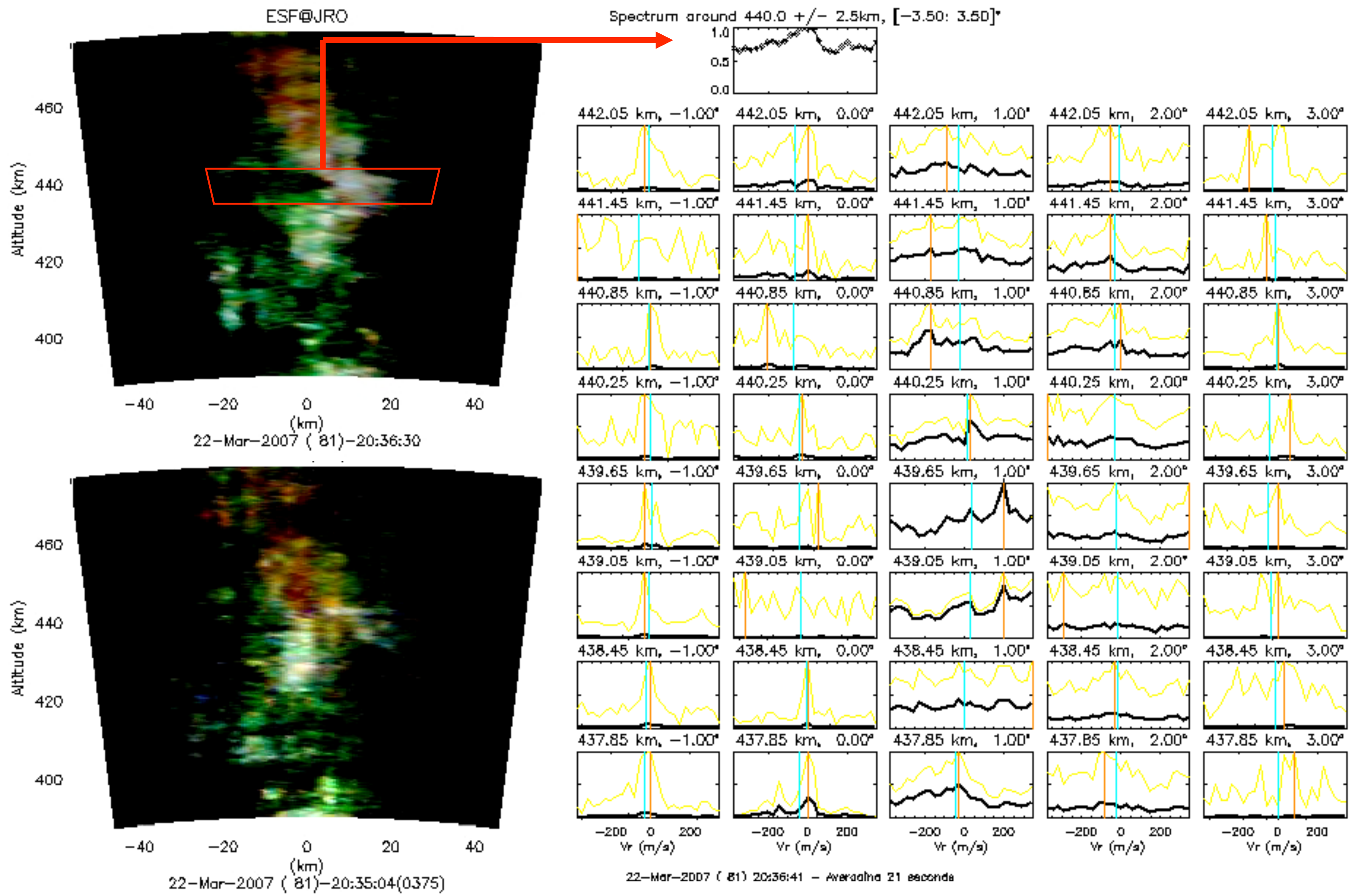

ESF Imaging experiment with IPP=300: Range aliased, but without frequency aliasing

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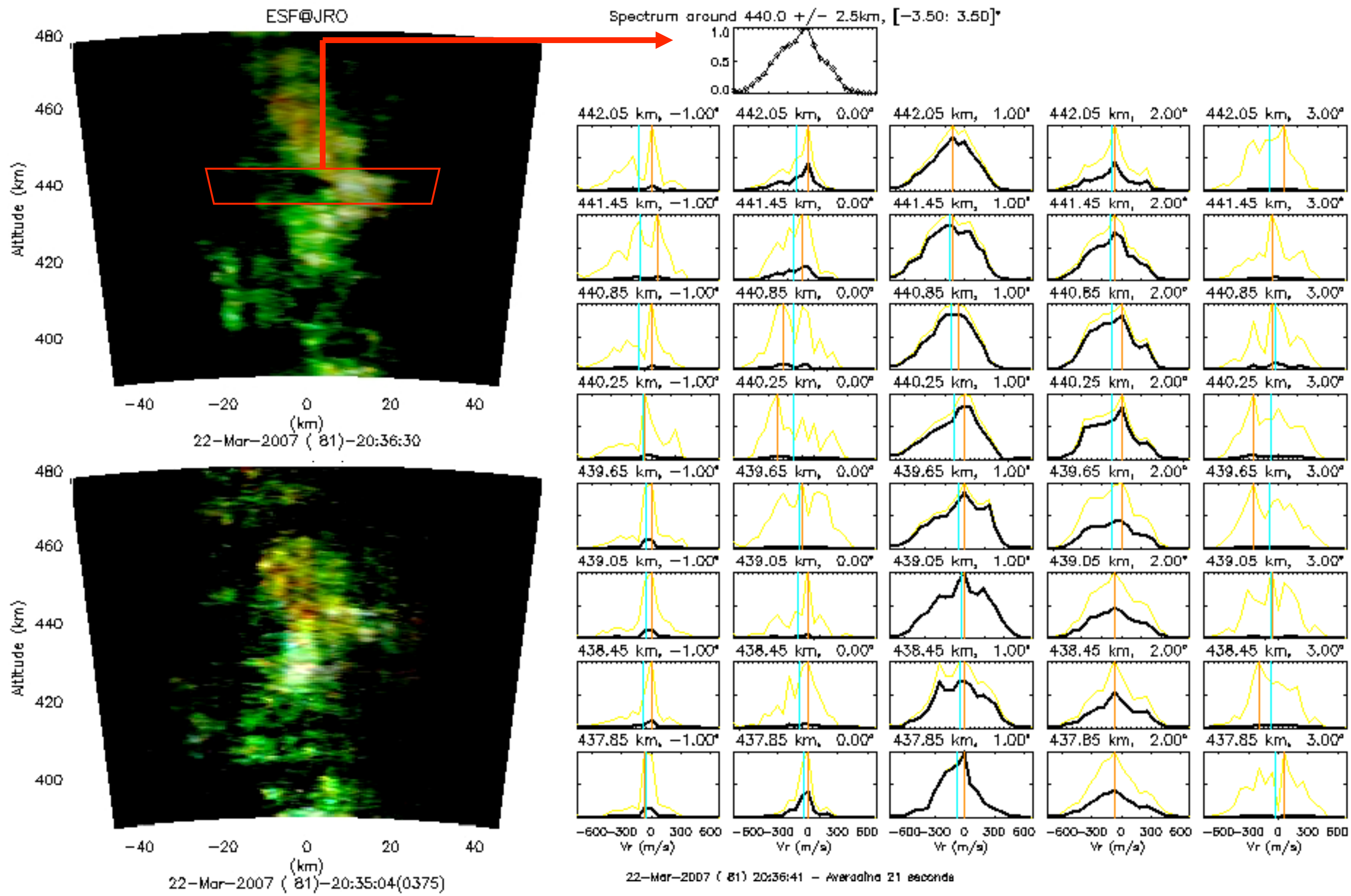
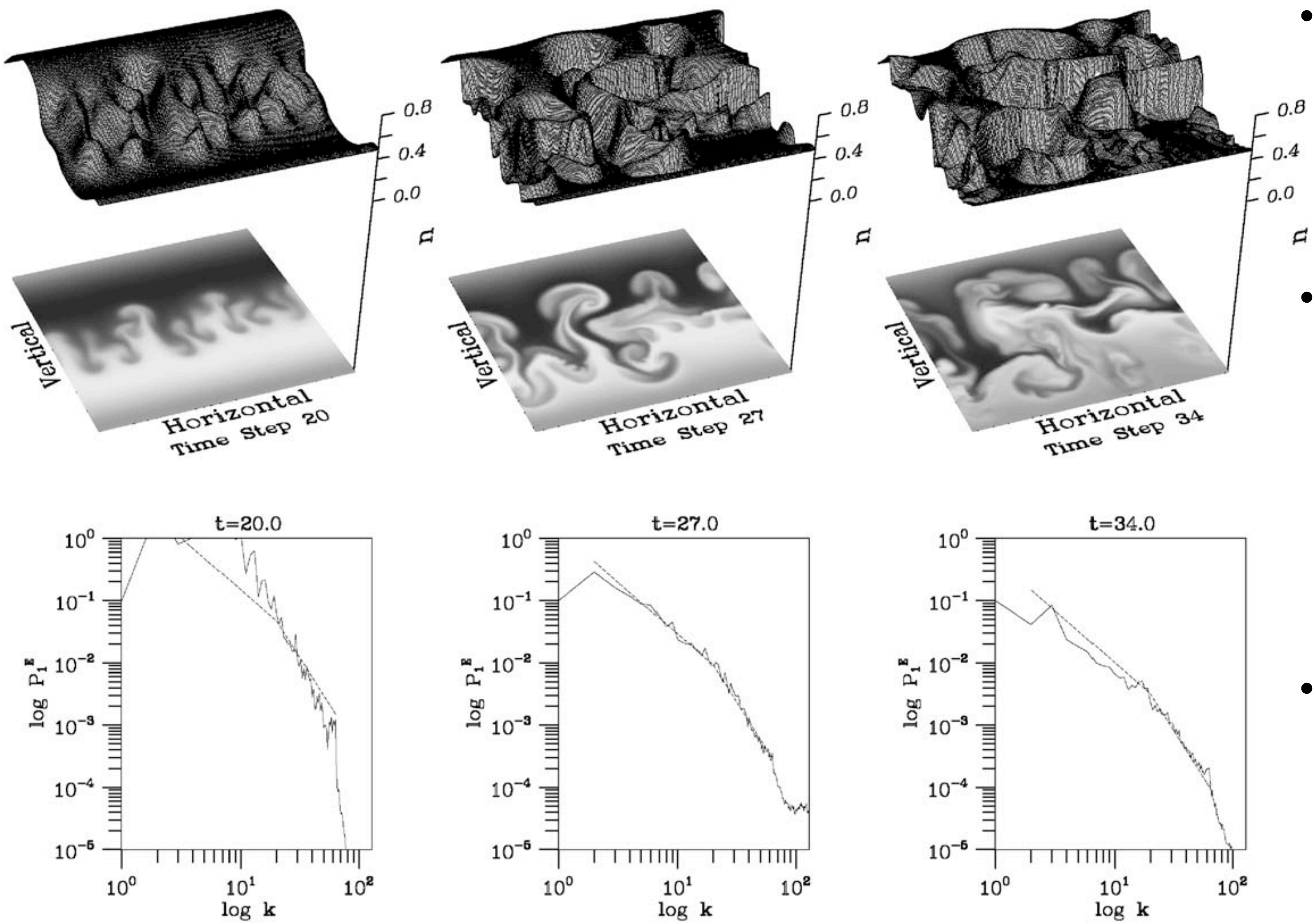


ESF Imaging + Wide spectra: Irregularity spectrum

Radio Observatorio de JICAMARCA Radio Observatory



- In *Hysell and Chau* [2004] we postulated that the wide spectra in the topside is produced by strong turbulence.
- The Doppler spectrum is predicted to be essentially Gaussian with a width equal to the RMS velocity of the plasma in the illuminated volume.
- We might be able to measure the irregularity spectrum by measuring the radar Doppler spectrum with different averaging volumes.

Jicamarca Themes (Unstable Ionosphere)

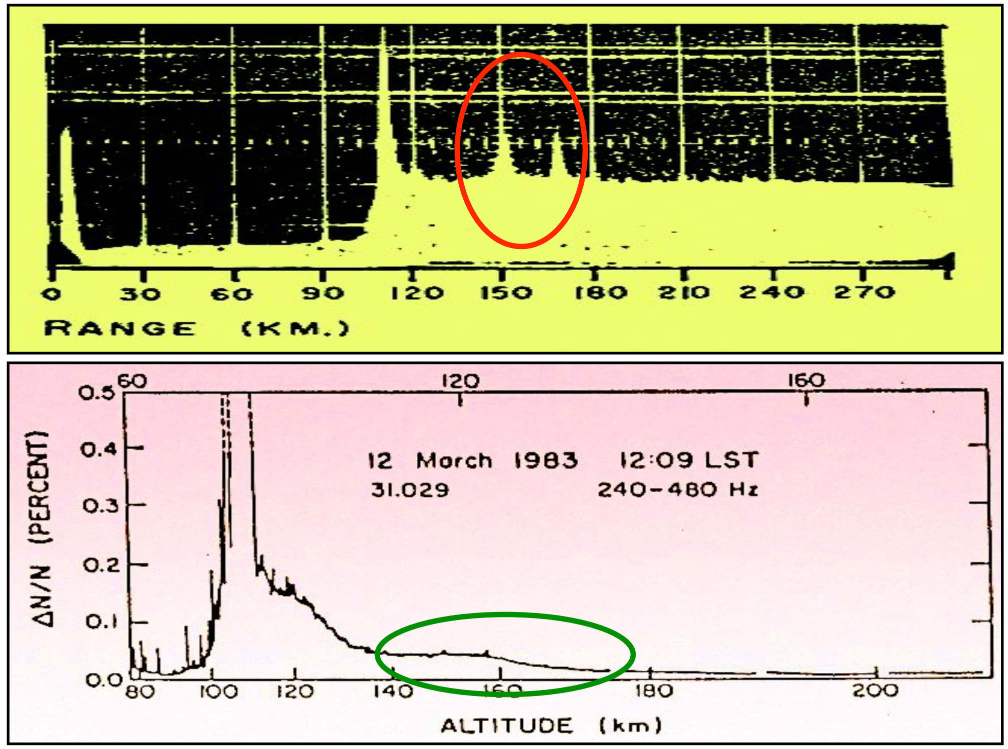
Radio Observatorio de JICAMARCA Radio Observatory

- **Understanding equatorial instabilities**
  - ***F* region**: What are the fundamental plasma processes, including nonlinear processes, that govern the generation of plasma plumes? What are the precursor phenomena in the late afternoon *F* region that control whether or not an *F*-region plume will be generated after sunset?
  - Daytime Valley echoes (or so-called **150-km echoes**). What are the physical mechanisms causing them? (still a puzzle after more than 40 years!).
  - ***E* region**: What are the nonlinear plasma physics processes that control the final state of the electrojet instabilities? To what extent do these instabilities affect the conductivity of the *E* region, and by extension, the conductivity of the auroral zone *E* region, where similar, but stronger and more complicated, instabilities exist?

150-km echoes: First detection

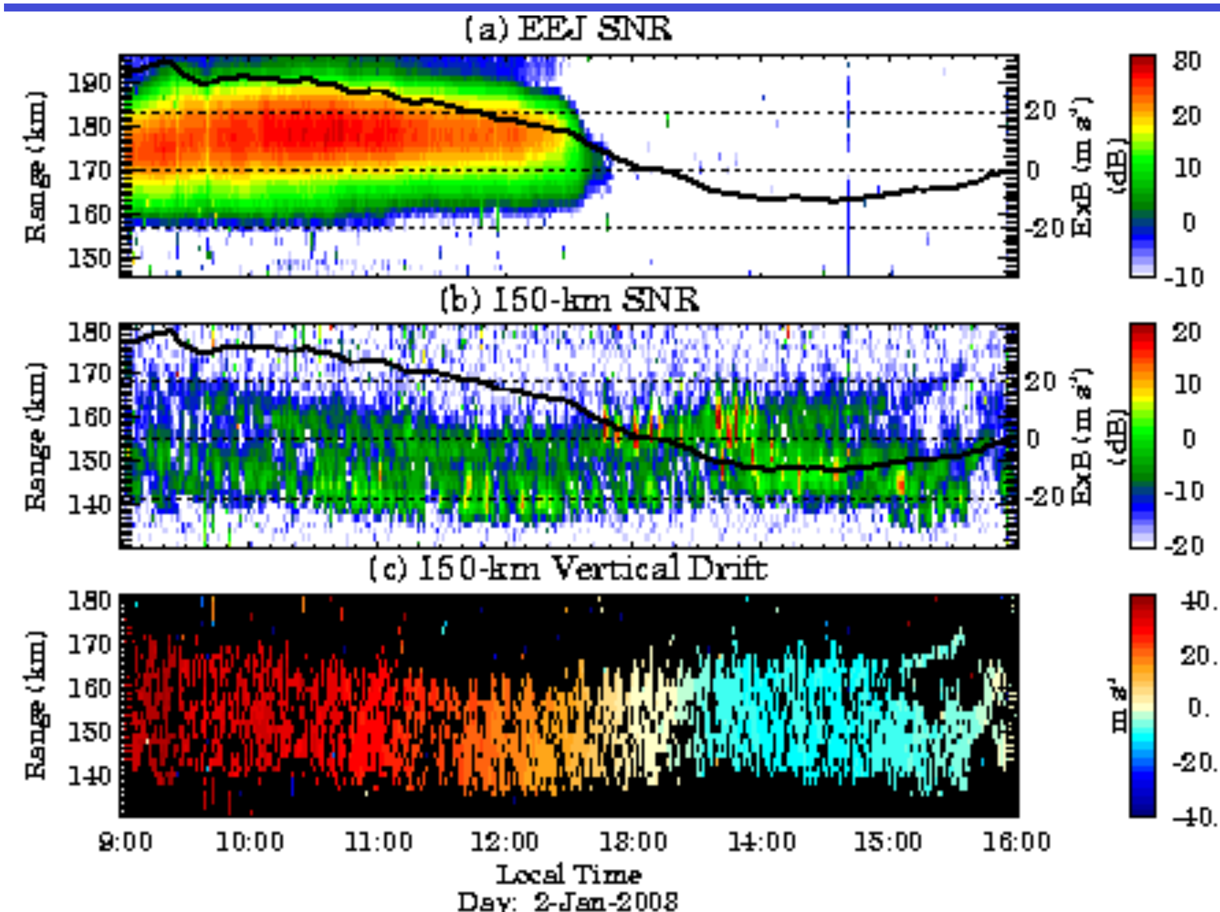
Radio Observatorio de JICAMARCA Radio Observatory

- Jicamarca Observations
  - Balsley [1964]
- Rocket Observations
  - Thumba, India [*Prakash et al.*, 1969]
  - Punta Lobos, Peru [*Smith and Royrvik*, 1985]



150-km echoes Perpendicular to B

Radio Observatorio de JICAMARCA Radio Observatory



<u>Main features</u>

•Daytime phenomena

•Occur between 130-180 km

•Necklace shape

•Come from field-aligned irregularities (?)

•Observed at different longitudes and within few degrees away Mag. Equator (?)

•Vz ~ vertical F-region ExB.

<u>Proposed Mechanisms</u>

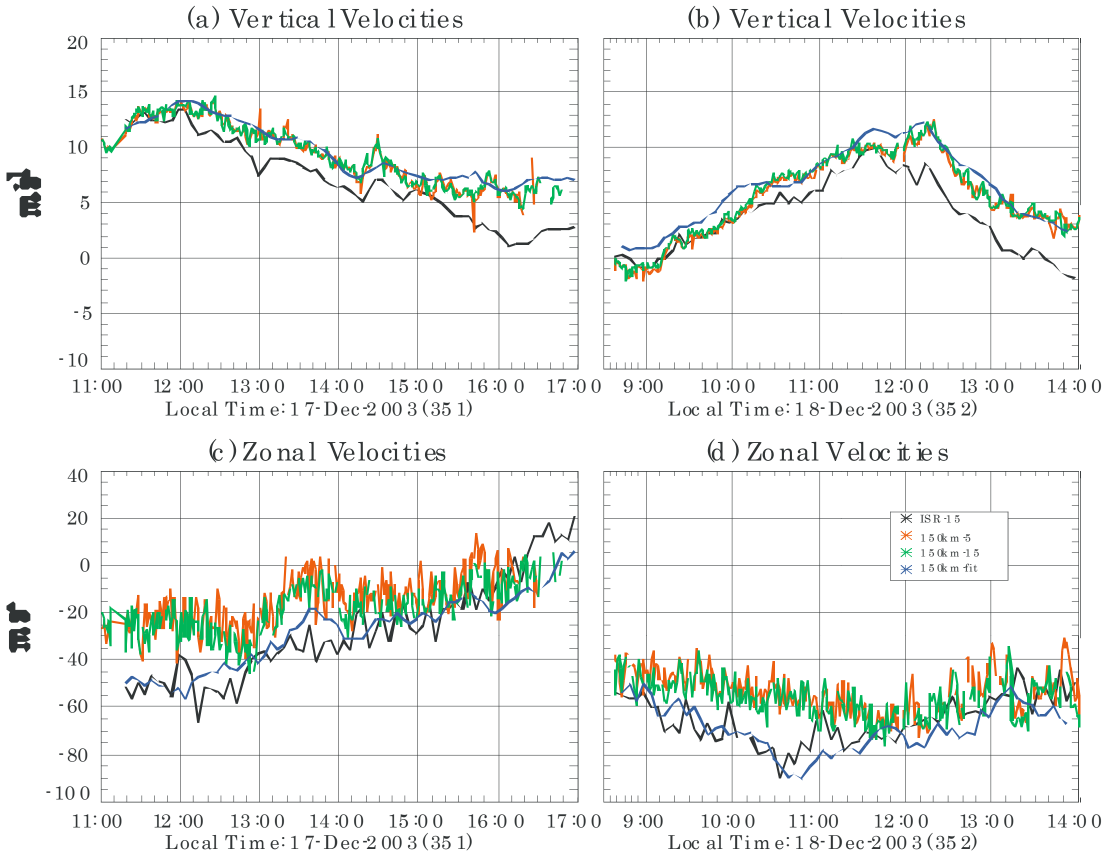
•Gravity wave wind driven interchange instability [*Kudeki and Fawcett*, 1993]

•Low-latitude Es layer instability providing free energy for the growth of interchange instability at equatorial 150-km [*Tsunoda and Ecklund*, 2004]

[from *Kudeki and Fawcett*., 1993 and *Fawcett*, 1999]

ISR Drifts vs 150-km drifts

Radio Observatorio de JICAMARCA Radio Observatory



$$V_x \approx -(\Sigma_H/\Sigma_P)V_z + \int (\sigma_P * U_n \mathrm{d}s)/\Sigma_P$$

Compared to 150km-5, the agreement:

<u>For Vertical results</u>

- Is very good with mean F-region ISR drift
- Is <u>excellent</u> with extrapolated ISR drifts (less differences and higher correlation)

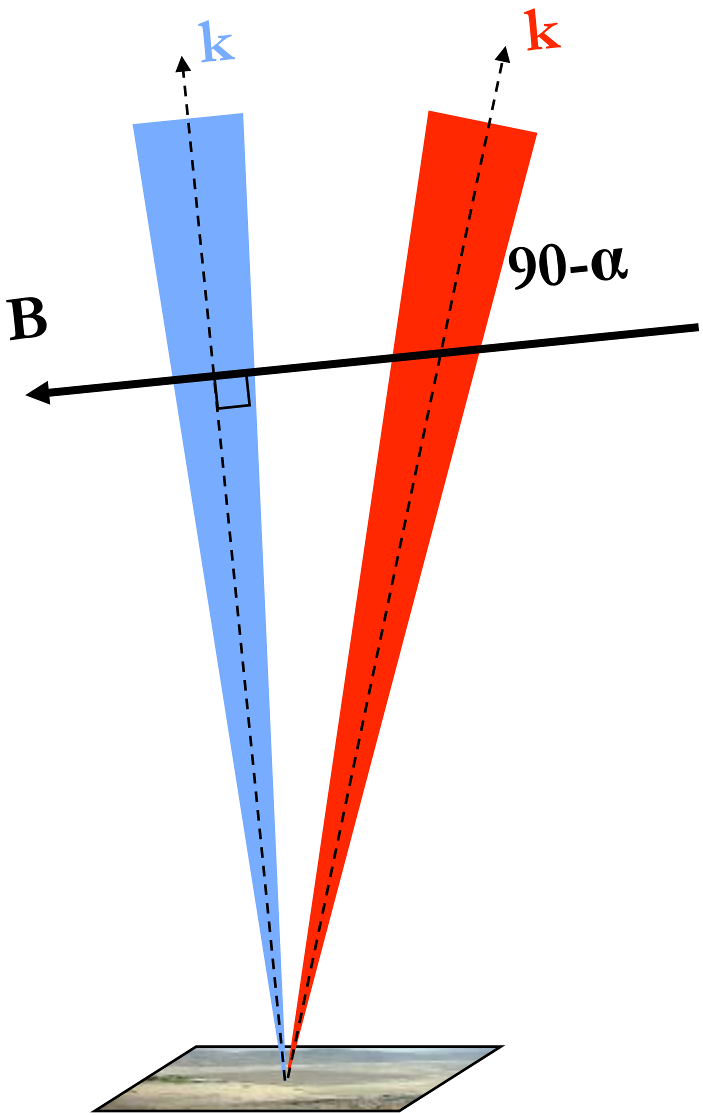
<u>Zonal results</u>

- Is good with ISR-15 and 150km-fit.
- Gets worse before noontime, but follows day-to-day variability

[from *Chau and Woodman.*, 2004]

Oblique vs. Perpendicular ISR: Geometry

Radio Observatorio de JICAMARCA Radio Observatory



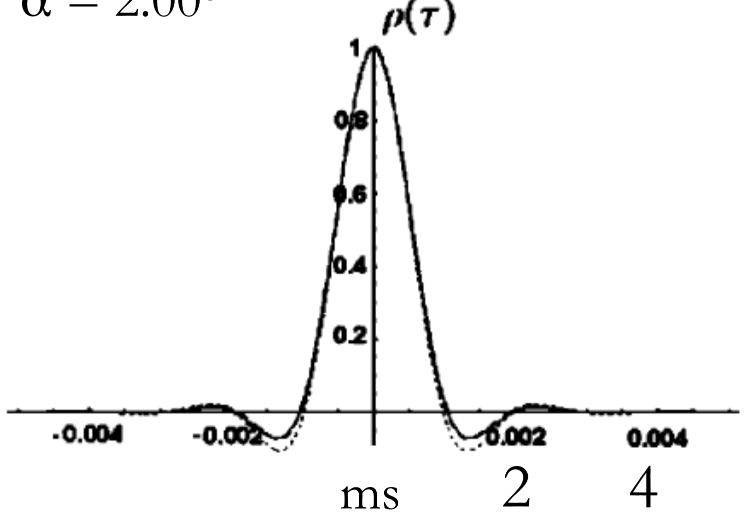
- Depending on α:
  - Oblique: α > 0
  - Perpendicular: α = 0
- What is the α boundary between modes?
- What are the antenna patterns used?
- What are the differences on ACFs and spectra between modes?
- How is the polarization of returned signals?
- How are the modes affected by coherent scatter echoes?
- What can be measured?

Oblique vs. Perpendicular: ACFs

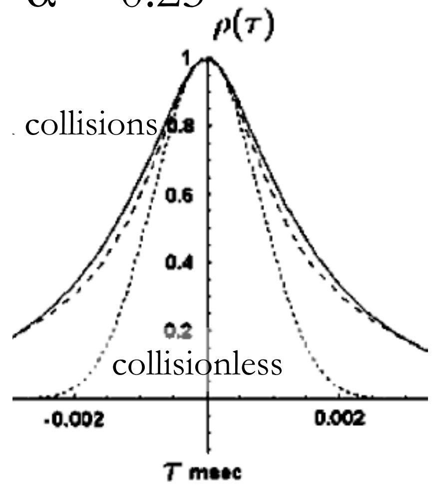
Radio Observatorio de JICAMARCA Radio Observatory

[from *Woodman*, 2004]

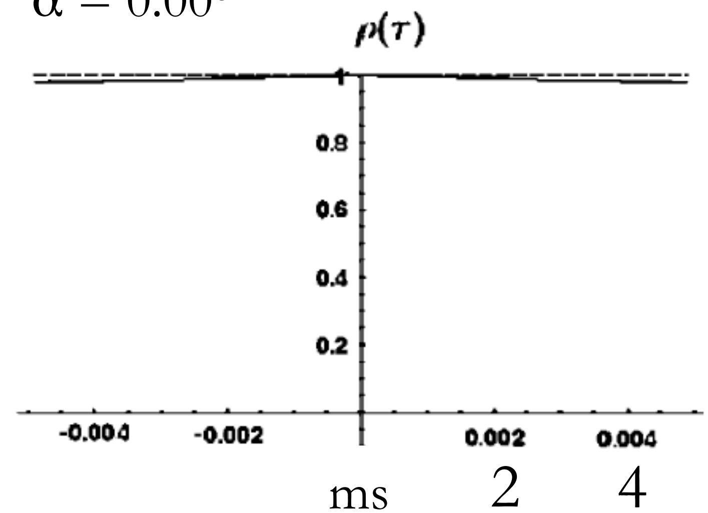
α = 2.00°



α = 0.25°



α = 0.00°



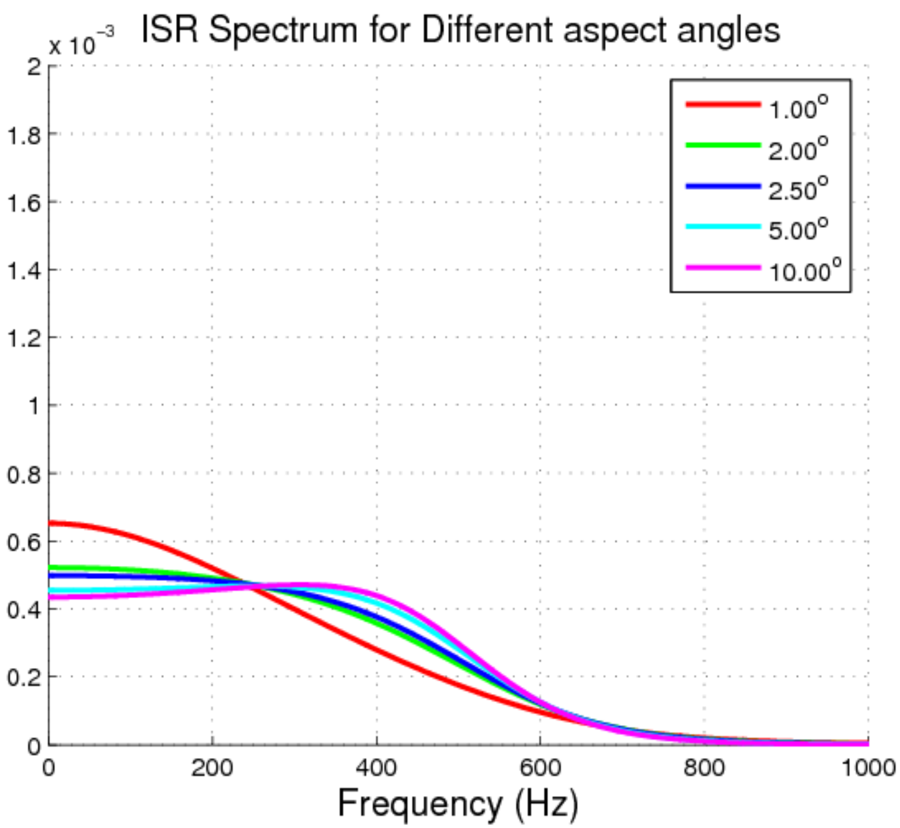
<u>Oblique</u>

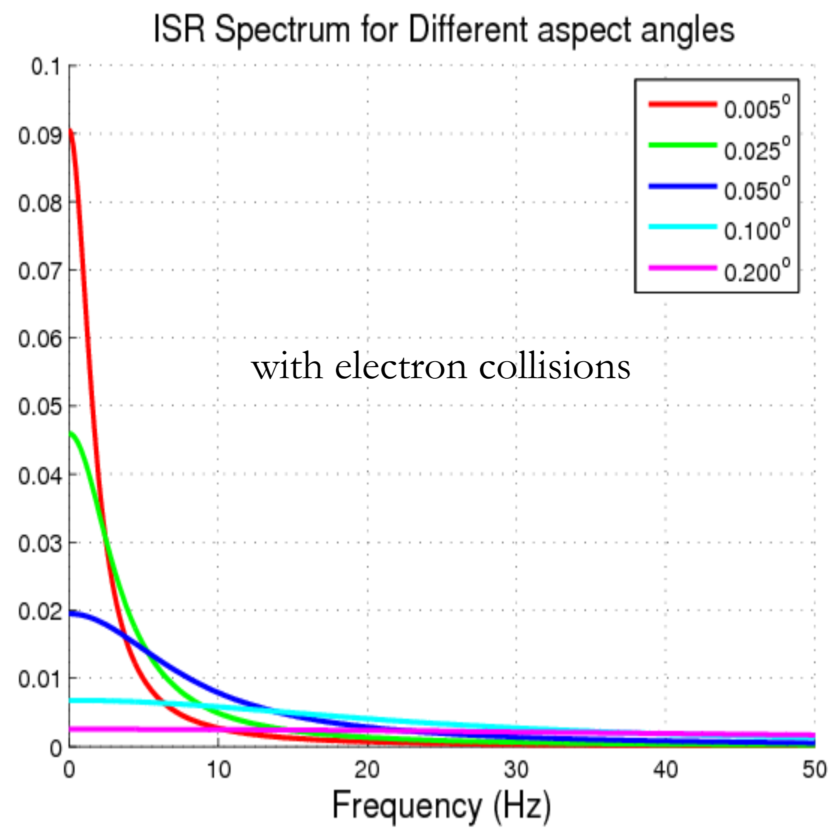
- ACFs are narrow
- 1 ms = 150 km (for monostatic measurements)
- ACFs are very similar to the non-collisional, unmagnetized case.
- ACFs are dominated by the dynamics of the ions
- Within the pulse (or IPP) estimation is needed to avoid range ambiguity
- Critical angle: $\alpha = 0.334^{o}$ (where ions and electrons behave as if they had equal "mass").

<u>Perpendicular</u>

- ACFs are very wide. Coulomb collisions and magnetic field effects need to be considered.
- ACFs dominated by the dynamics of the electrons (electrons behave "heavier" than ions).
- Very quickly gets wider (for small α values).
- Due to long correlation times, pulse-to-pulse estimation can be performed, and very accurate vertical and zonal drifts are estimated.

Oblique vs. Perpendicular: Spectra





Oblique

- Spectra are wide (>1000 m/s or 300 Hz at 50 MHz) and independent of α within typical antenna beam widths.

Perpendicular

- Spectra get narrower (less than 150 m/s) for smaller α and change very quickly.
- Measured spectra results from a convolution of spectra with different widths due to finite antenna beam width.

Off-perpendicular to B 150-km echoes

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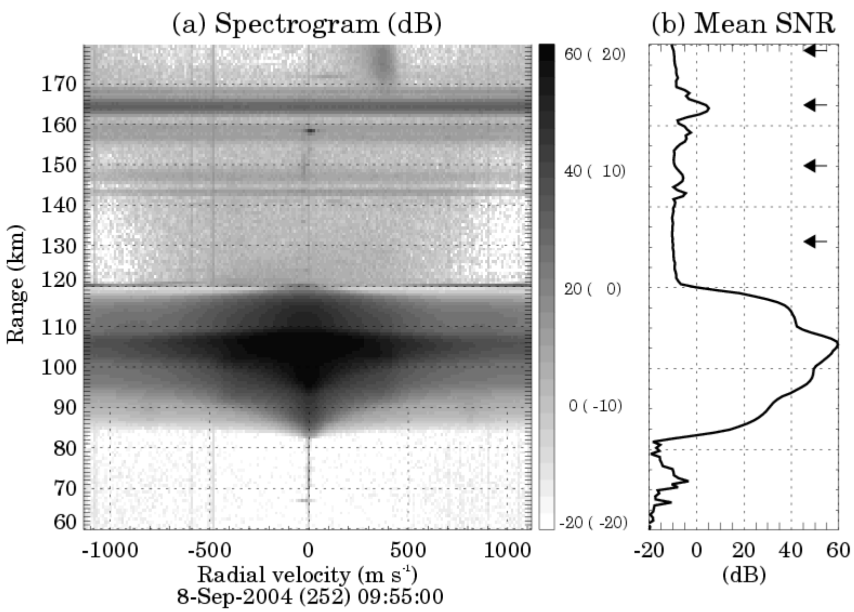

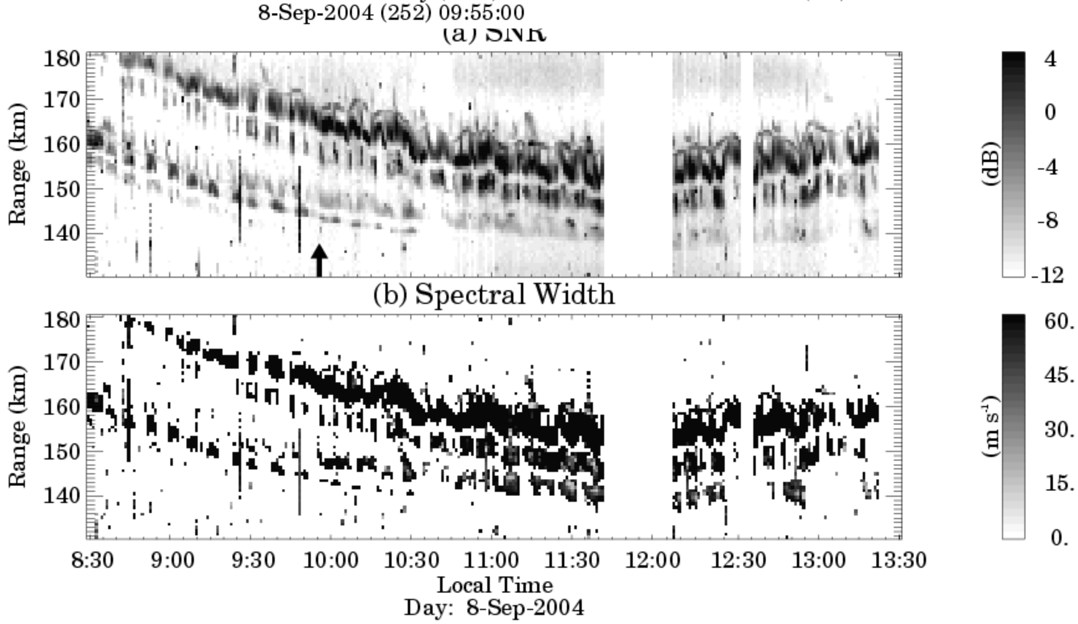

- Surprisingly, 150-km echoes are also observed at few degrees away from perpendicular to B (~1.8°) ("Oblique").
- Oblique echoes present similar altitude-time dependence to Perpendicular observations.
- Oblique 150-km echoes present unexpected wide spectra (spectra widths > 1000 m/s).
- Questions:
  - What is the actual spectrum shape?
  - What is the angular brightness of these irregularities?
  - Are these echoes due to density enhancements?

[from *Chau*, 2004]

Multi-beam Experiments: 1.83º vs. Perpendicular (1)

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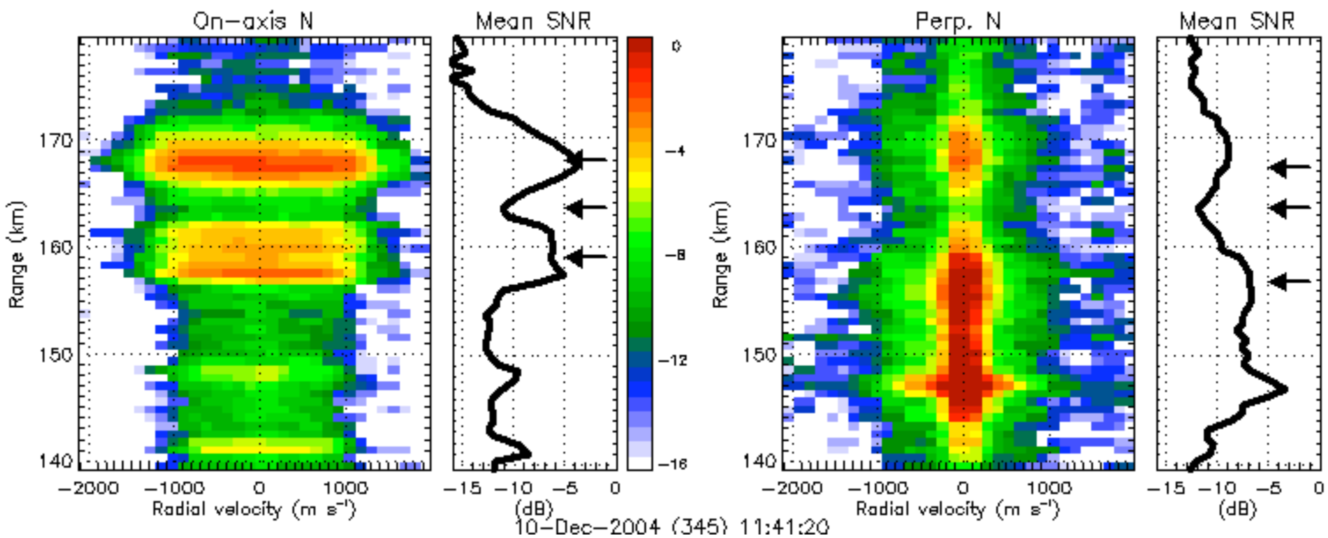
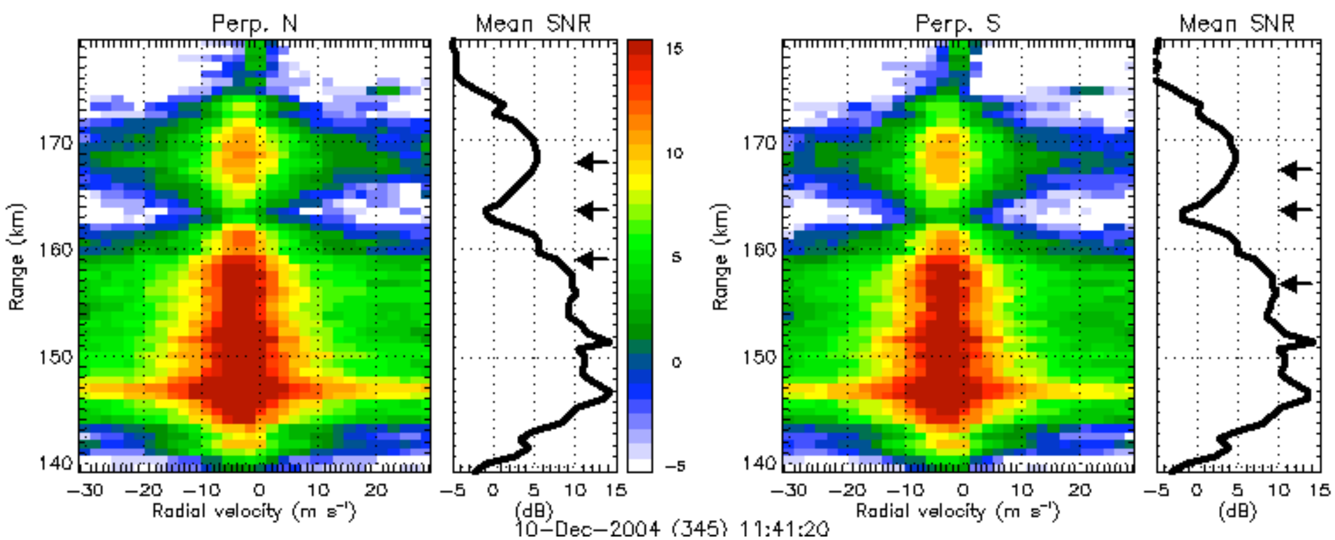


Spectrograms

- No coherent integrations
- Median filter =3, to remove interference, and Perpendicular contributions (in Perpendicular beam).



Spectrograms

- 32 coherent integrations
- Spectral components are similar to typical 150-km low power observations

Multi-beam Experiments: 1.83° vs. Perpendicular (2)

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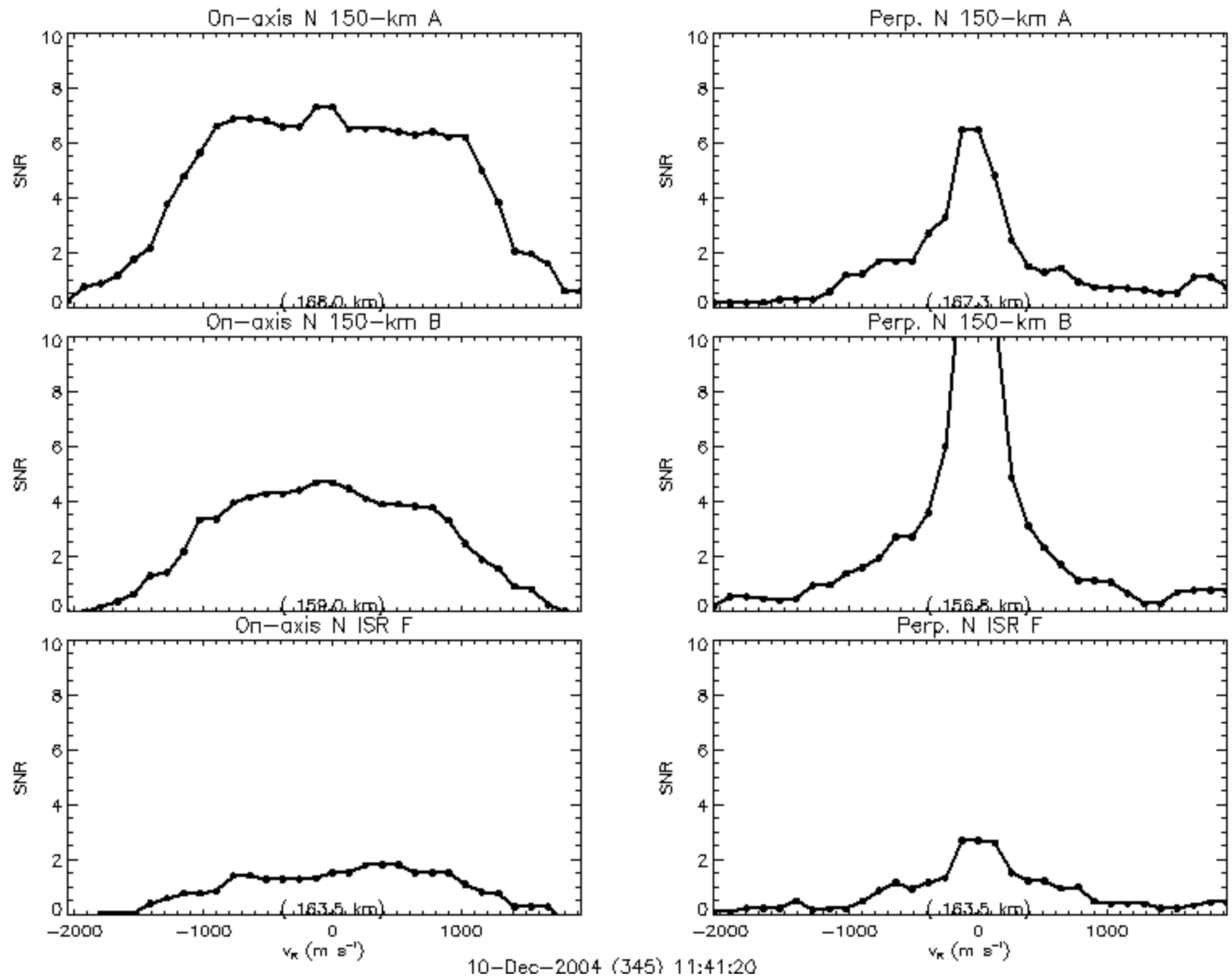

<u>Spectra cuts</u>

•No coherent integrations

•Median filter =3, to remove interference and Perpendicular contributions (in Perpendicular beam).

150-km ISR spectrum (1)

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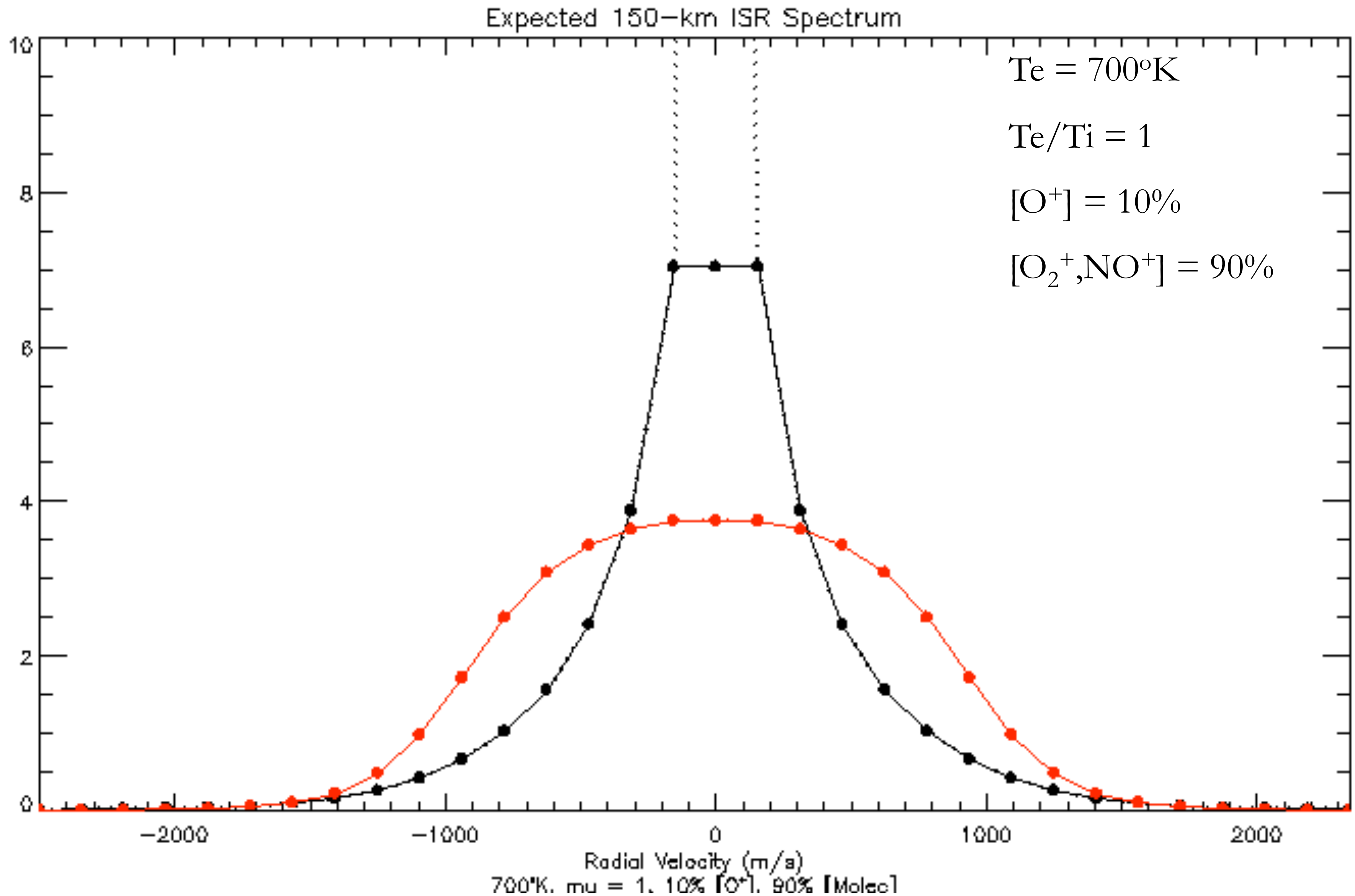
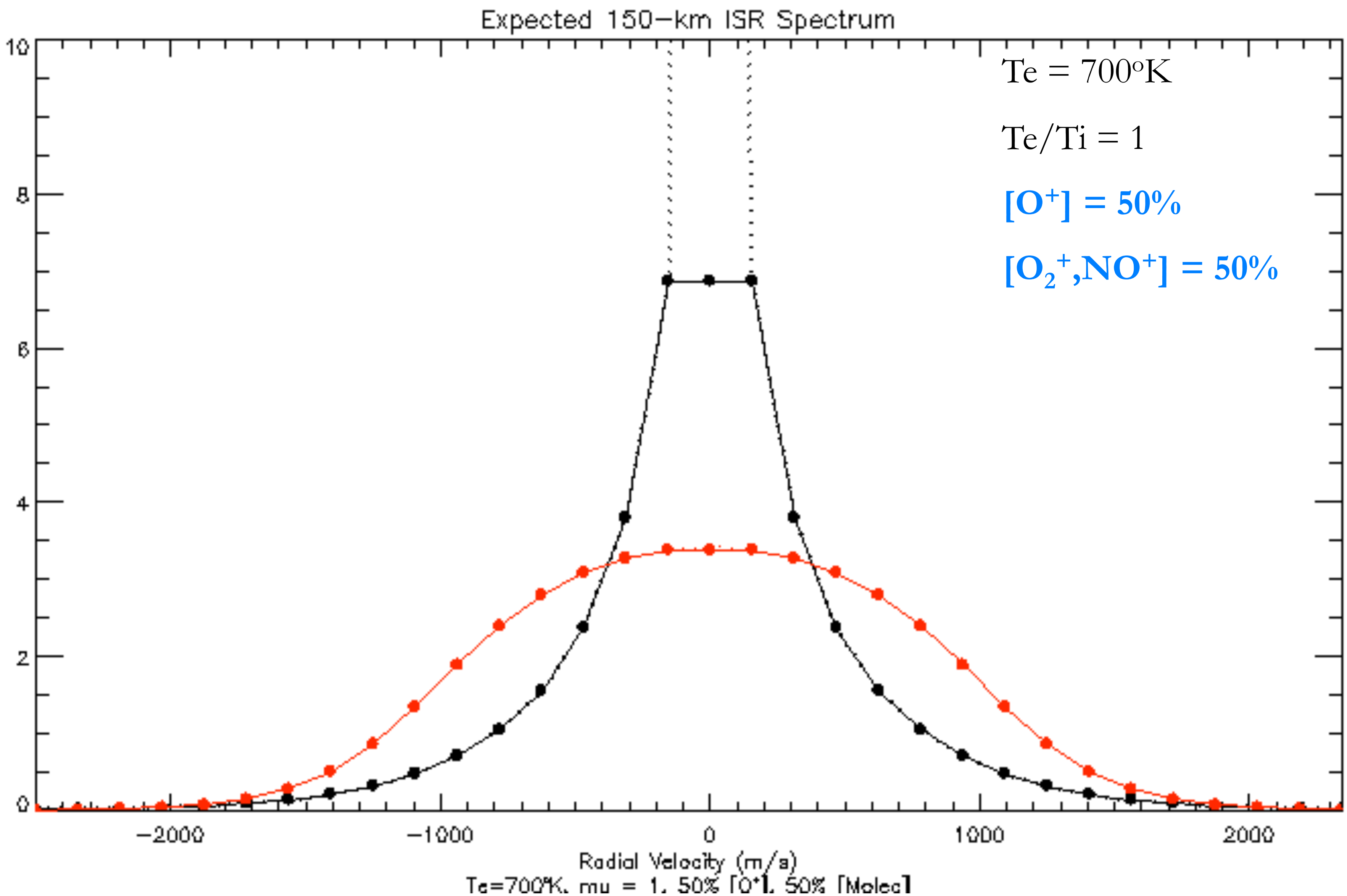


150-km ISR spectrum (2)



150-km ISR spectrum (3)

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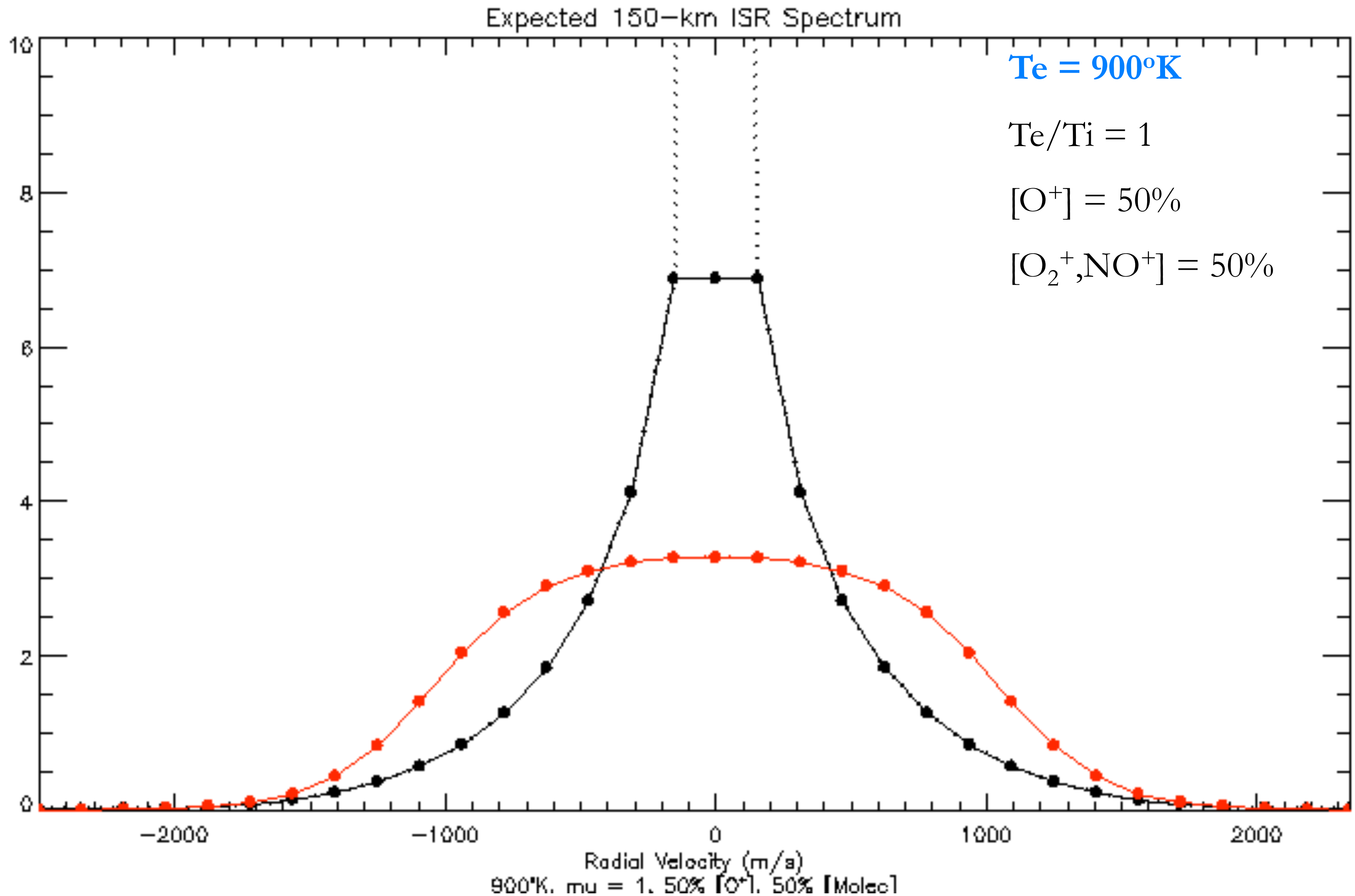

150-km ISR spectrum (4)

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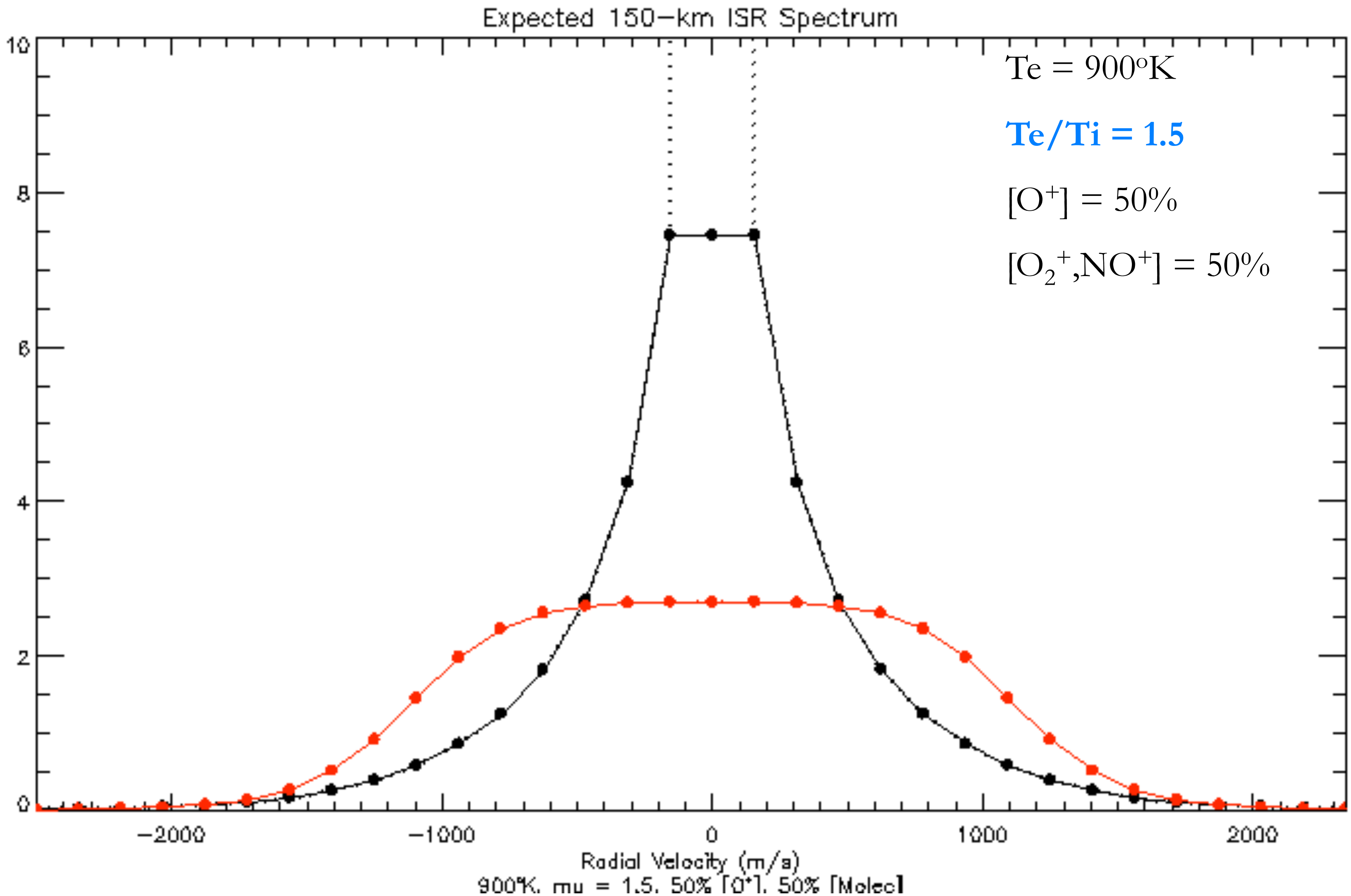
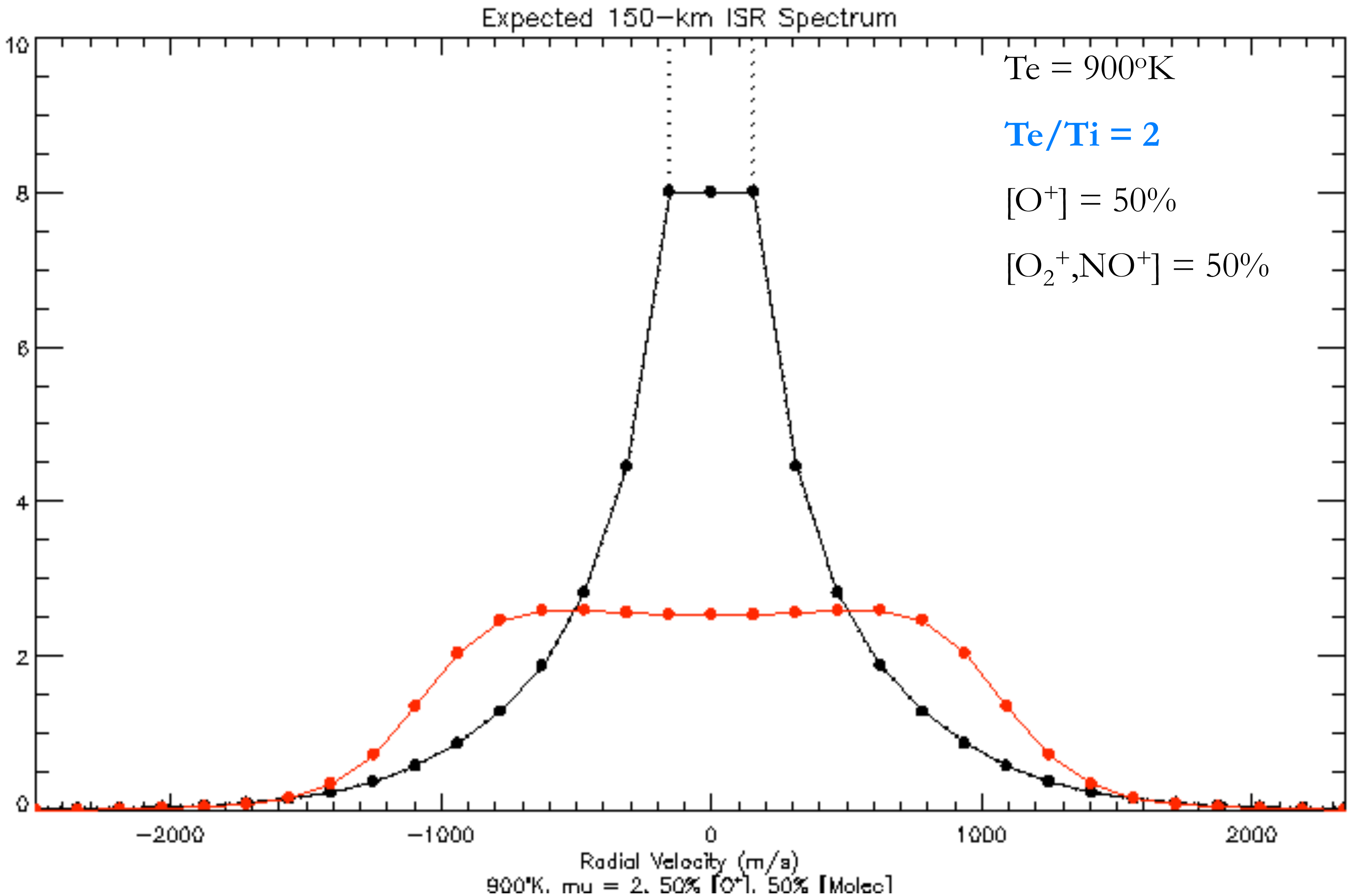


150-km ISR spectrum (5)



Multi-beam Experiments: 1.83^o vs. Perpendicular (3)

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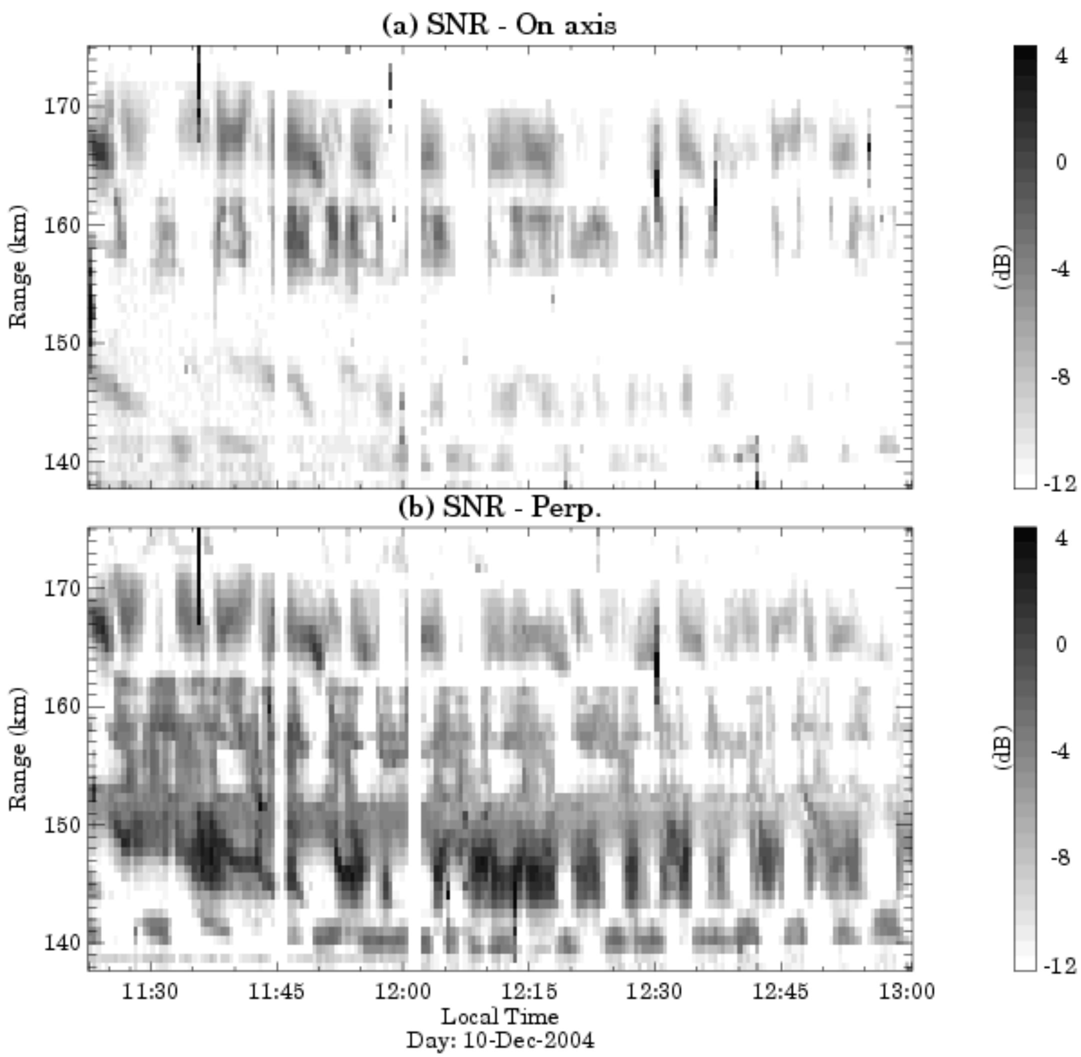

<u>RTI</u>

•There is a one-to-one correspondence between echoes observed between 160 and 180 km.

•Below 160 km there is a small correlation between Oblique and perpendicular echoes. There is more occurrence of perpendicular echoes.

Multi-beam Experiments:
1.83° vs. Perpendicular (No Cusp) (4)

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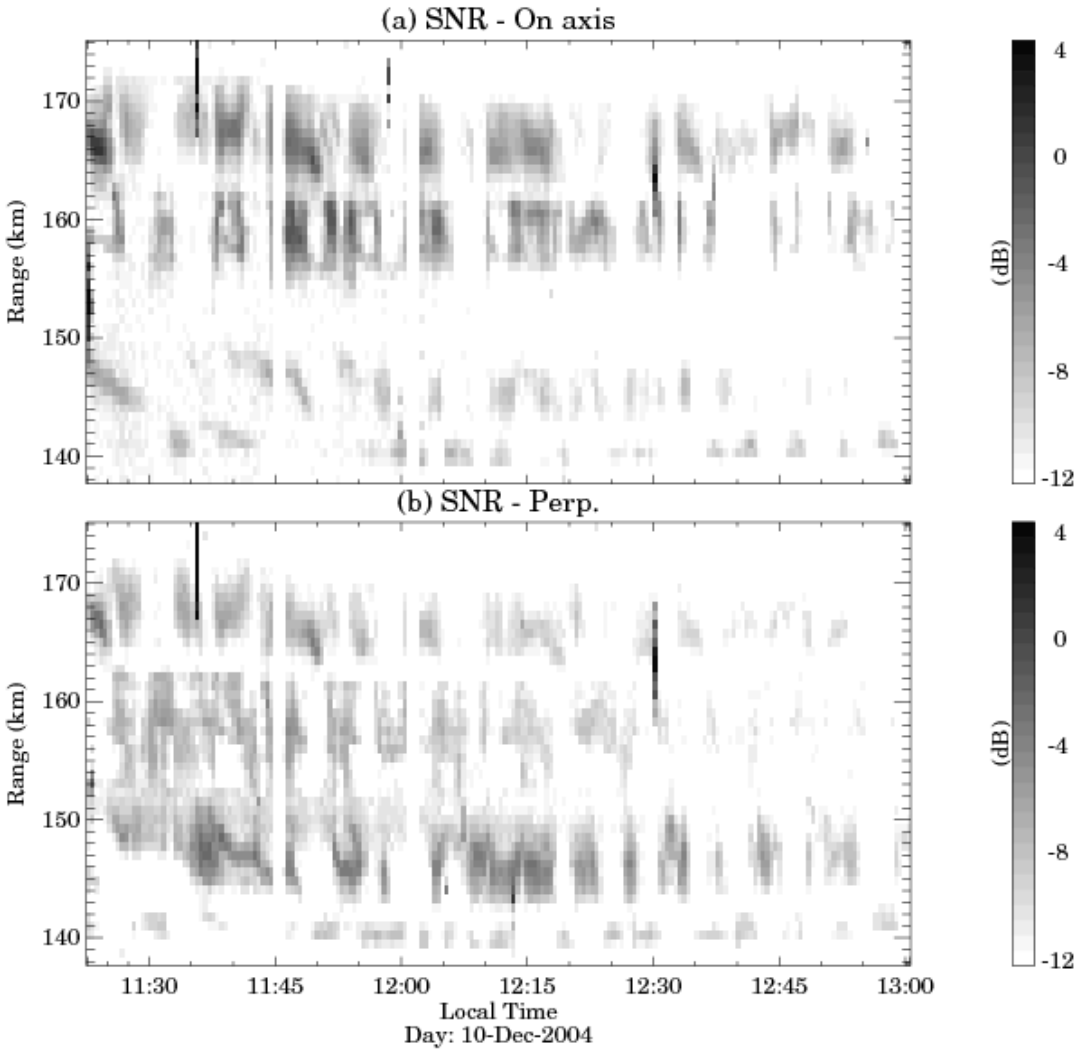

RTI after removal of "Cusp"

- Removal of "slow" component by using a 5 running average filter.
- There is a good correlation between upper echoes (above 155 km) and the lower echoes around 140 kms.
- Echoes are stronger at angles closer to Perp, between 145 and 155 km.
- We need to find out if there is a time delay between echoes observed at two different beams.

Multi-beam Experiments:
1.83^o vs. Perpendicular ("DC") (5)

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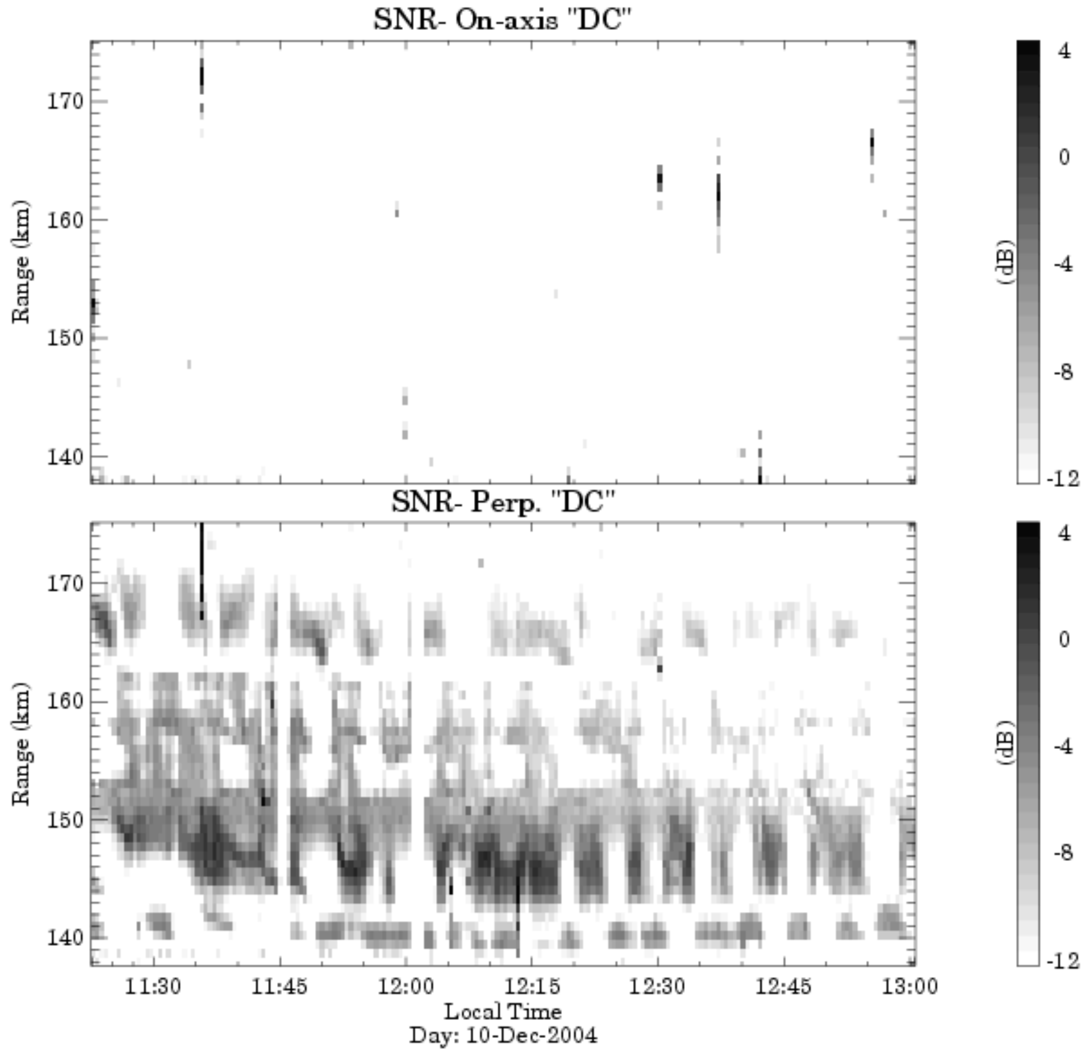

RTI just "Cusp"

- Showing only "DC" component

Multi-beam Experiments: 1.83° vs. Perp. (Time series) (6)

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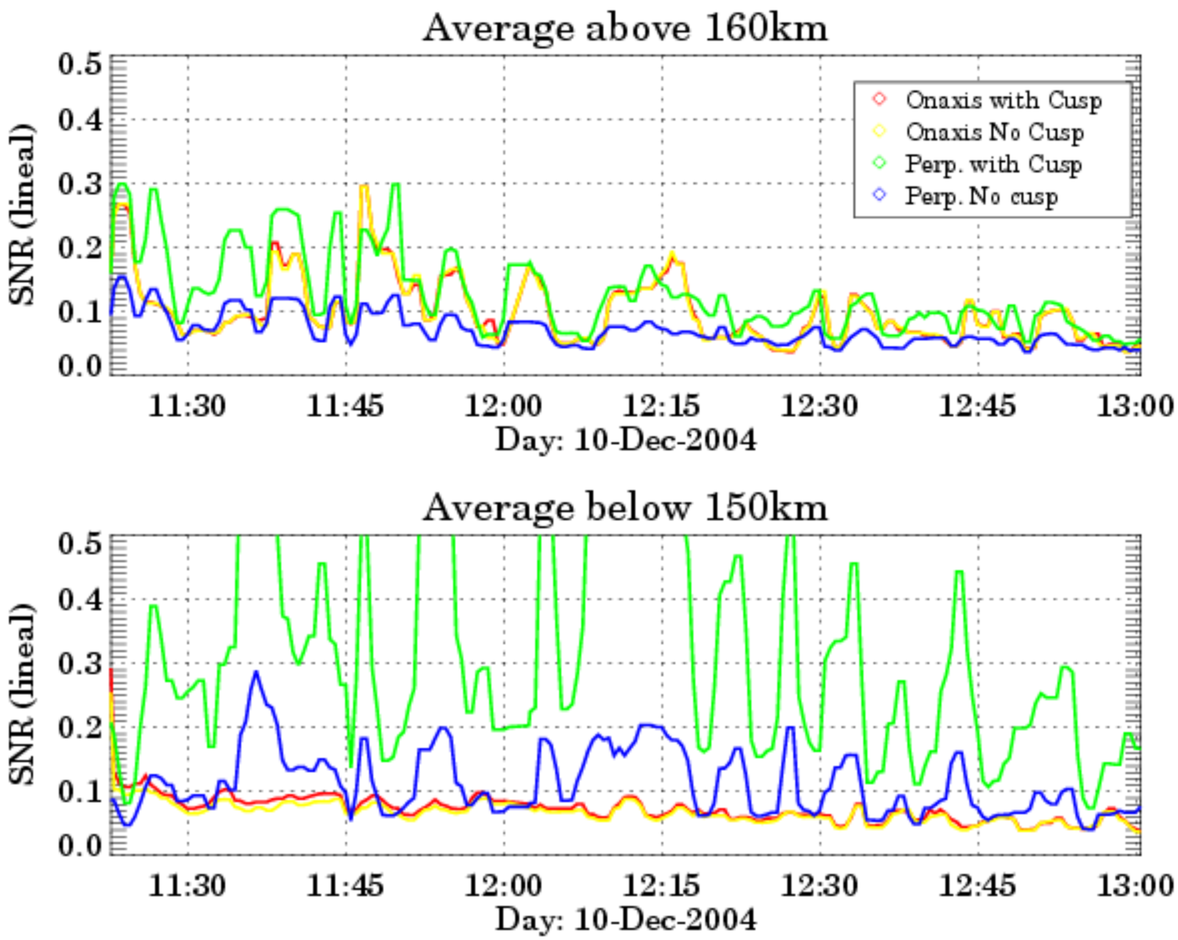

<u>Averaged SNR</u>

•Upper echoes (above 160 km) show a good correlation for both beams and similar echo strengths (green and yellow).

•Lower echoes show stronger echoes at Perp (green stronger than the rest)

•By comparing lower Perp echoes without "DC" (blue) to the on-axis echoes, there is a good correlation but with a time delay of few minutes.

Multi-beam Experiments: 1.83^{o} vs. Perp. (Time series and Corr.) (7)

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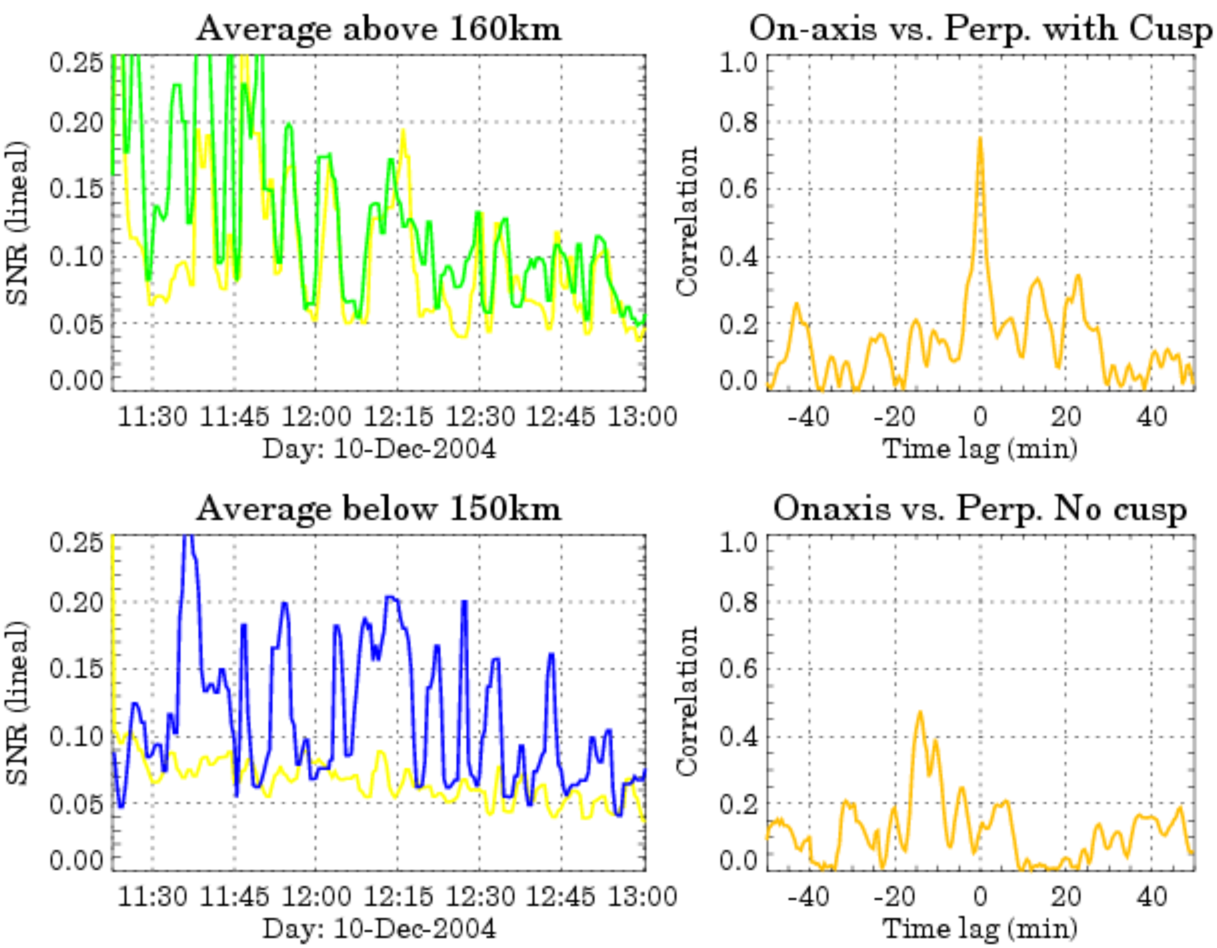

Averaged SNR

- Upper echoes (above 160 km) show a good correlation (0.8) for both beams and similar echo strengths (green and yellow), without time delay.
- By comparing lower Perp. echoes without "DC" (blue) to the on-axis echoes (yellow), there is a relatively good correlation (0.4) but with a time delay of ~15 minutes, implying ~5m/s northward motion around 140 kms.

Multi-beam Experiments: 1.83º vs. 4.95º (1)

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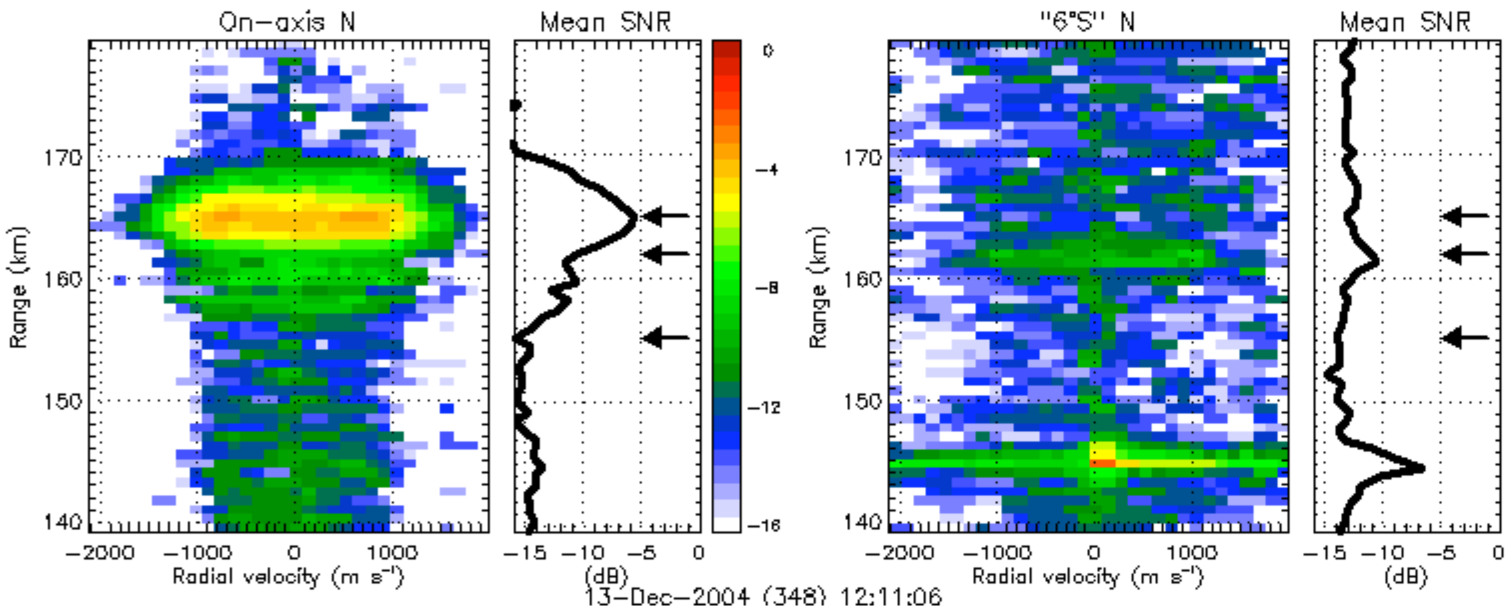
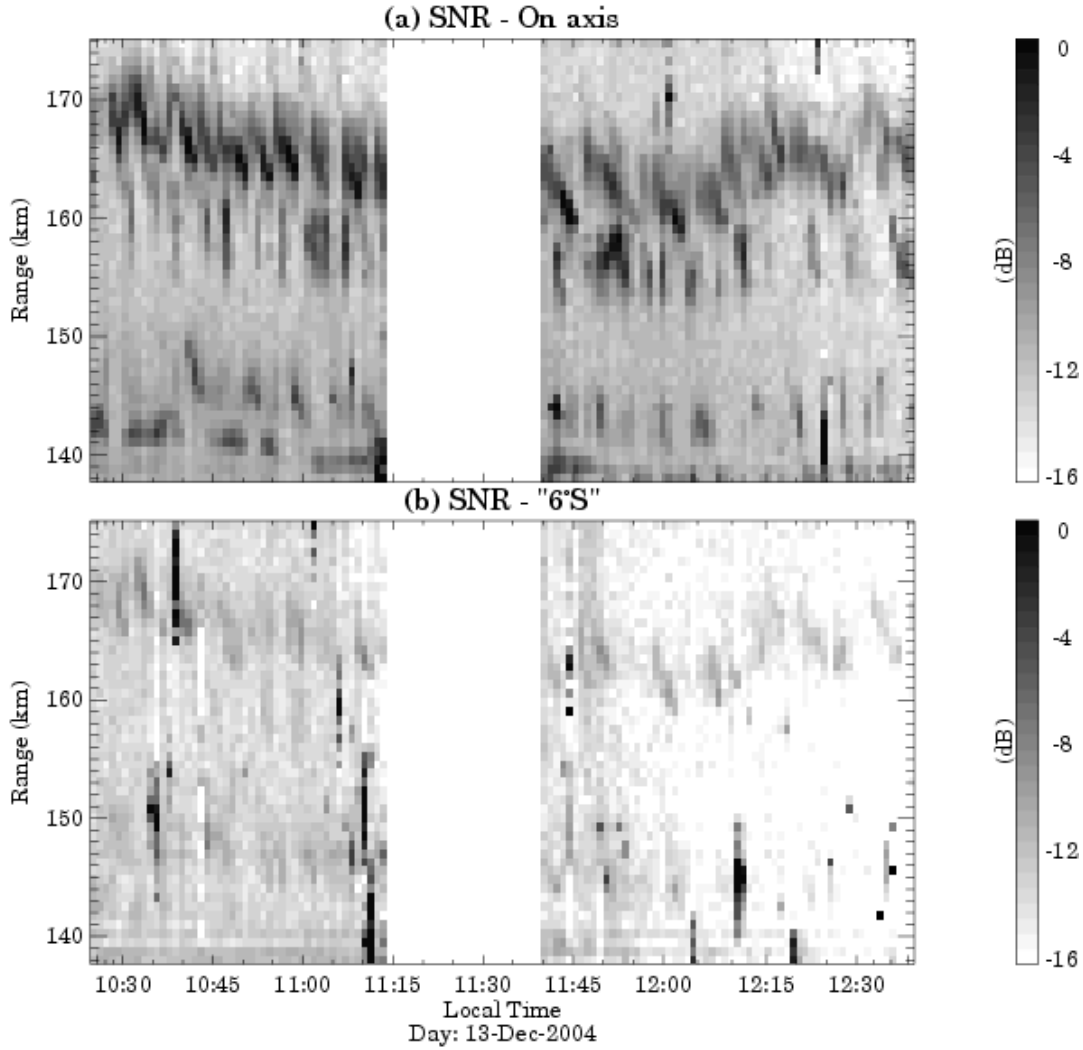


<u>Spectrograms</u>

- •No coherent integrations
- •Median filter =3, to remove interference.
- •Echoes at more oblique angles are weaker.
- •The echo around 145km in the "6ºS" beam comes from a meteor.

Multi-beam Experiments: 1.83º vs. 4.95º (2)

Radio Observatorio de JICAMARCA Radio Observatory



RTI

- There is a one-to-one correspondence between echoes observed between 160 and 180 km, but closer to B echoes are stronger (even after considering 4dB antenna gain differences).
- Note that in both beams, there are not strong echoes below ~155km, as is usually observed with perpendicular beams.

150-km angular brightness

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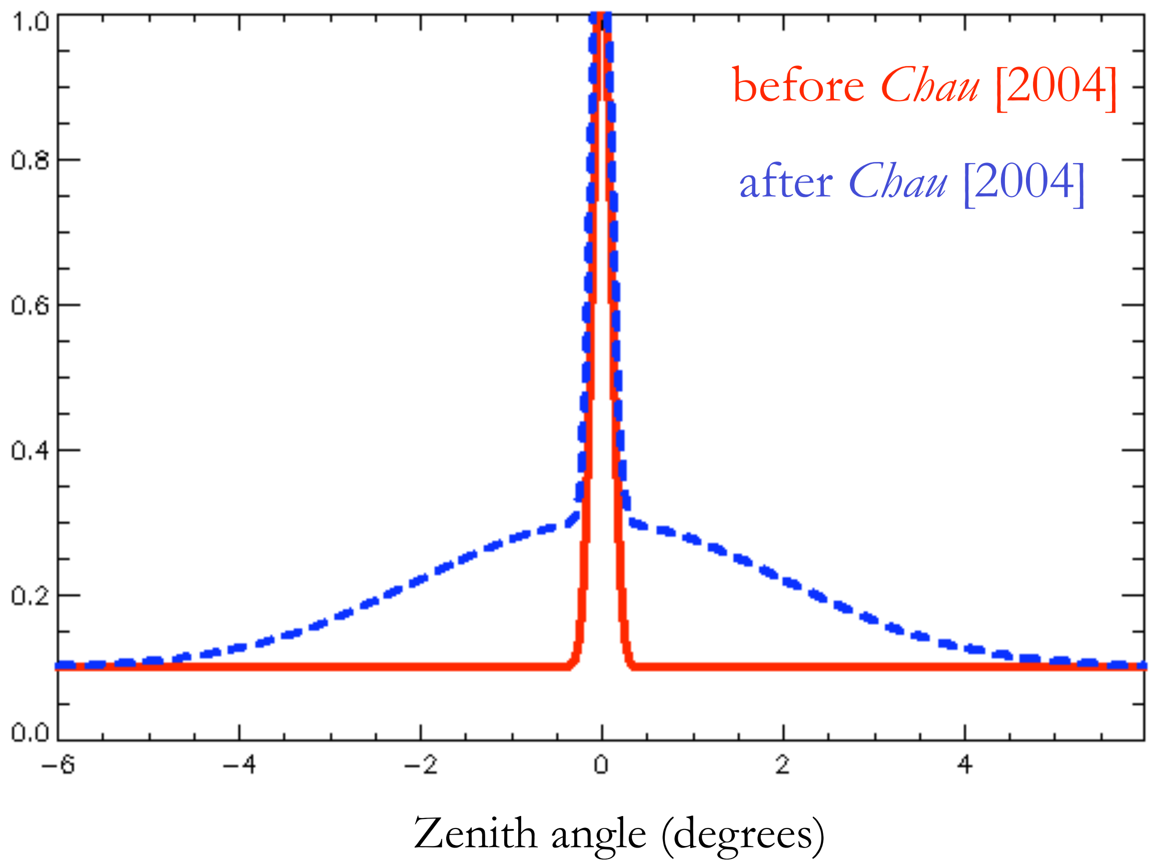

- Thermal signatures (ISR echoes) present an isotropic brightness.
- Before *Chau* [2004], 150-km echoes were assumed to be very aspect sensitive, i.e., coming from very elongated field-aligned irregularities (Gaussian shapes with ~0.1° width)
- Off-perpendicular to B observations, indicate a non-Gaussian brightness distribution for the 150-km irregularities.

Faraday Density Experiments (1)

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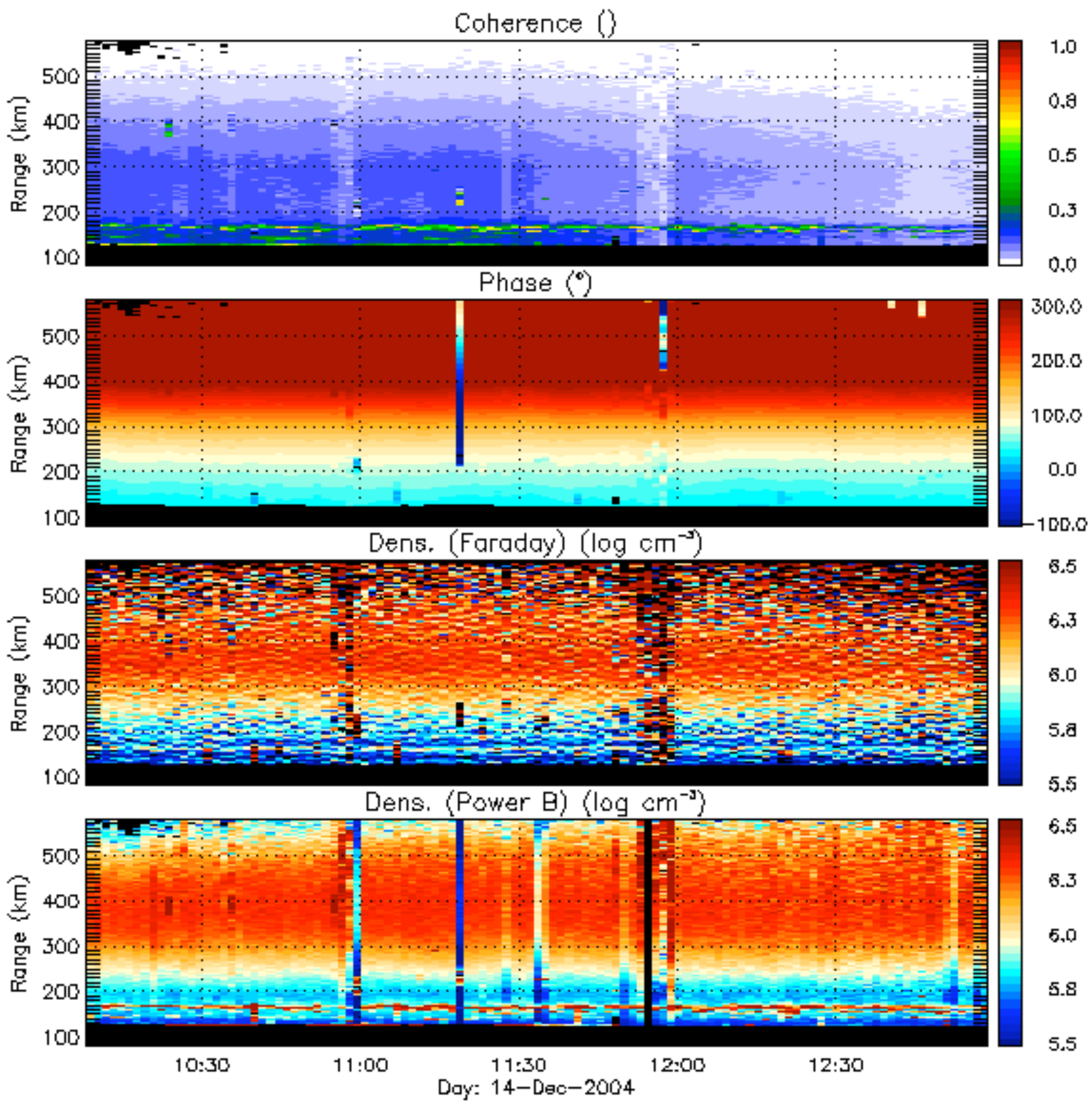

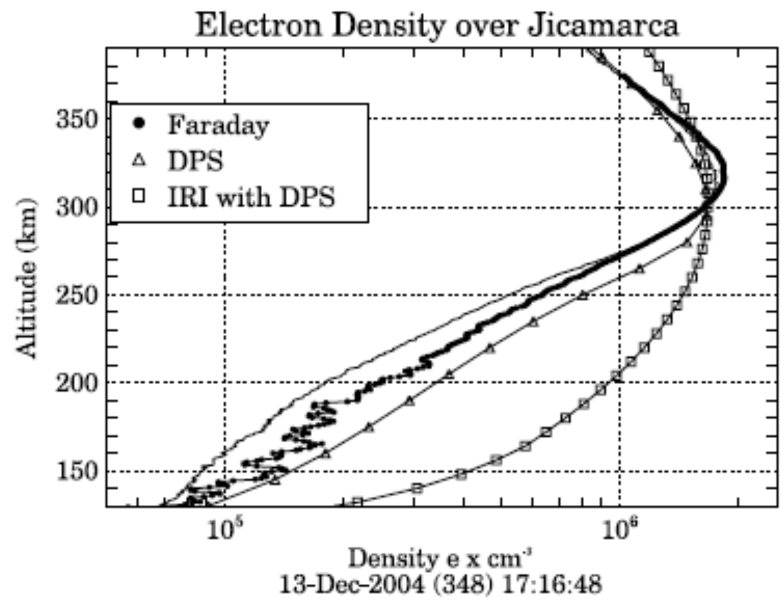

[from *Chau and Woodman*, 2005]

Parameters

•IPP = 600 km

•Baud width=0.75 km

•Binary code: 28

•N averages: 19968

•N smooth: 5

Faraday density experiments (2)

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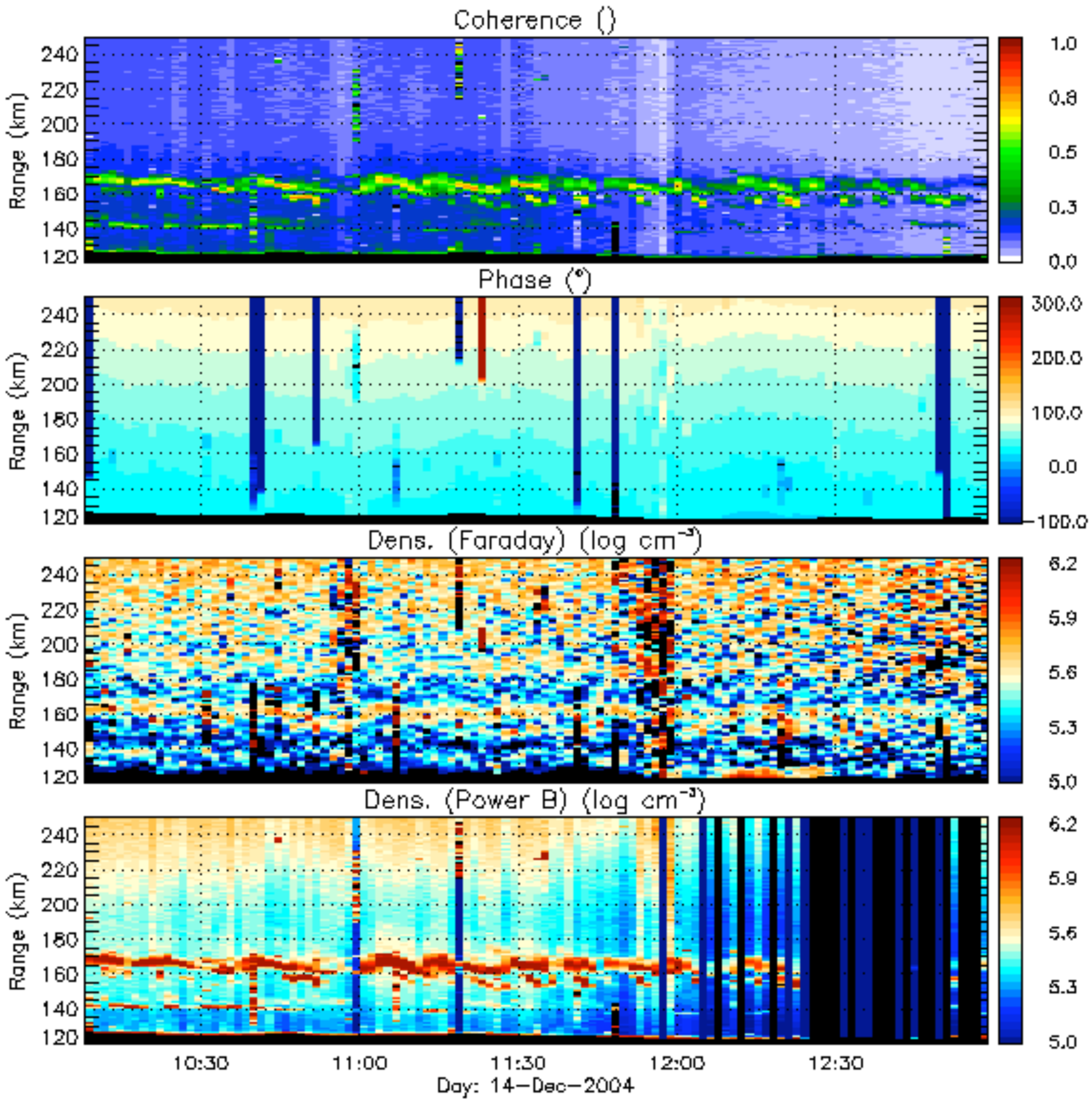

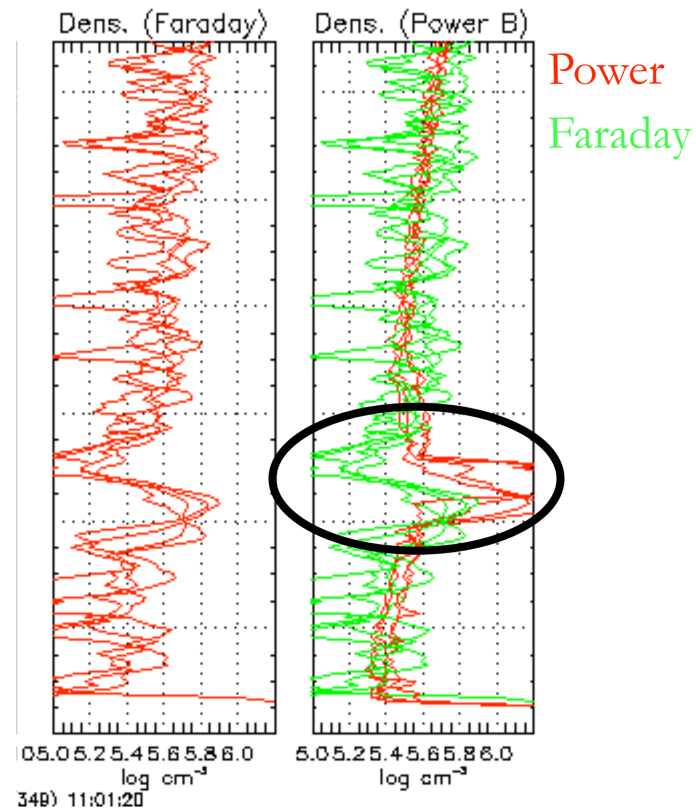

Instead of density enhancements, 150-km echoes appear to correlate with density depletions below or above.

Faraday density experiments (2)

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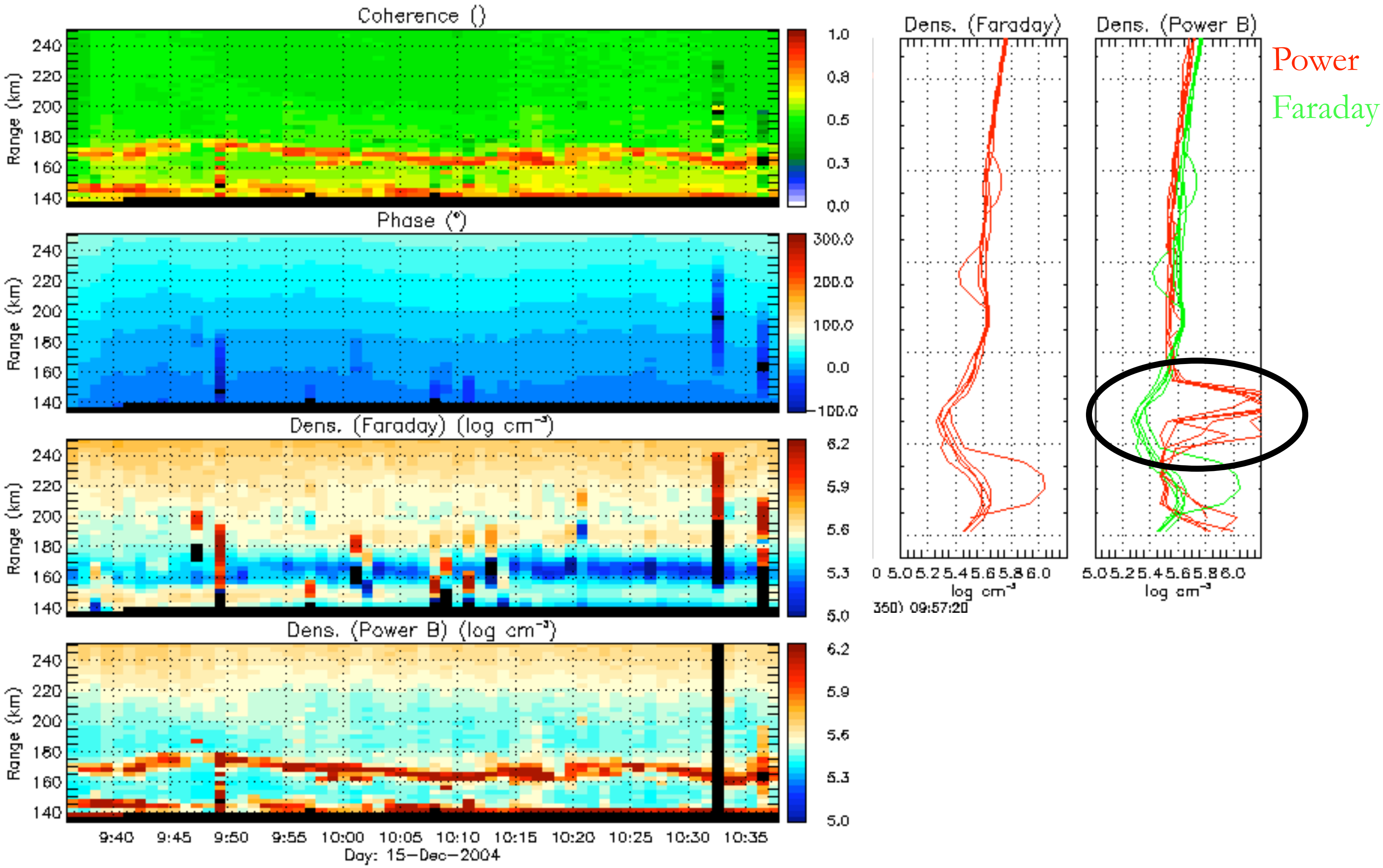
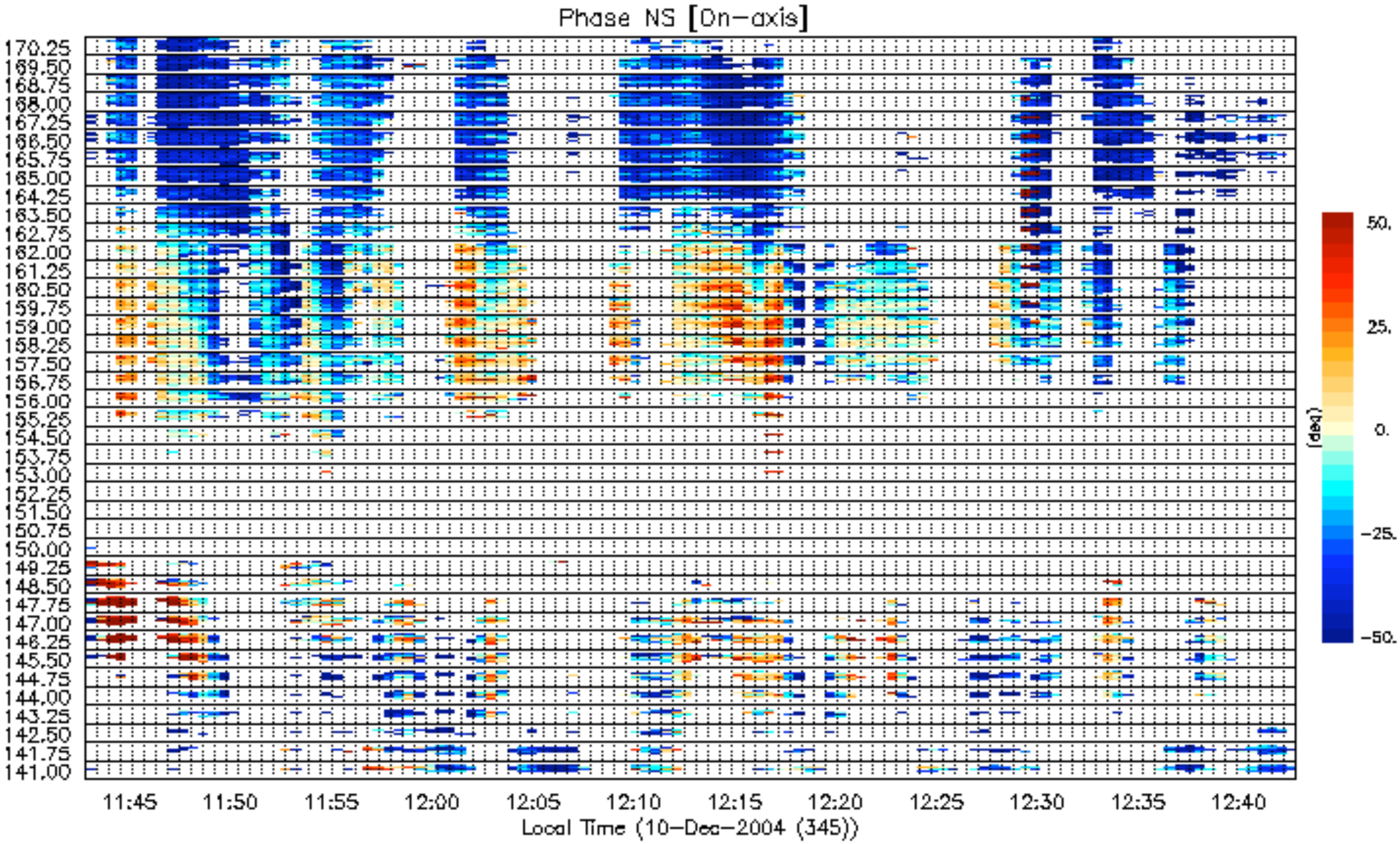


NS Structure: On-axis



NS Structure: Around Perp to B.

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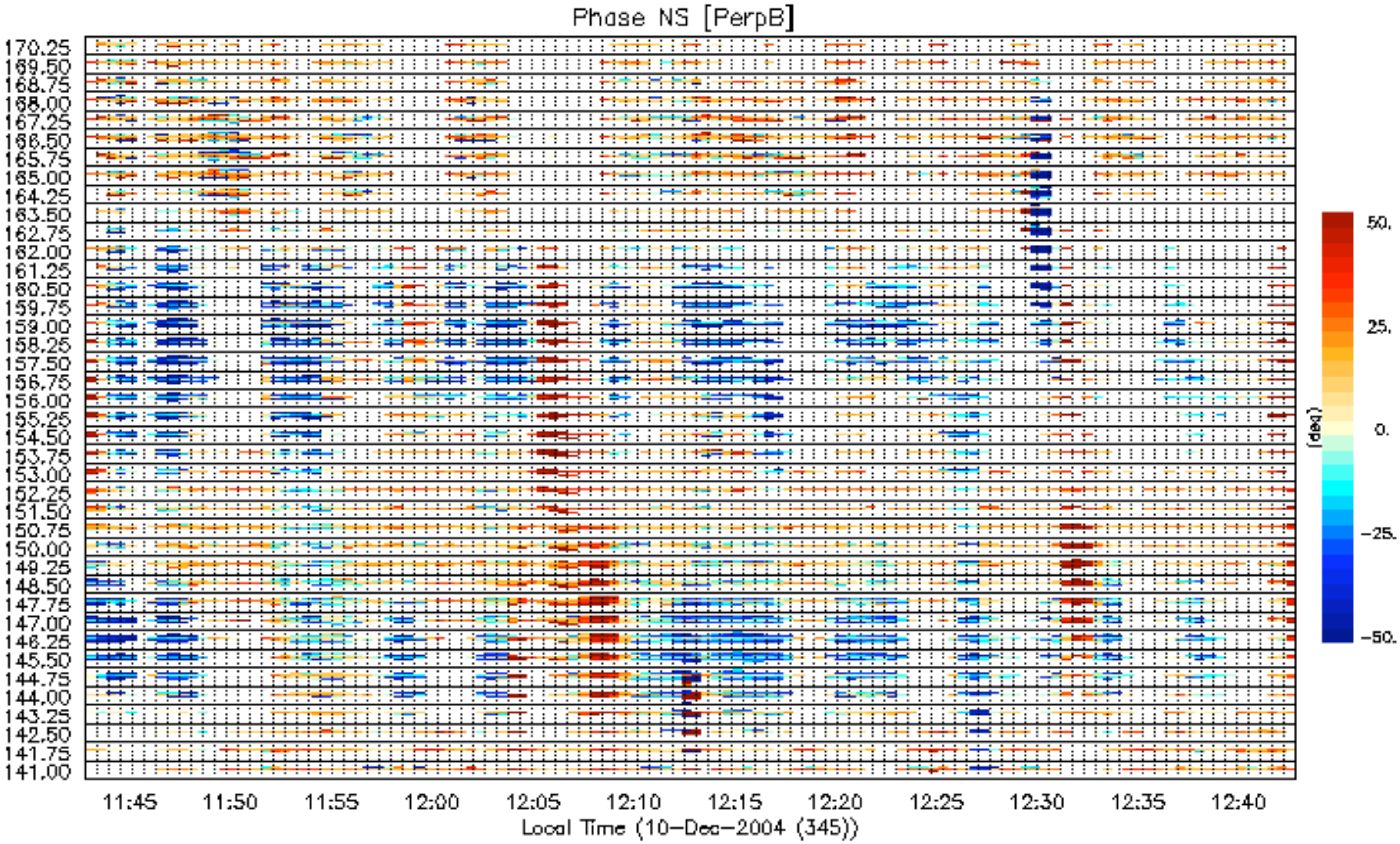

NS Structure: Perp to B

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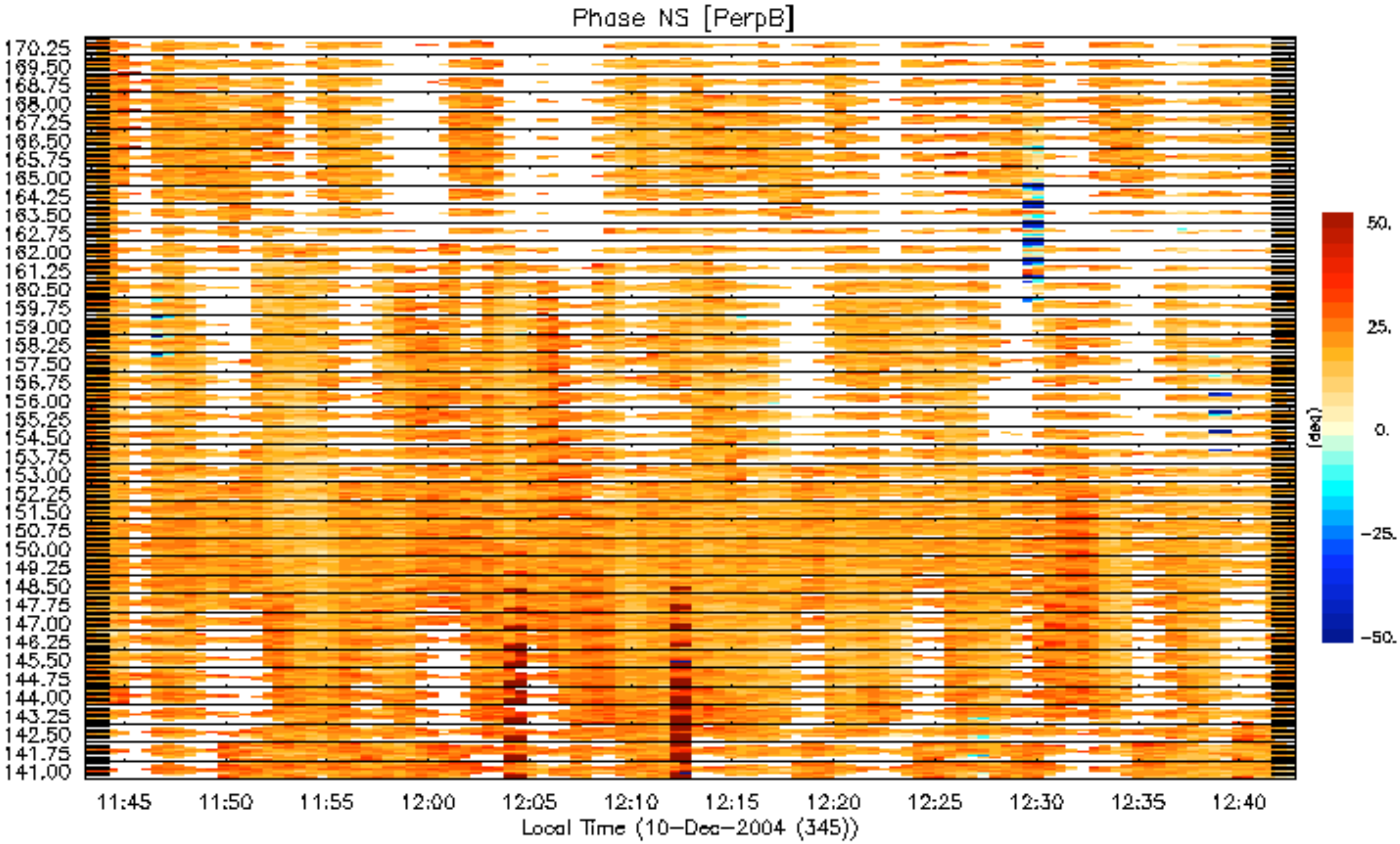

Spectrum and NS Structure

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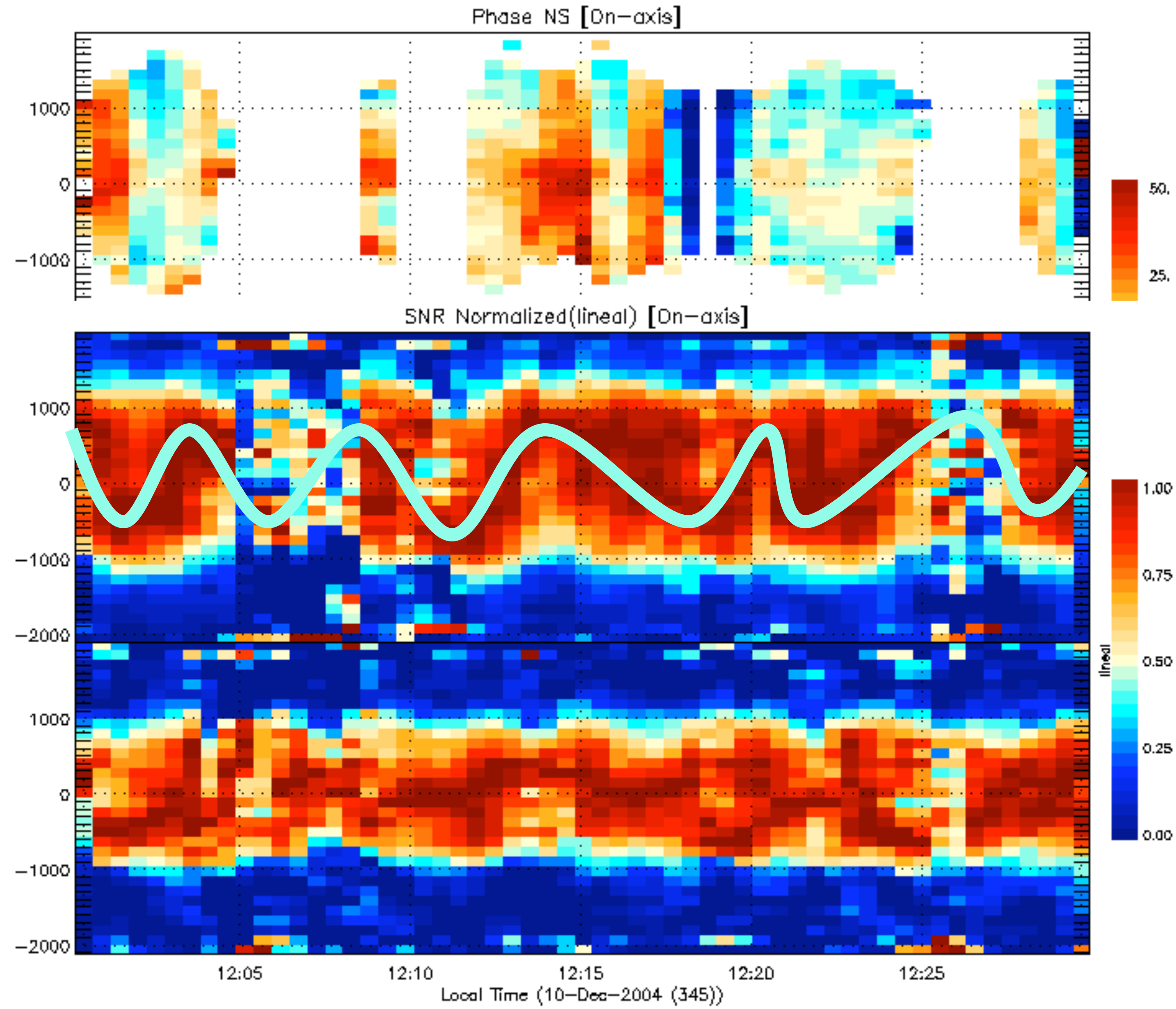

•Above 150 km: Spectra is wider and with an oscillating peak with a period ~5-10 min.

•Below 150 km: Spectra is narrower, peak is not well defined.

•Spectra structure appear to be associated to changes in location of the scattering center.

Recent 150-km findings (1)

- Multi-beam wide spectra
  - Spectra off-perpendicular to B are very wide (> 1000 m/s).
  - It appears that they do not present a smooth shape, present frequency structure, e.g., oscillating with a period of ~5-10 min above 160 km
  - Echoes get weaker as the angle respect to B is larger.
  - Above ~160 km, perp. and oblique echoes are highly correlated and of comparable strength.
  - Below ~150 km, perp. and oblique beams are correlated, but with ~15 min delay, maybe due to a meridional wind.
  - Between 150 and 160 km, echoes are much stronger at Perp. beams.

Recent 150-km findings (2)

- Density from Faraday measurements
  - Errors are high, but one see deterministic patterns as function of time and altitude that are correlated with the 150-km echoes.
  - 150-km enhanced echoes, although present wide spectra, do not occur on regions of high densities.
  - Enhanced echoes appear to occur on regions of +ve and -ve density gradients (see depleted regions above and below enhanced echoes).

Recent 150-km findings (3)

Radio Observatorio de JICAMARCA Radio Observatory

- Interferometry results
  - Scattering centers of "oblique" echoes oscillate both in time (5-10 min) and altitude (5-8 km)
  - Scattering centers from angles "close to perp. to B" echoes also oscillate, but apparently not in phase with the oblique centers, suggesting a meridional modulation.
  - Scattering centers of FAI also oscillates but with smaller amplitudes, they do not coincide with off-perp. echoes.