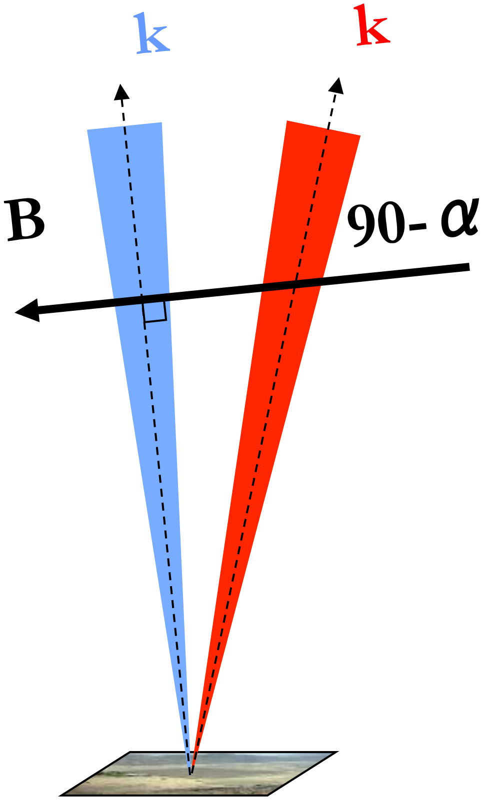
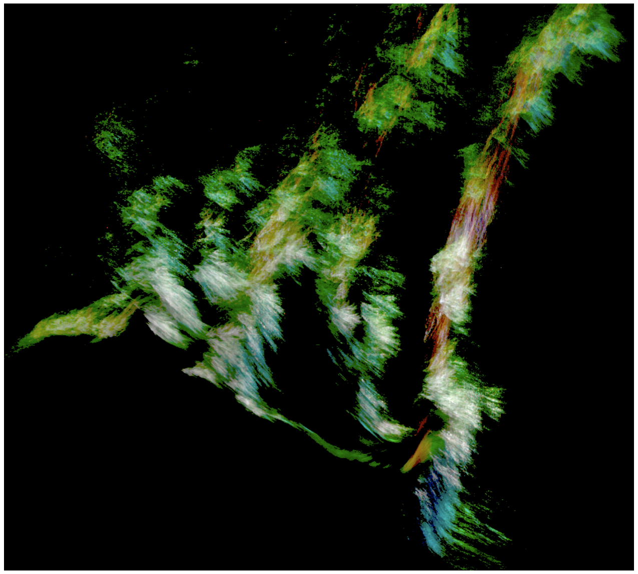
The Equatorial Aeronomy at the Jicamarca Radio Observatory and relationship to high latitude research



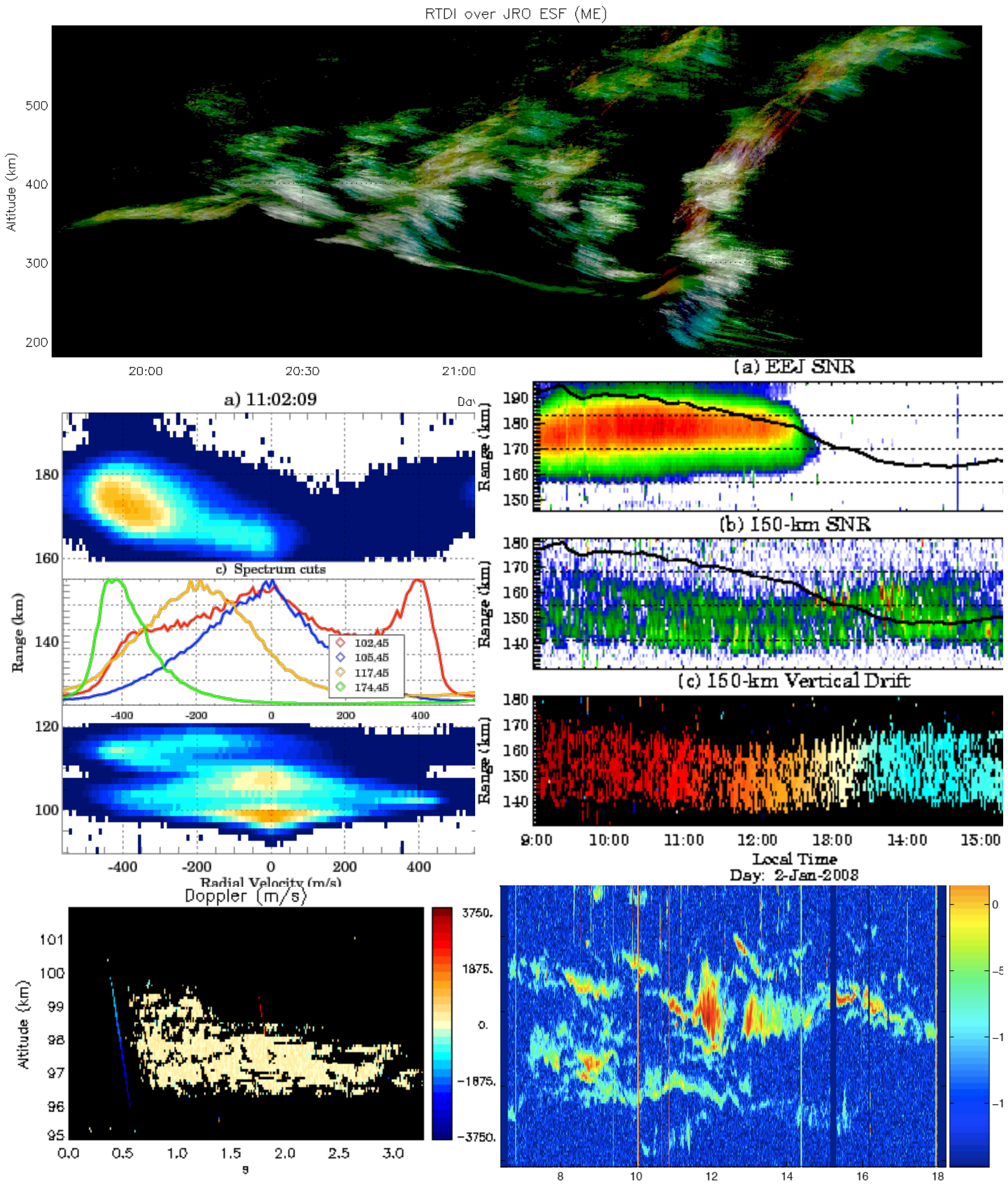


J. L. Chau et al.
Radio Observatorio de Jicamarca, Instituto Geofísico del Perú, Lima

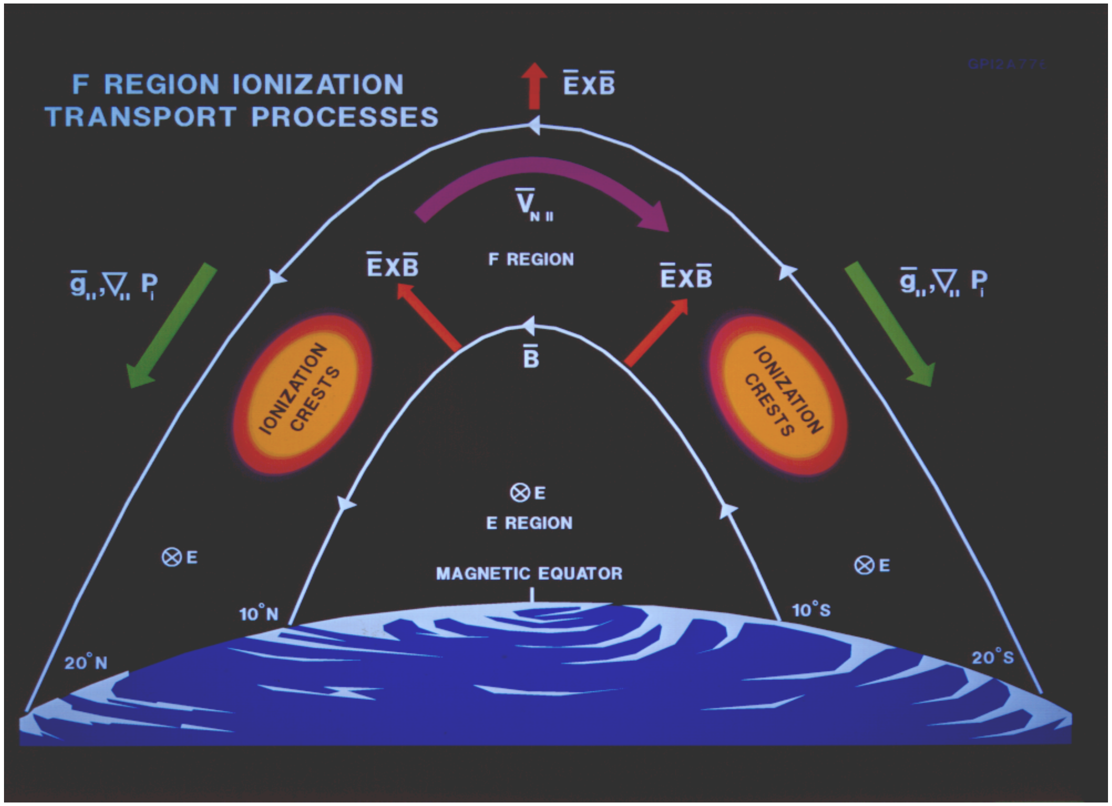
EISCAT School, Sodankyla, Finland, August 30, 2012

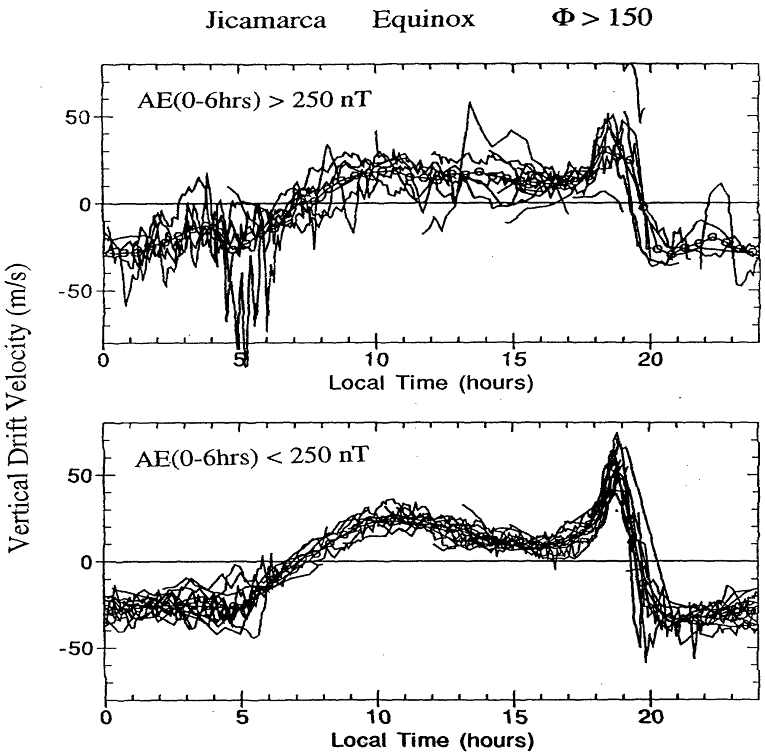
Outline

- The Equatorial ionosphere
- The Jicamarca Radio Observatory
  - Incoherent Scatter Radar Modes
  - Coherent scatter studies
- Selected Research Topic Related to High Latitudes:
  - 150-km NEILS



Equatorial Ionosphere



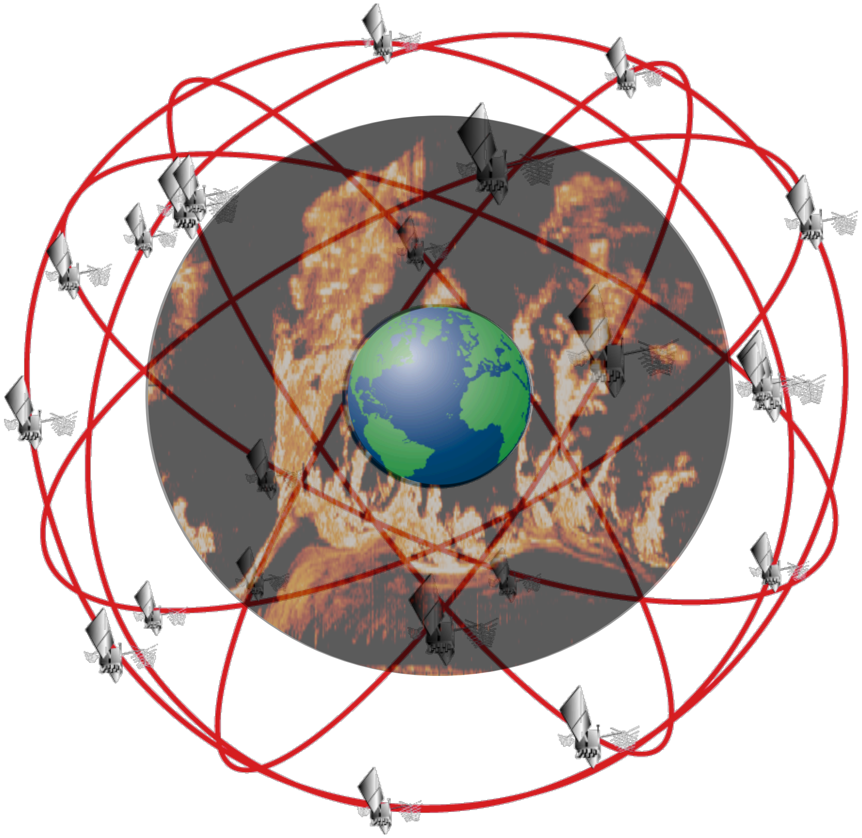


[from *Fejer et al*, 1999]

- **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.

GPS System



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

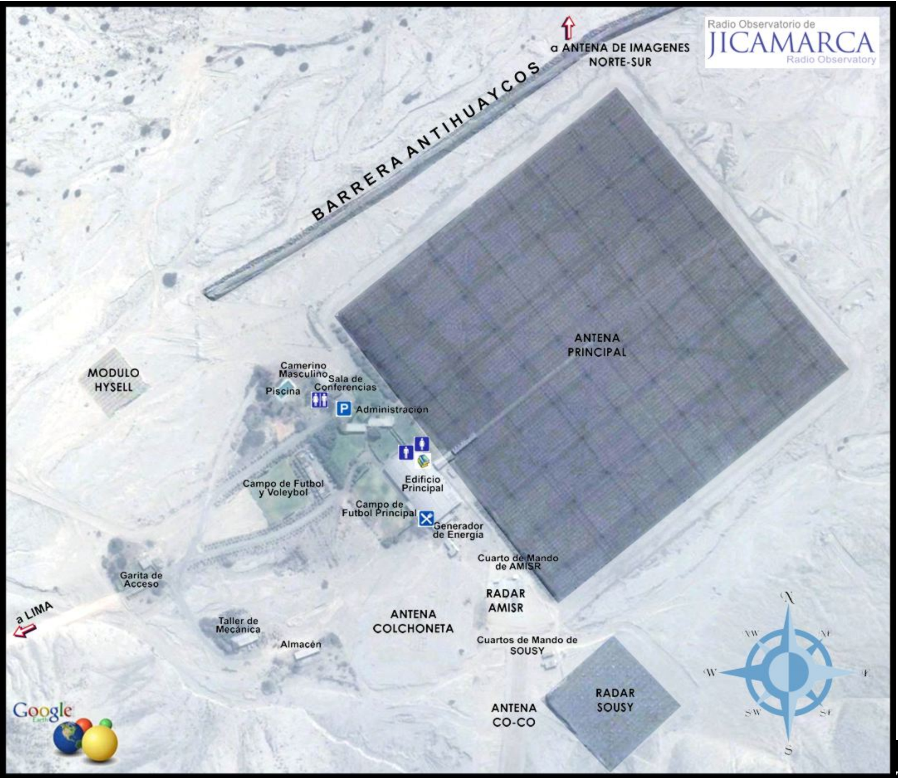
<u>Applications</u>

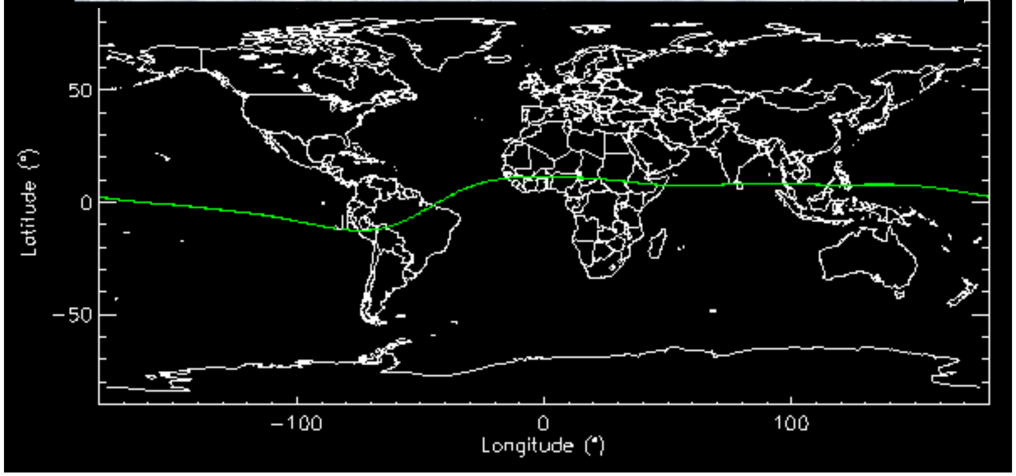
- Civil, military
- Scientific: Geodesy, Meteorology, Aeronomy

The Jicamarca Radio Observatory

Radio Observatorio de JICAMARCA Radio Observatory

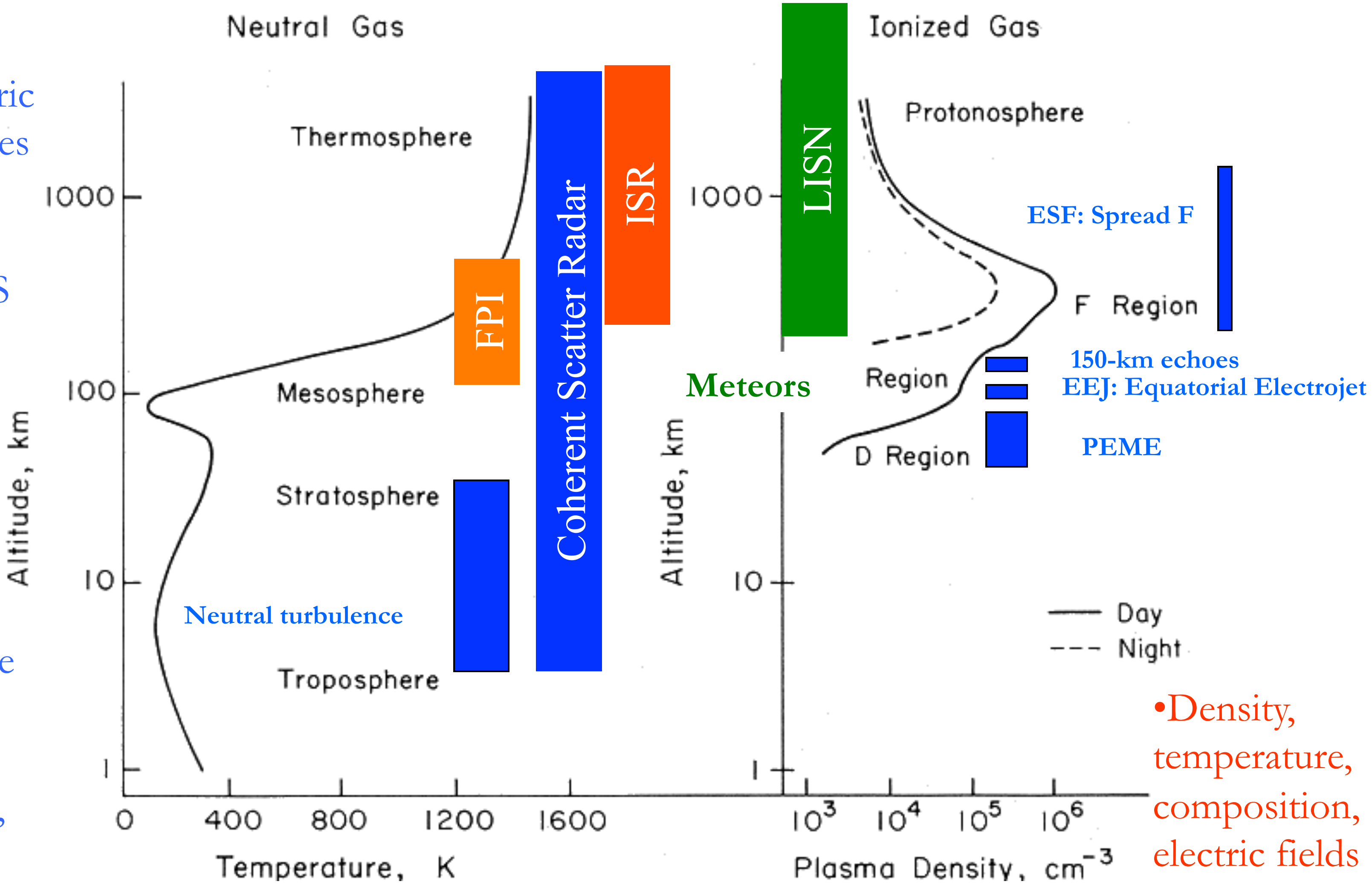
- Built in 1961 by the US NBS and then donated to IGP in 1969.
- Operating frequency: 50 MHz
- Antenna type: array of 18,432 dipoles, organized in 8x8 cross-polarized modules.
- Pointing directions: within 3 degrees from on-axis. Phase changes are currently done manually.
- Transmitters: 3 x 1.5 MW peak-power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





¿What do we study at Jicamarca?

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



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

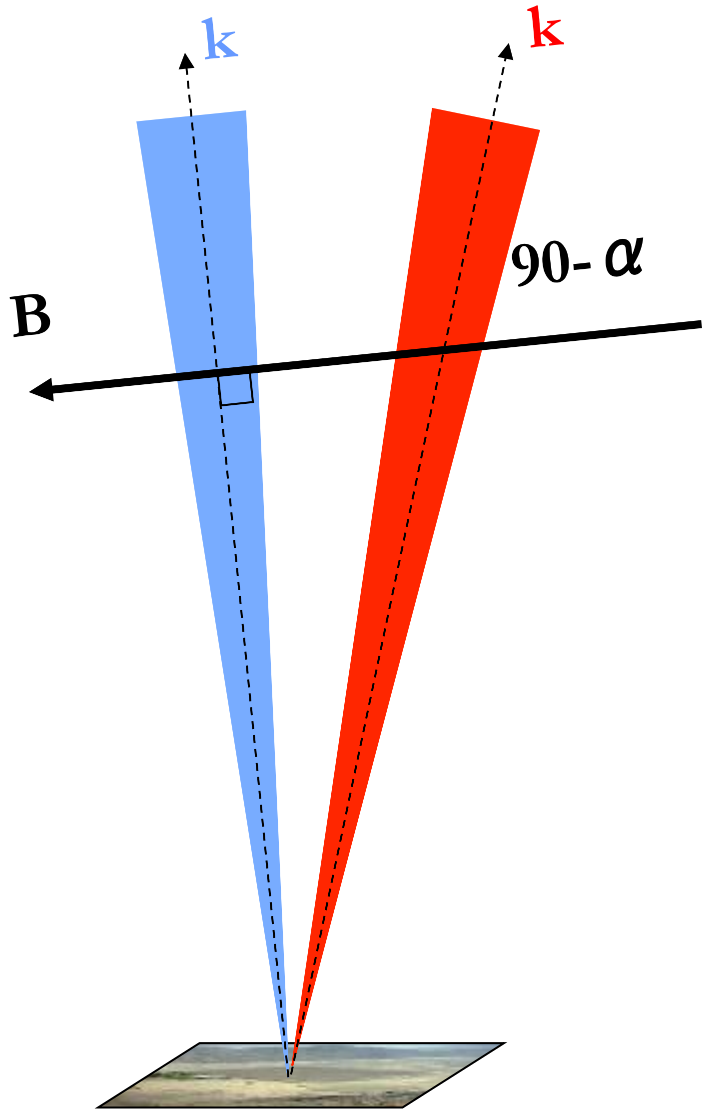
- Density, temperature, composition, electric fields
- Modeling, space weather

Jicamarca Themes (Stable Ionosphere)

- **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?

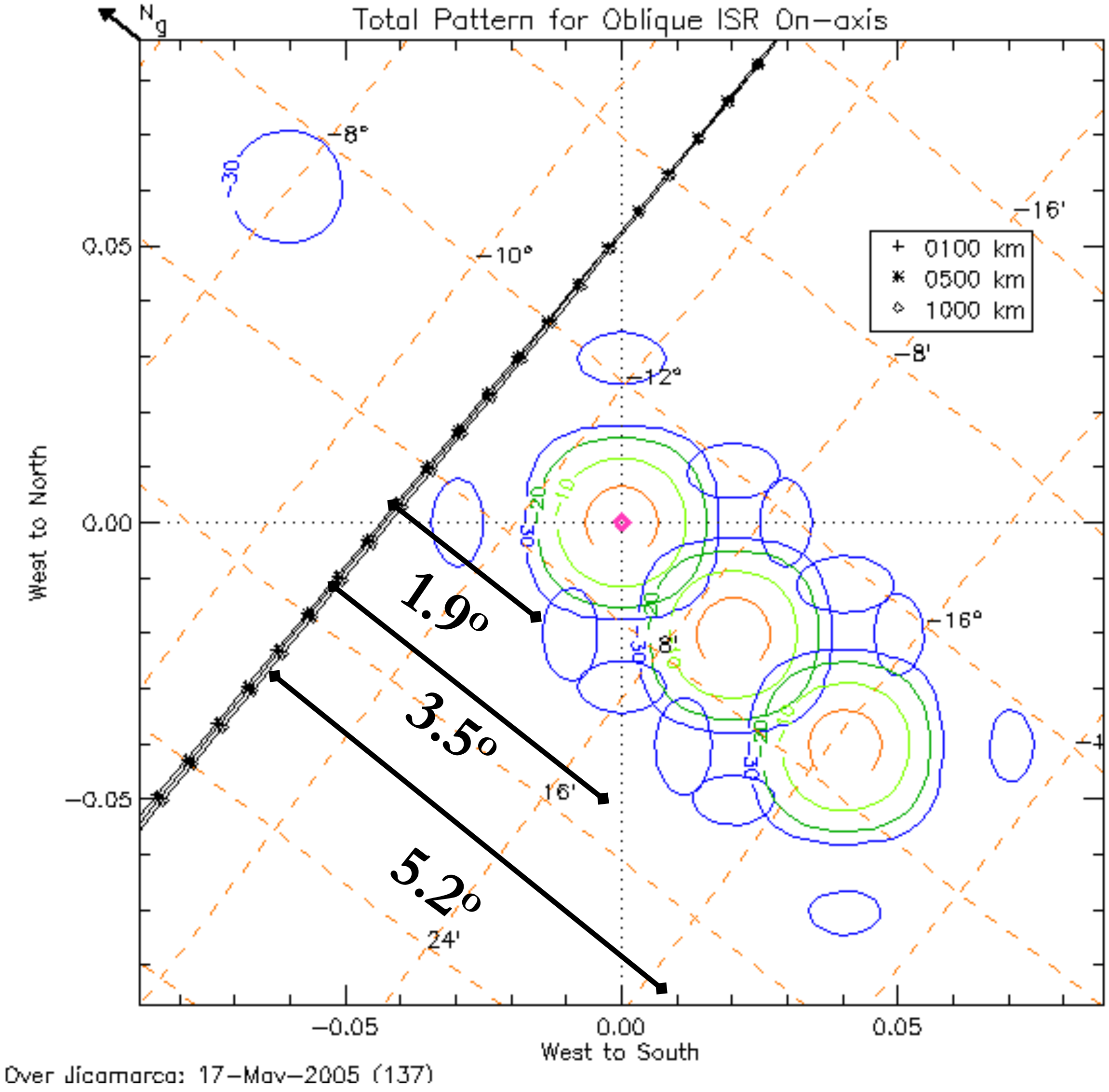
Incoherent Scatter Techniques

Oblique vs. Perpendicular ISR: Geometry



- Depending on α :
  - Oblique: $\alpha > 0$
  - Perpendicular: $\alpha = 0$
- 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 ISR: Antenna Patterns



- Three standard beam positions are used:
  - On-axis ($\alpha = 1.9^o$)
  - "4.5" ($\alpha = 3.5^o$)
  - "6.0" ($\alpha = 5.2^o$)
- Maximum antenna gain is obtained with "On-axis" and less with "6.0".
- Be careful of possible sidelobes pointing perpendicular to **B**, since locus of perpendicularity changes from year to year.
- Scattered signals will be convolved with the antenna pattern.

Perpendicular ISR: Antenna Patterns

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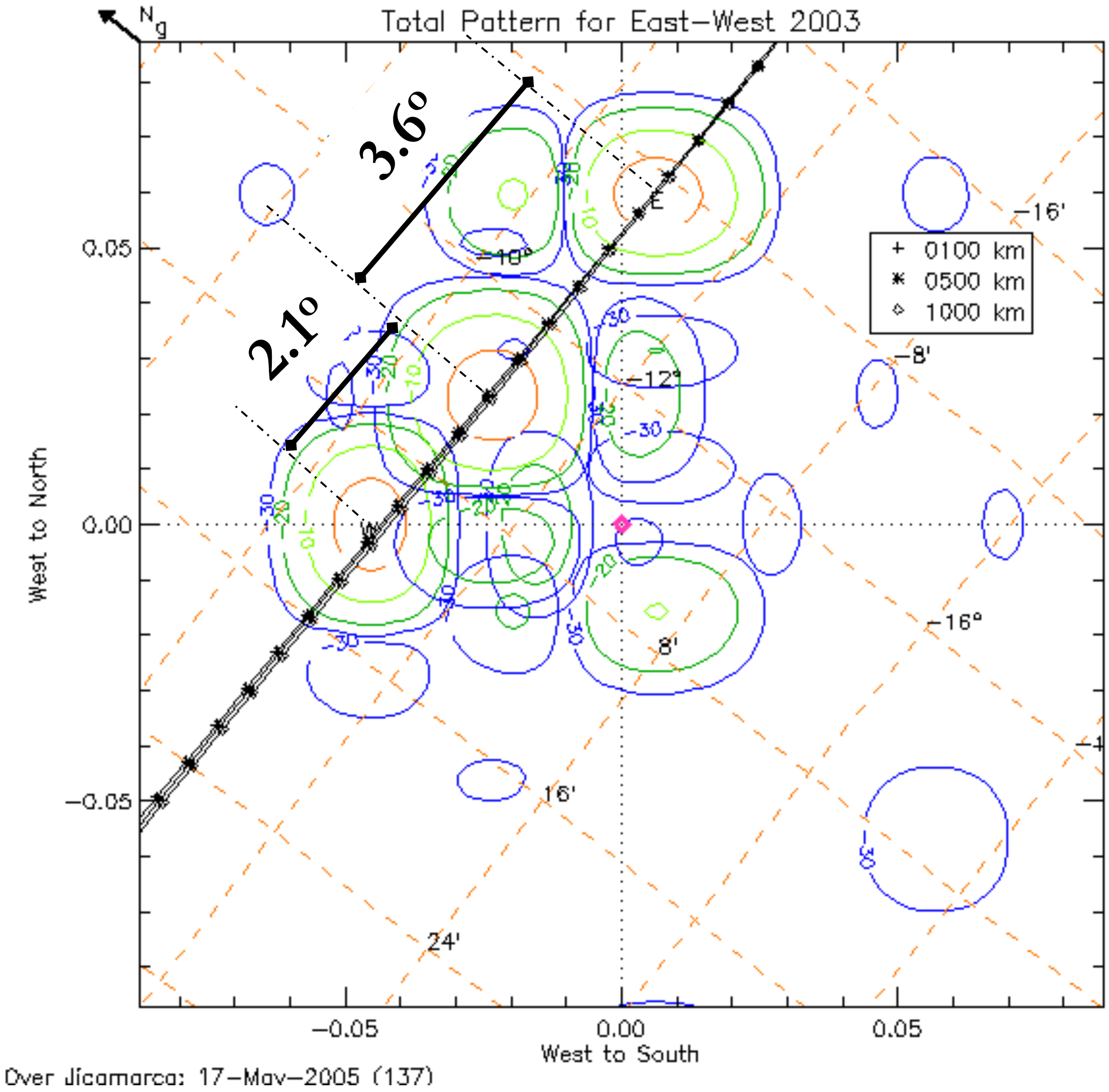
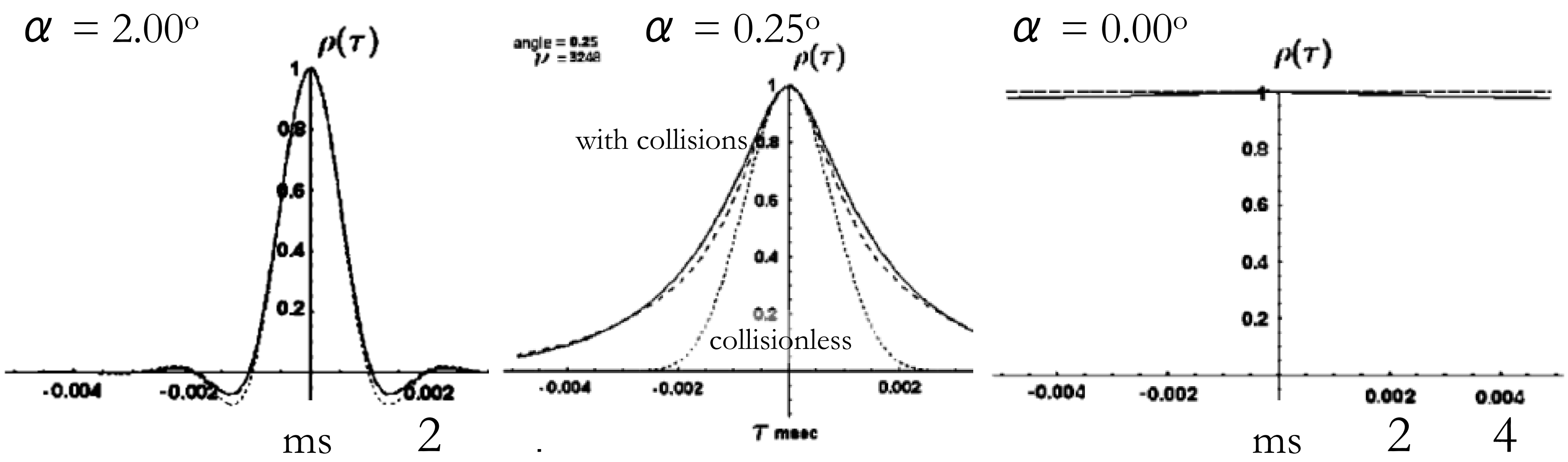


- Three standard beam positions are used:
  - Vertical (both polarizations)
  - "East" (3.6° with respect to vertical). One linear polarization.
  - "West" (~2.1°). The other linear polarization
- Maximum antenna gain is obtained with "Vertical" and less with "East".
- Either Vertical or East-West modes are run at the time, unless wider beams are used (i.e., smaller antennas).
- Recall that the scattered signals will be convolved with the antenna pattern.

Oblique vs. Perpendicular: ACFs

[from *Woodman*, 2004]



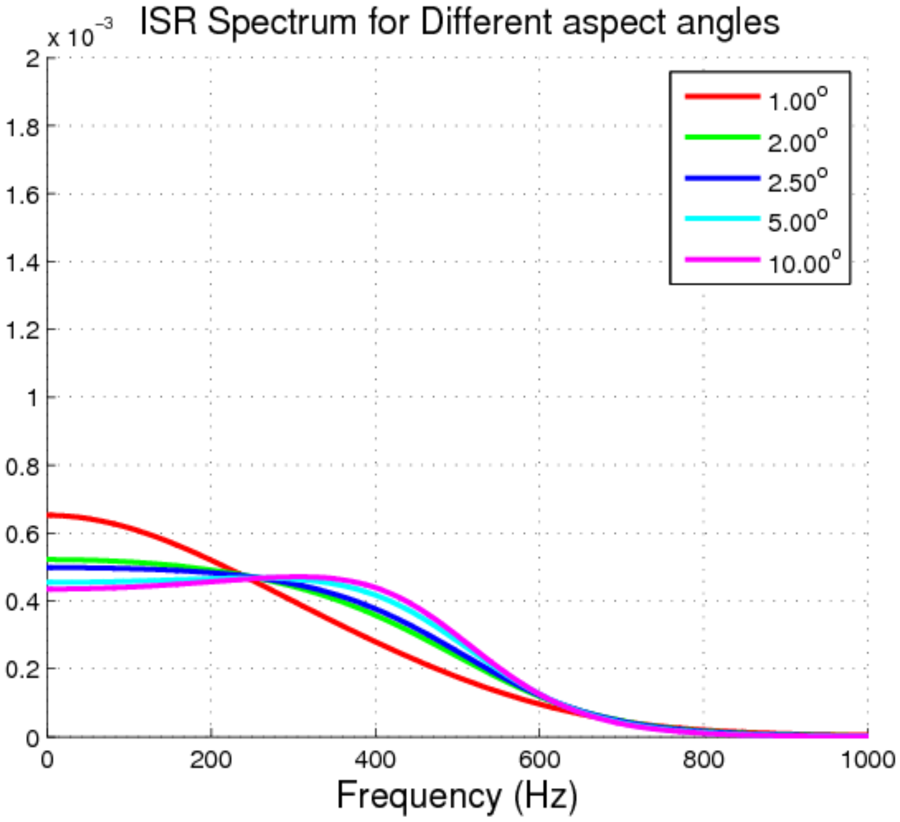
<u>Oblique</u>

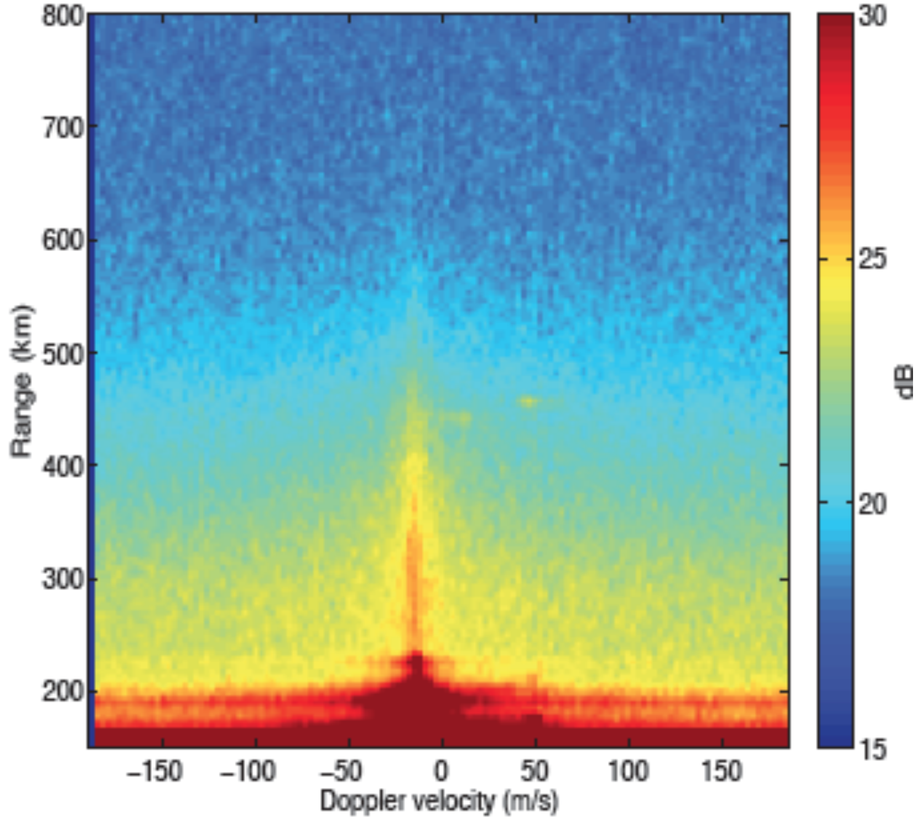
- ACFs are narrow
- 1 ms = 150 km (for monostatic measurements)
- ACFs are very similar to the non-collisional, unmagnetized case like those observed with EISCAT radars.
- ACFs are dominated by the dynamics of the ions
- Within the pulse (or IPP) estimation is needed to avoid range ambiguity
- Critical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

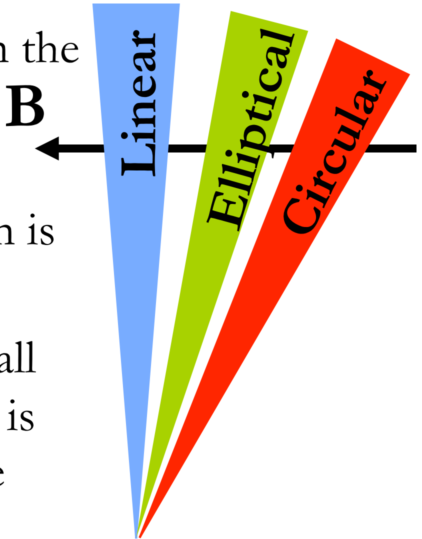
- Spectra are wide (>1000 m/s or 300 Hz at 50 MHz) and independent of α within typical antenna beam widths.

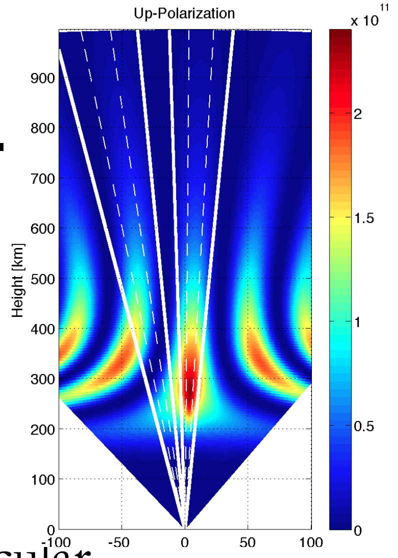
Perpendicular

- 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.

Oblique vs. Perpendicular: Faraday Rotation

- Faraday “rotation” arises from the difference between the indexes of refraction corresponding to the two characteristic modes of a magnetoionic medium.
- Phase difference between these modes of propagation is proportional to the integrated electron density.
- Given Jicamarca’s 50 MHz frequency (the lowest of all ISRs), significant “rotation” from ionospheric signals is observed and from this absolute electron densities are obtained.





Oblique

- Quasi-longitudinal approximation is valid for $\alpha > 0.4^{o}$.
- Two-circular polarizations are transmitted and received.
- Small “cross-talk” due to elliptical modes need to be corrected for $\alpha < 2.0^{o}$ We do this correction by flipping every other pulse.

$$N_e(h) = K_f d\phi/dh$$

[from *Farley*, 1969]

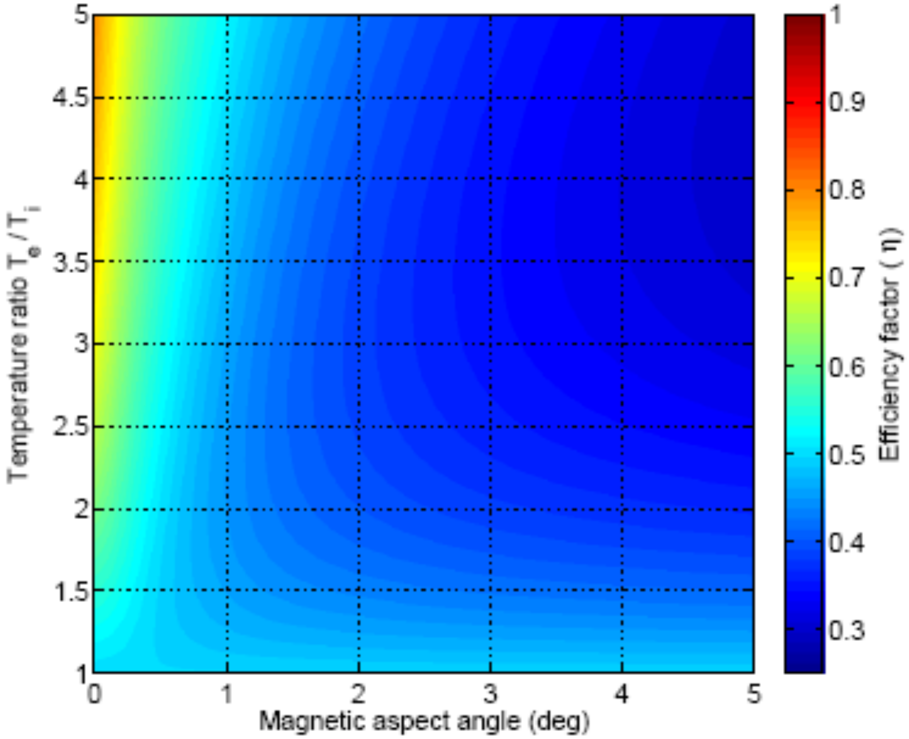
Perpendicular

- Quasi-transverse approximation.
- A linear polarization is transmitted to excite both quasi-transverse modes (parallel and transverse to B).
- On reception two linear polarizations are received.
- Each linear polarization is a convolution of linear and highly elliptical modes due to the finite beam width.

[from *Kudeki et al.*, 2003]

Oblique vs. Perpendicular: Power measurements

- Electron density measurements can also be obtained from absolute ISR power measurements.
- However, the absolute ISR power is also highly dependent on the pointing angle with respect to **B**. In addition, it is dependent on electron to ion temperature ratio (Te/Ti).

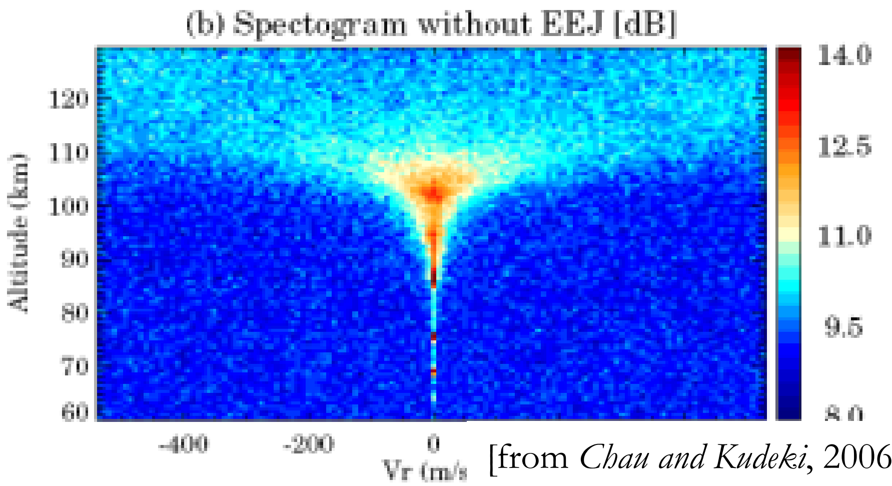


(a) [from *Milla and Kudeki*, 2006]

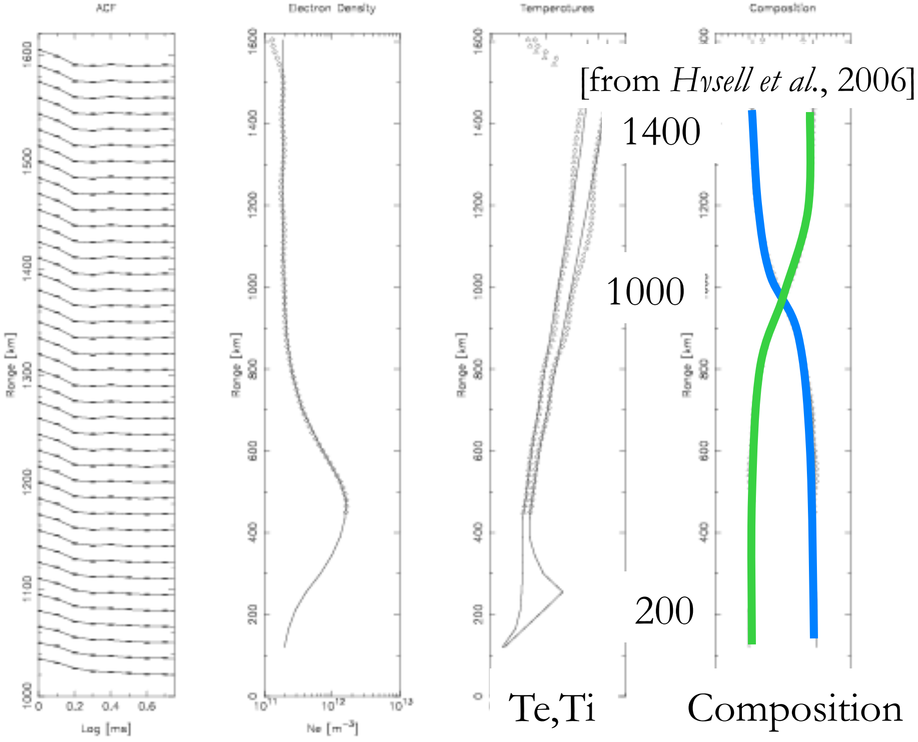
$$P_s(h) = K_s N_e(h) \sigma_{ne}(h) / h^2$$

Oblique vs. Perpendicular: Altitude issues

- Depending on the altitude of interest, collisions, temperatures and different ion composition, are the main parameters that changed the ISR spectrum shape. This is particularly true for Oblique measurements.
- Perpendicular spectra show very little, or none, dependence on these parameters.
- For example:
  - at *E* and *D* region altitudes, collisions with neutrals are important, the spectrum gets narrower as the altitude decreases.
  - At valley altitudes, in addition to typical [O^+], [NO^+] and [O_2^+] need to be considered [*Nicolls et al.*]
  - At topside altitudes, more ion species are present [O^+],[H^+] and [He^+].

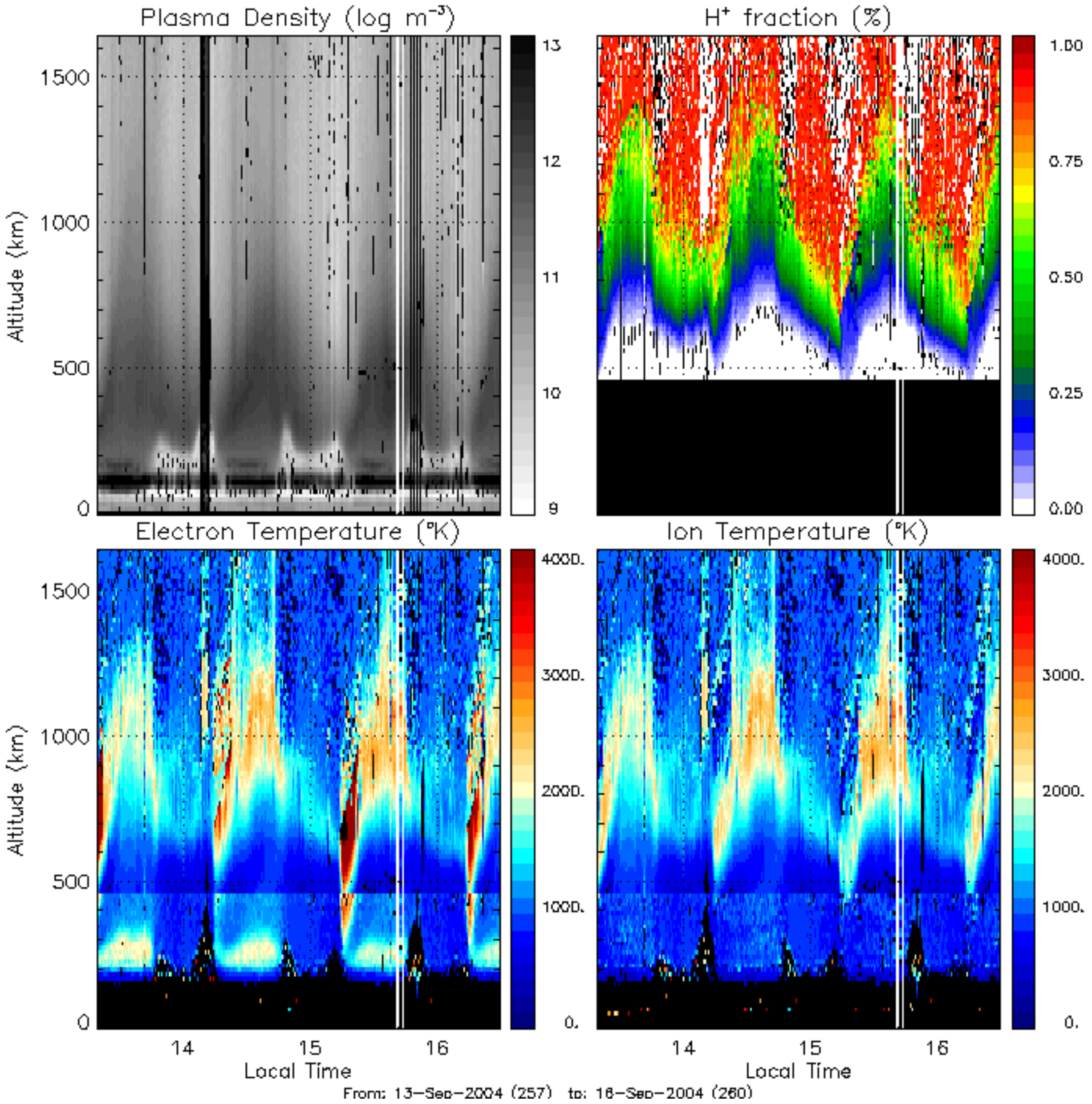


[from *Chau and Kudeki*, 2006]



[from *Hysell et al.*, 2006]

Oblique ISR Examples



•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.

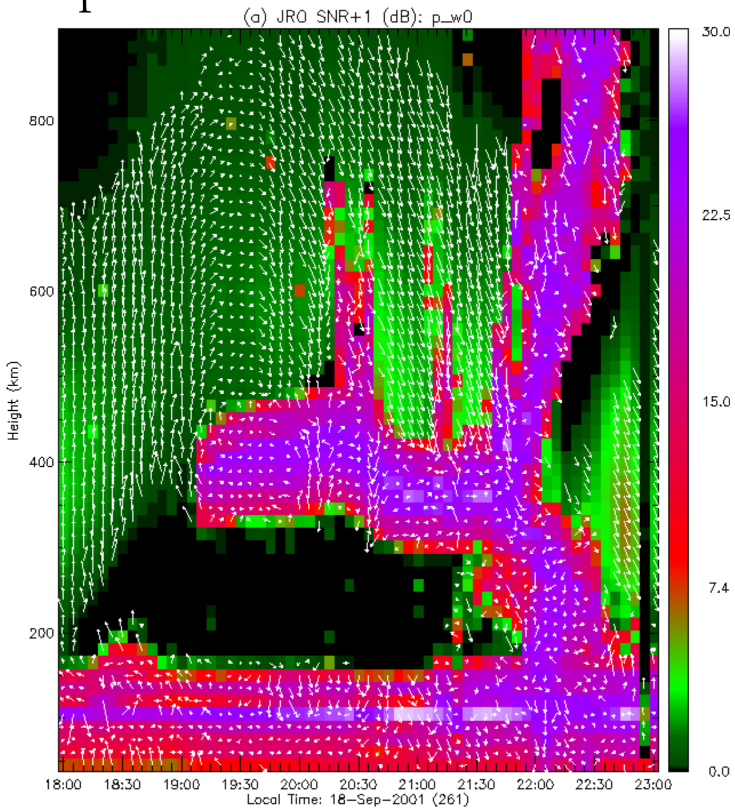
-Density, temperatures and composition above 500 km.

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

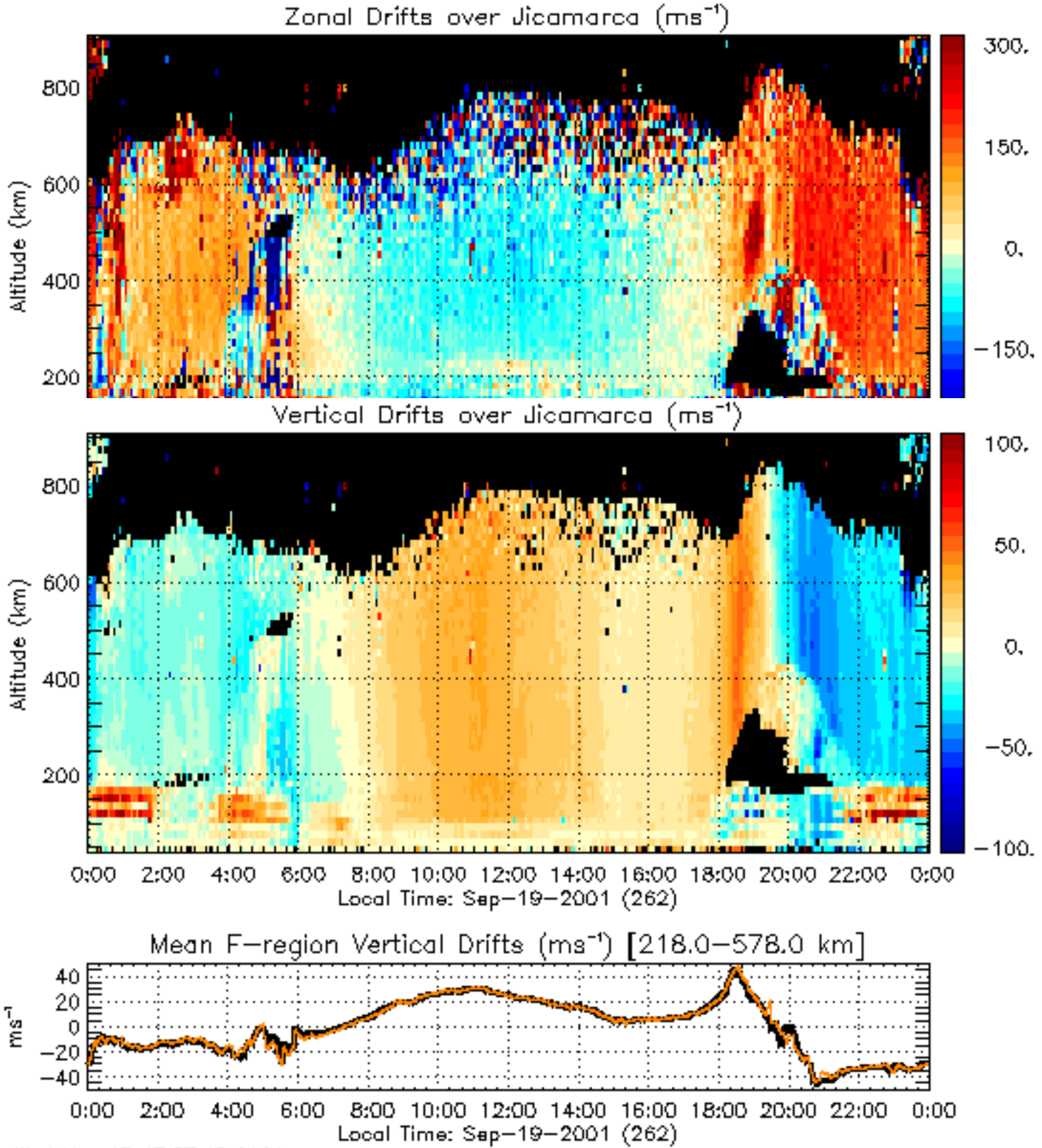
-Good for Topside work and sunrise observations.

Perpendicular ISR Examples

- •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]



JRO, Wed May 17 17:57:43 2006

3 beam mode: EW Drift +Faraday (3BF)

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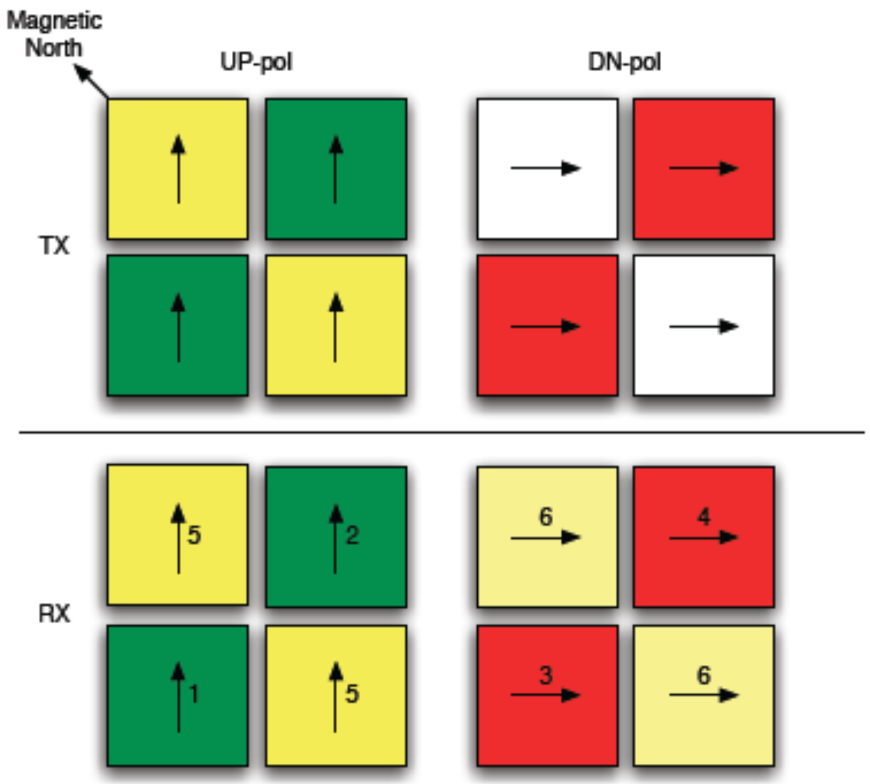

RX1 WU: West 1 (Quarter)
RX2 EU: West 2 (Quarter)
RX5 SU-NU: South (Co-Pol)

RX3 WD: East 1 (Quarter)
RX4 ED: East 2 (Quarter)
RX6 SD-ND: South (X-Pol)

- Three beam pointing directions:
  - West and East (perp-to-B)
  - South (off perp-to-B)
- Six antenna channels, two per each pointing direction.
- 1 polarization diversity (south)
- 2 spatial diversities (west and east)
- We can measure:
  - Vertical and zonal drifts
  - Electron densities
  - Electron and Ion temperatures

3BF Transmitting beams

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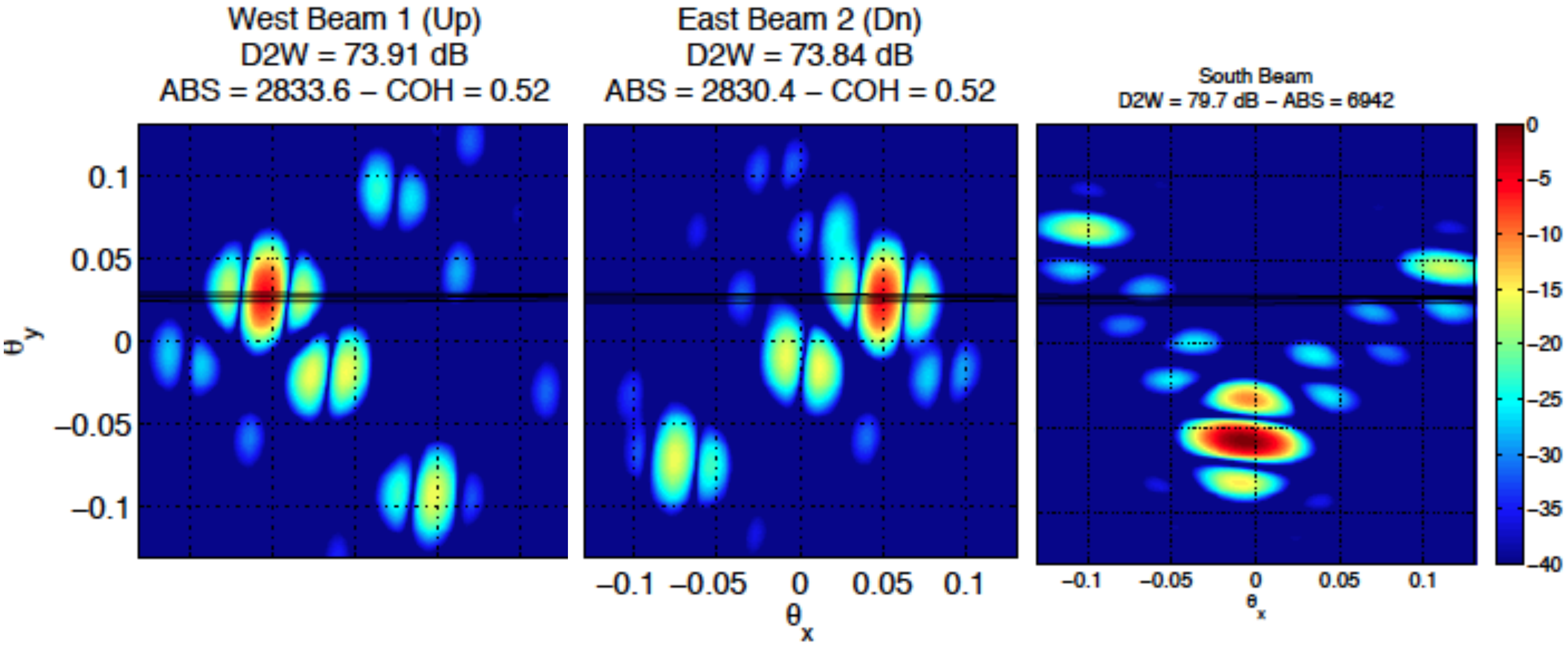
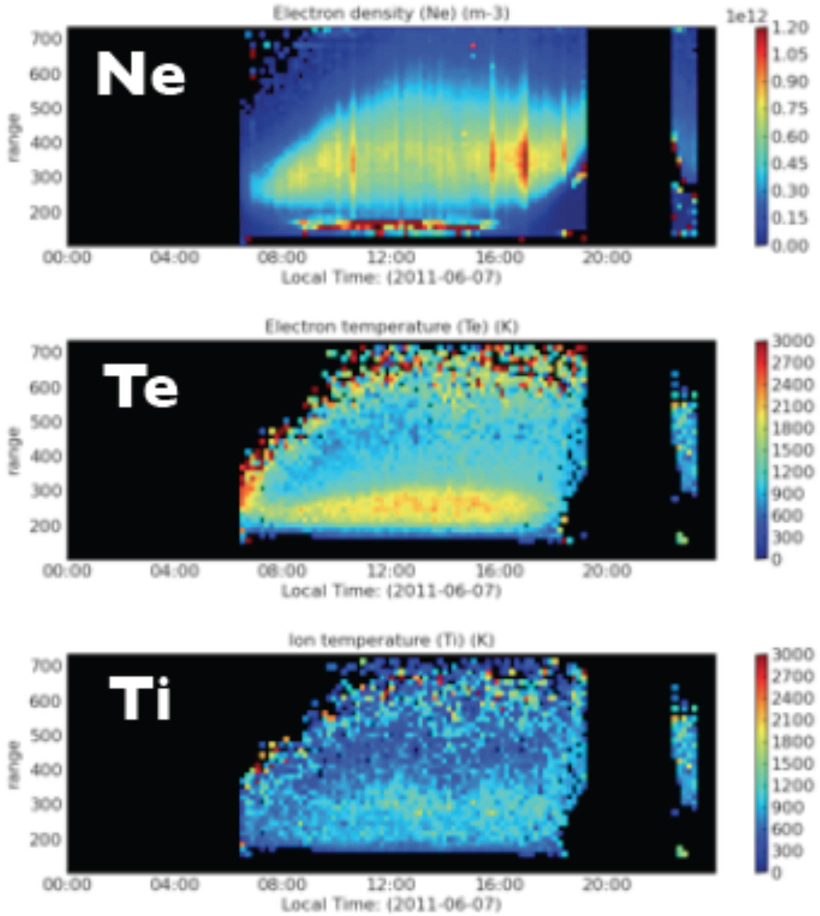
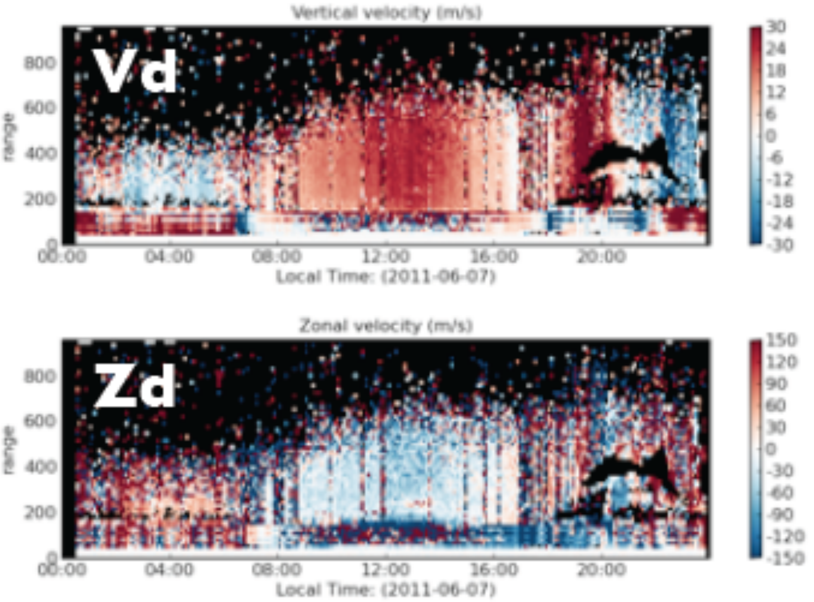


3BF examples: Vz, Vx, Ne, Te, Ti



Using the 3BF mode, we can measure simultaneously F-region densities, temperatures and drifts.



However, there is a price to pay.
We have lost some altitude coverage.

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

- 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

Jicamarca Themes (Unstable Ionosphere)

- **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?

Coherent echoes over Jicamarca (1)
RTIs above 100 km

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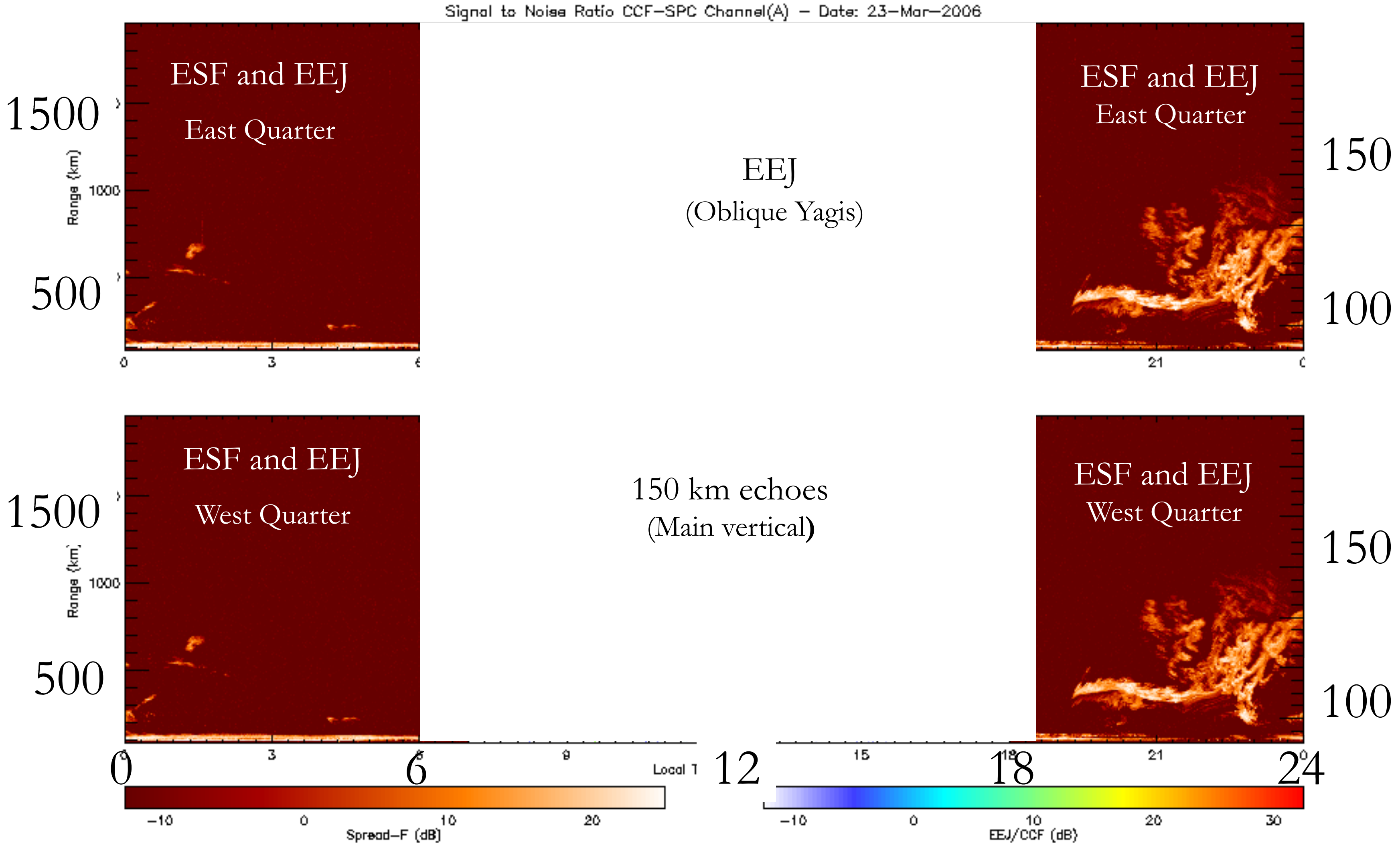


ESF and EEJ
East Quarter

EEJ
(Oblique Yagis)

ESF and EEJ
East Quarter

ESF and EEJ
West Quarter

150 km echoes
(Main vertical**)**

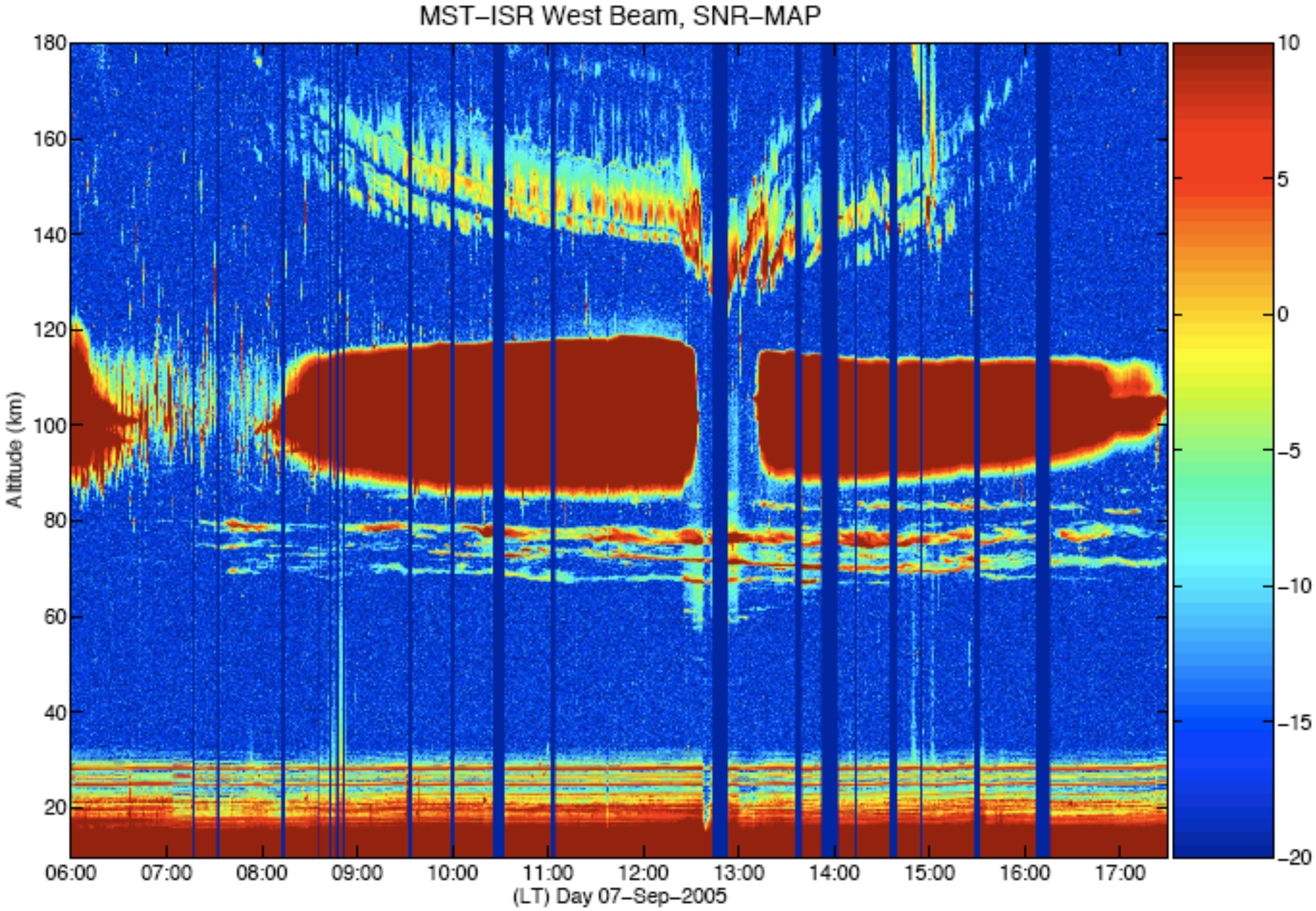
ESF and EEJ
West Quarter

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

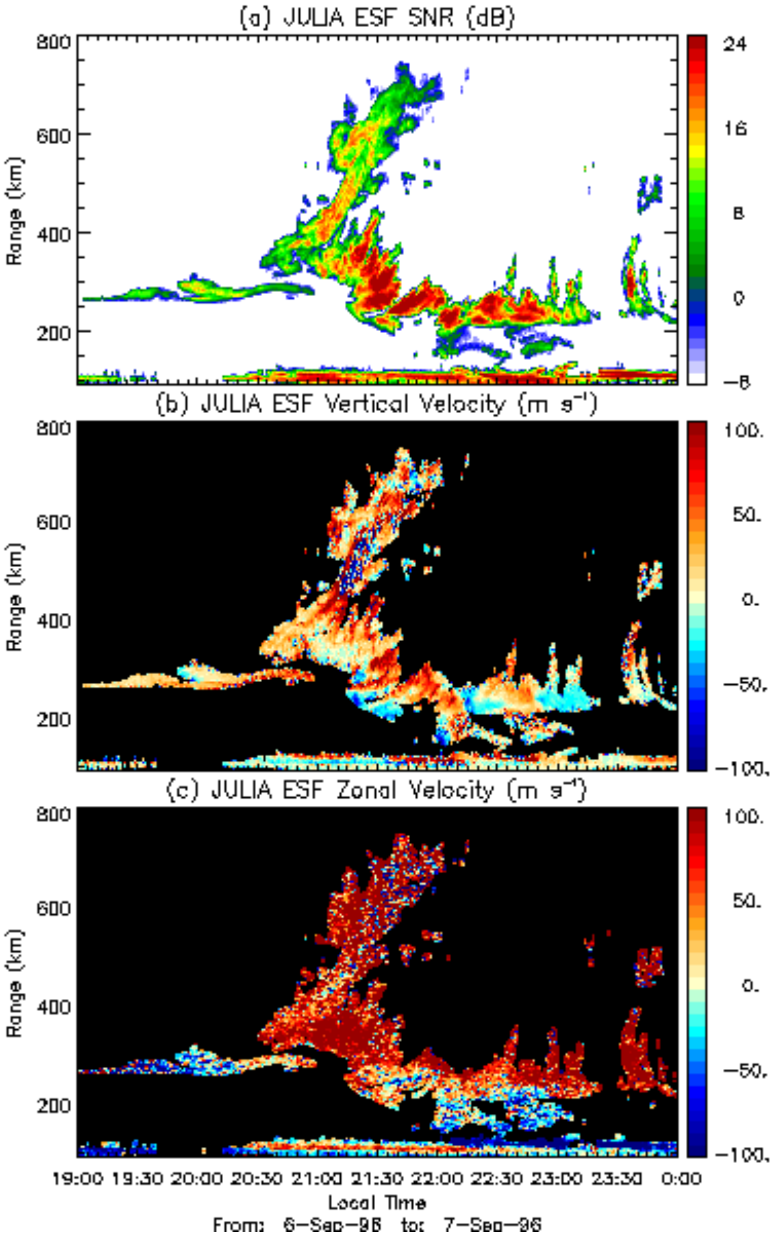
EEJ echoes
All Day
(Daytime stronger)

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

Mesospheric echoes
Daytime

Stratospheric and Tropospheric echoes
All Day

ESF: Type of echoes

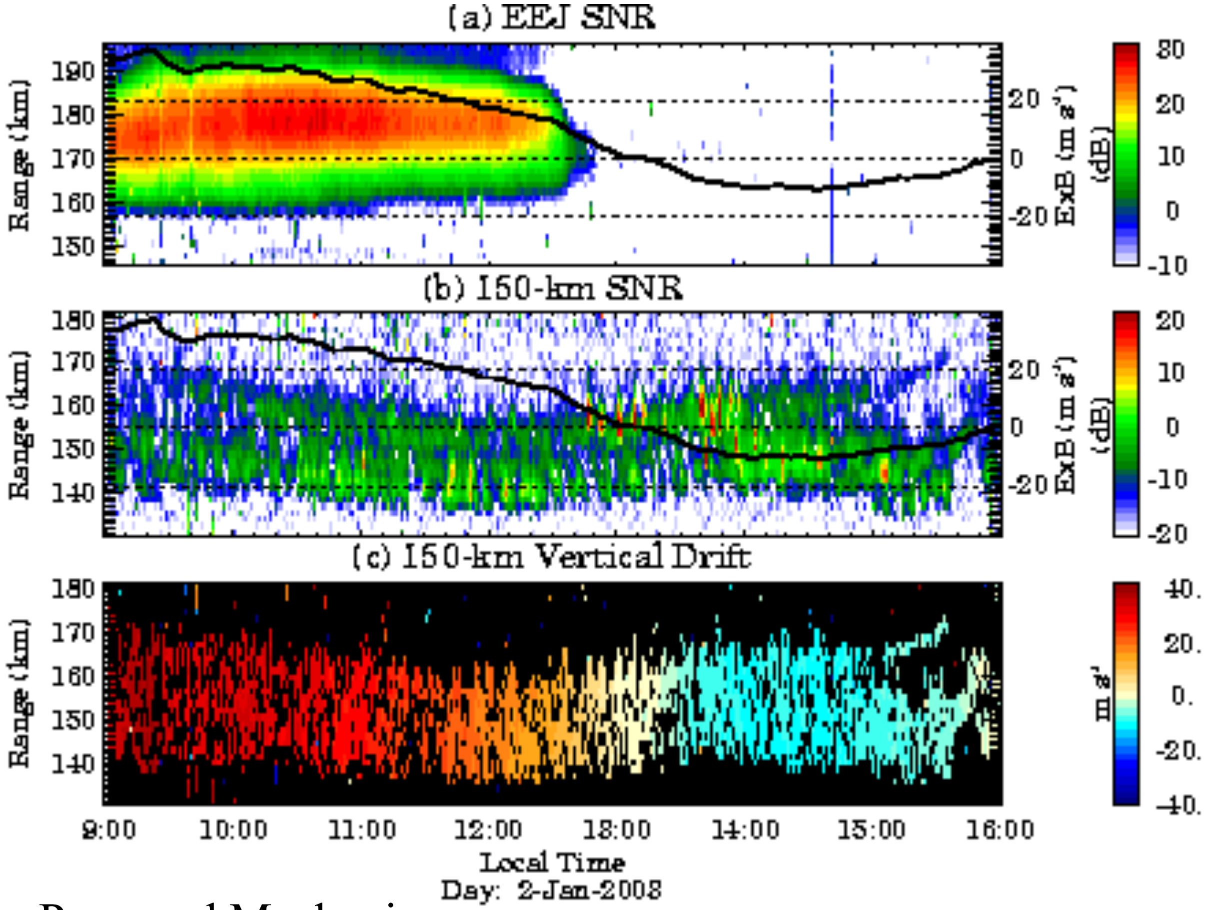


- Nighttime
- Main type (interchange or generalized Rayleigh-Taylor instabilities)
  - Bottomtype layers
    - Composed of kilometer scale waves
    - Drift westward
  - Bottomside
    - Drift eastward
    - Greater vertical displacement
  - Topside (Plumes)
    - Drift eastward and upward
    - A variety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

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

150-km Echoes: FAI and NEILS

Perpendicular to B main features



<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 from Mag. Equator
- At Jicamarca they are observed all seasons
- 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]

Equatorial Daytime Valley Region (1)

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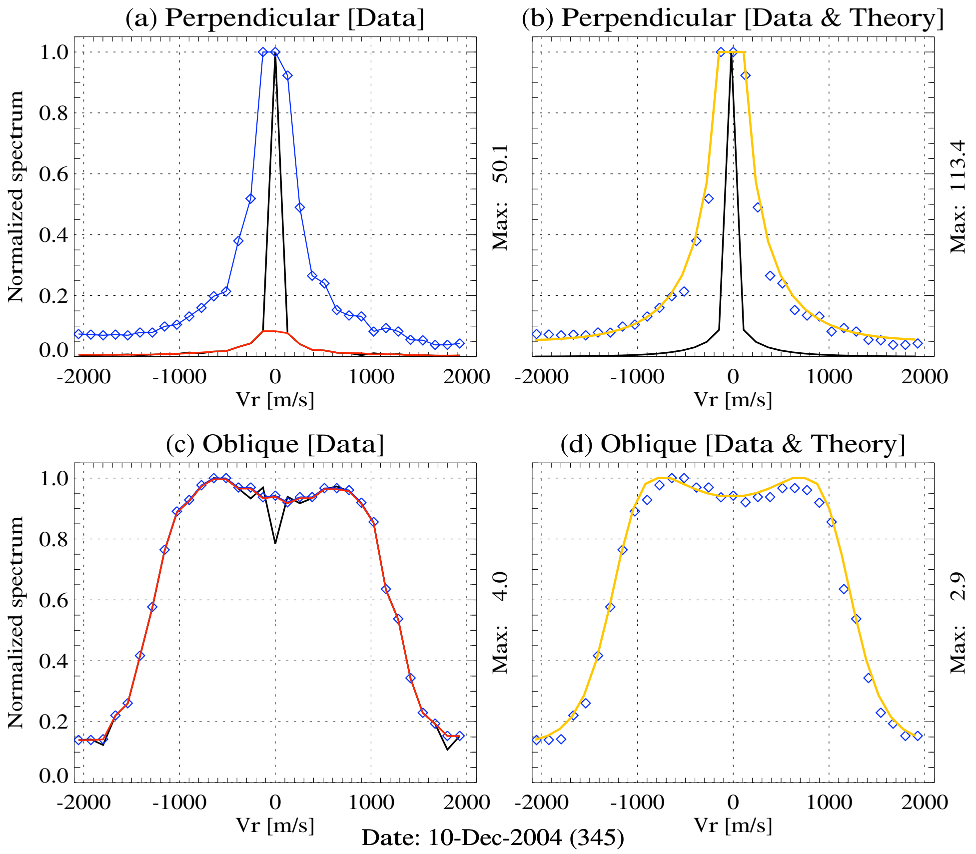
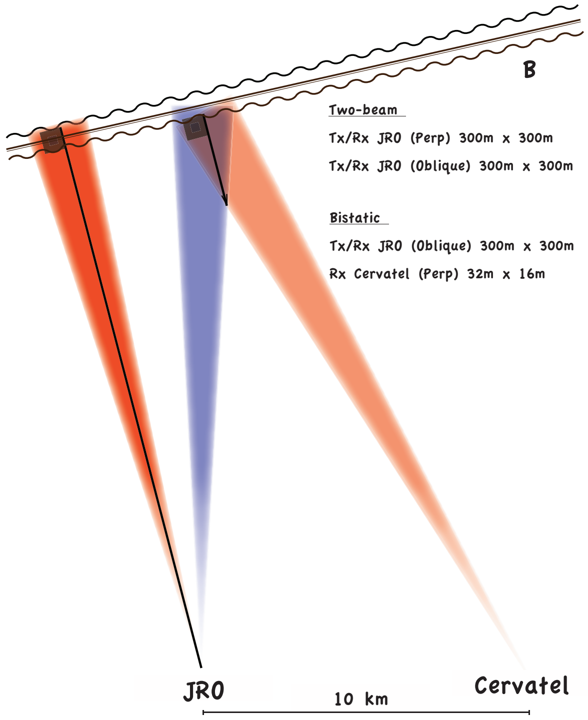
- In this region occurs the transition between the dominant molecular ions of lower altitudes and F-region dominant atomic oxygen ion.
- Collisions with neutrals start to be less important as the altitude increases.
- Magnetic field lines around 140–170 km are mapped to both the north and south E regions that are located outside the EEJ belt.
- Intermediate layers are known to occur at these altitudes but so far they have not been observed at equatorial regions during the day.
- Large electron to temperature ratios are expected and observed during the day.
- Maximum photoelectron production rate occurs around 150 km.
- Asymmetry in the Oblique spectra
- NS oscillations of scattering centers

150-km NEILS and 150-km EW Structure





Naturally enhanced ion-line spectra around the equatorial 150-km region

J. L. Chau[1], **R. F. Woodman**[1], **M. A. Milla**[2], **and E. Kudeki**[2]

[1]Radio Observatorio de Jicamarca, Instituto Geofísico del Perú, Lima
[2]Electrical and Computer Engineering, University of Illinois at Urbana-Champaing, IL, USA

Perpendicular Spectrograms

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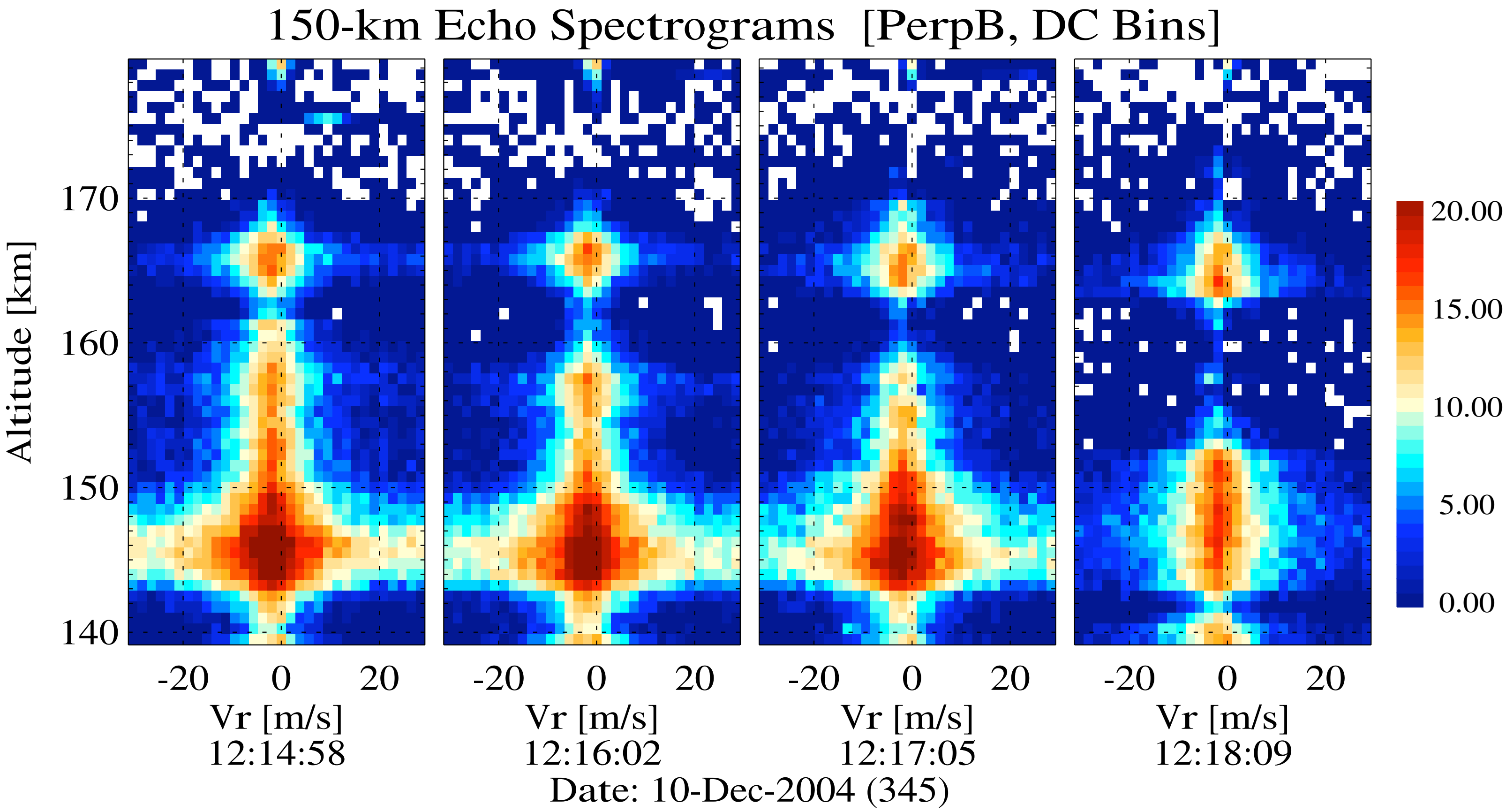
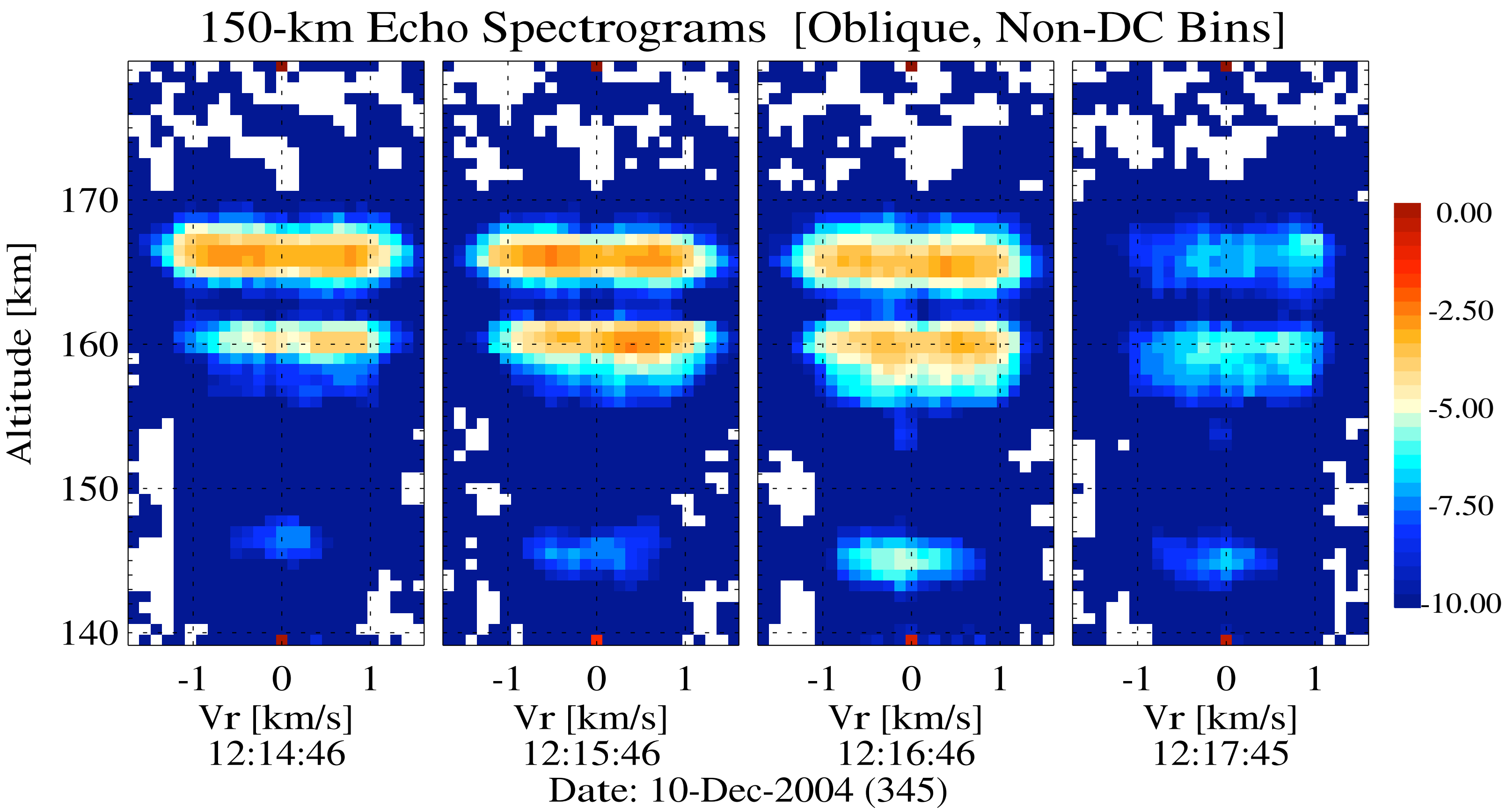
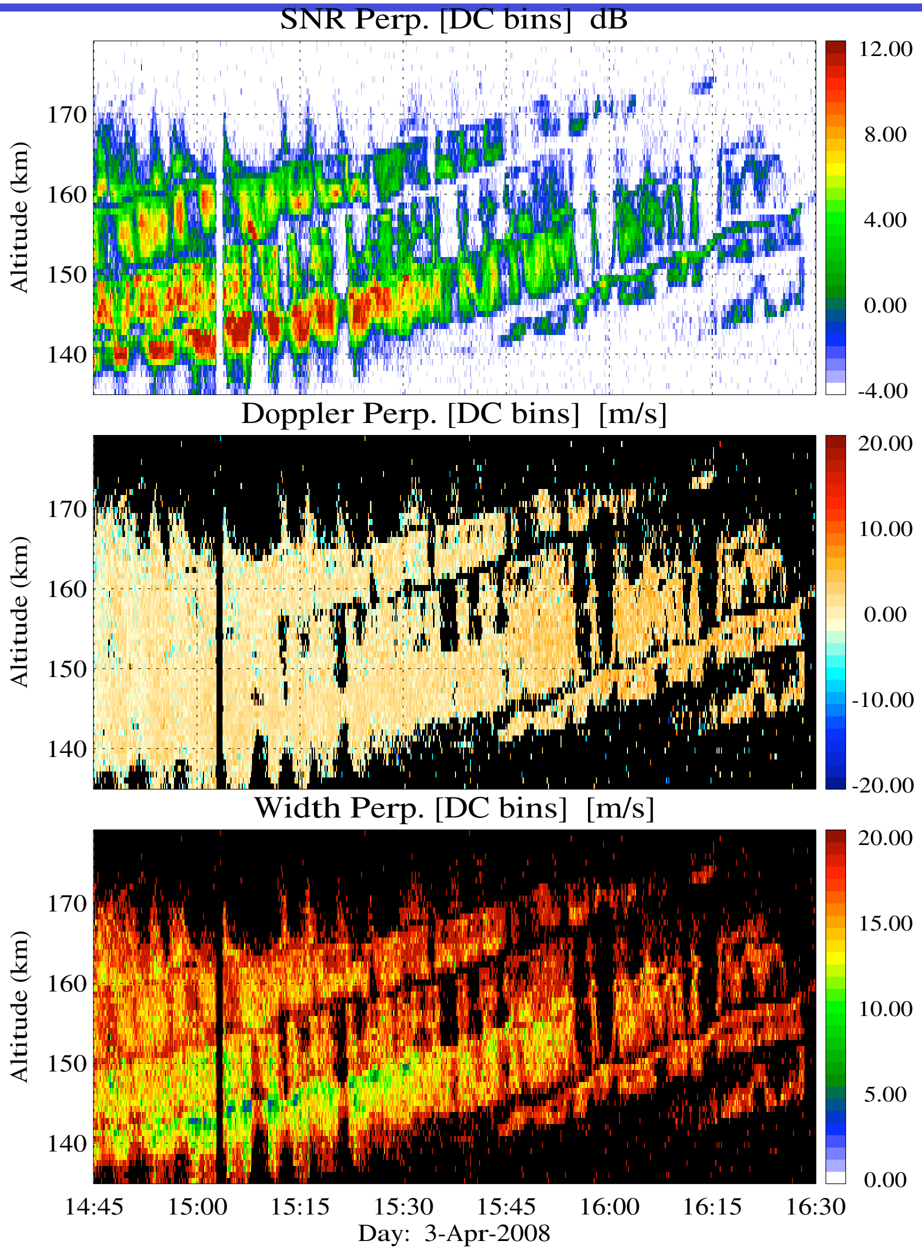


Oblique spectrogram



150-km Perpendicular Parameters



150-km Oblique Parameters

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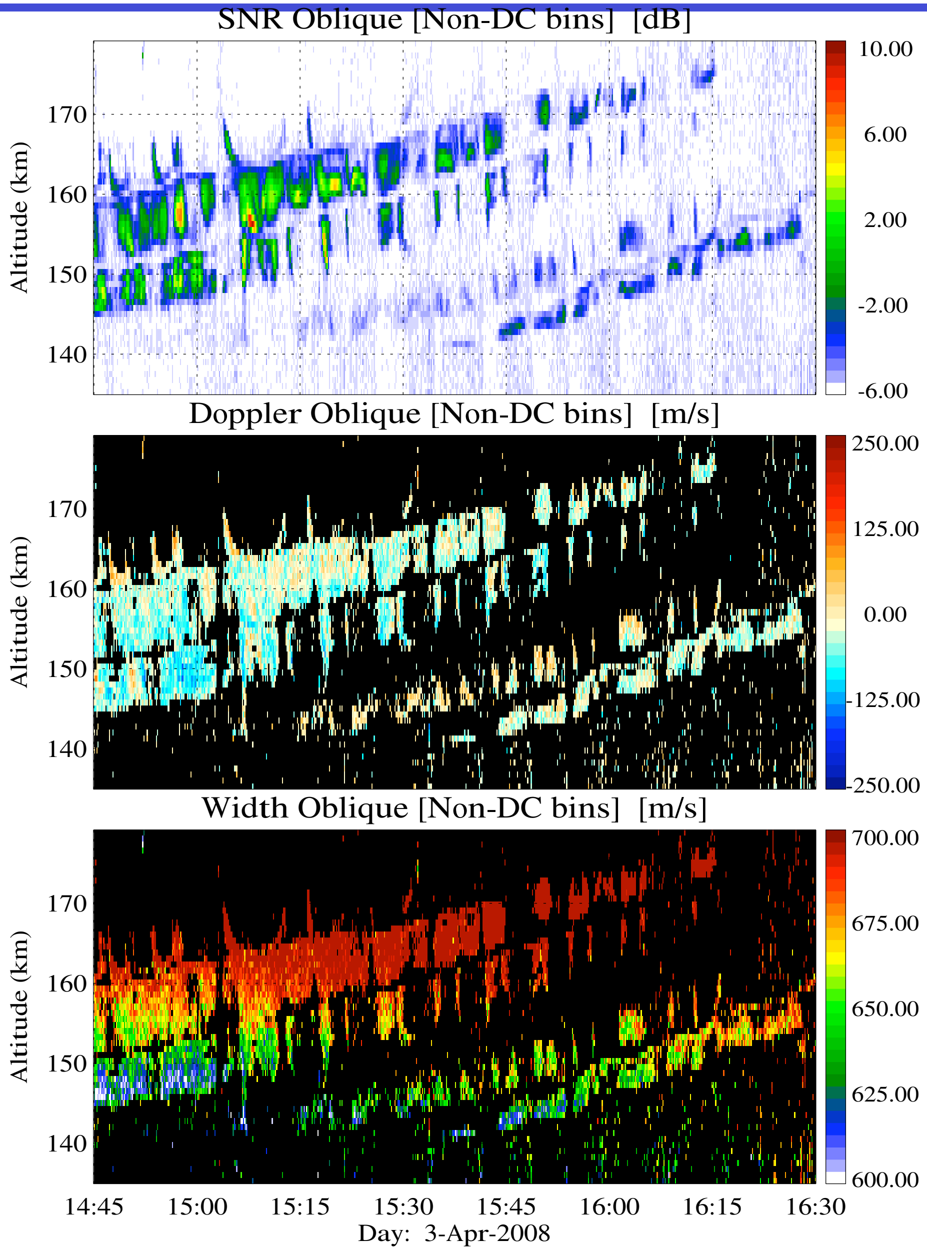

Solar flare 07-Sep-2005

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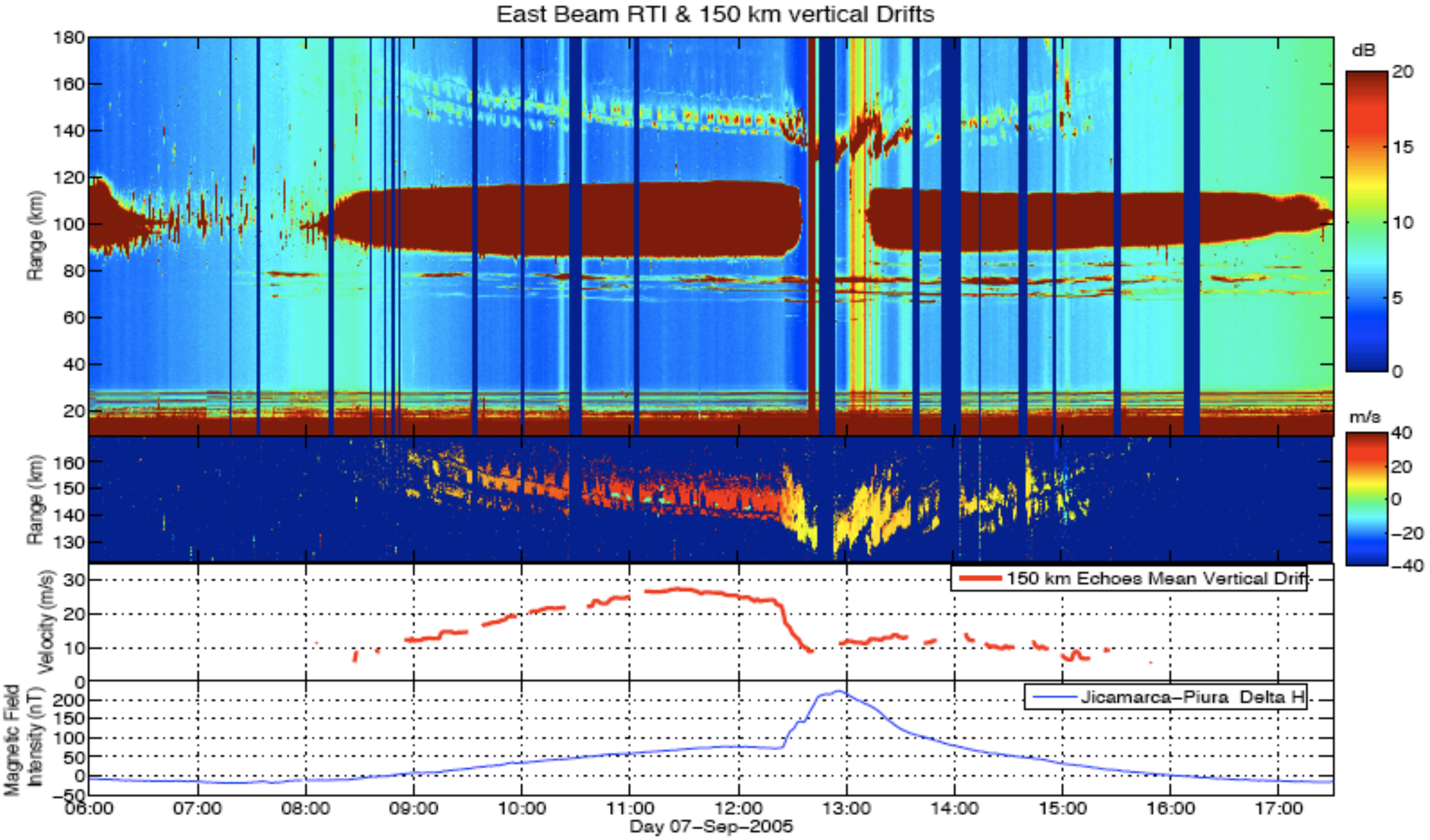

Spectrum and NS Structure: Off-Perp.

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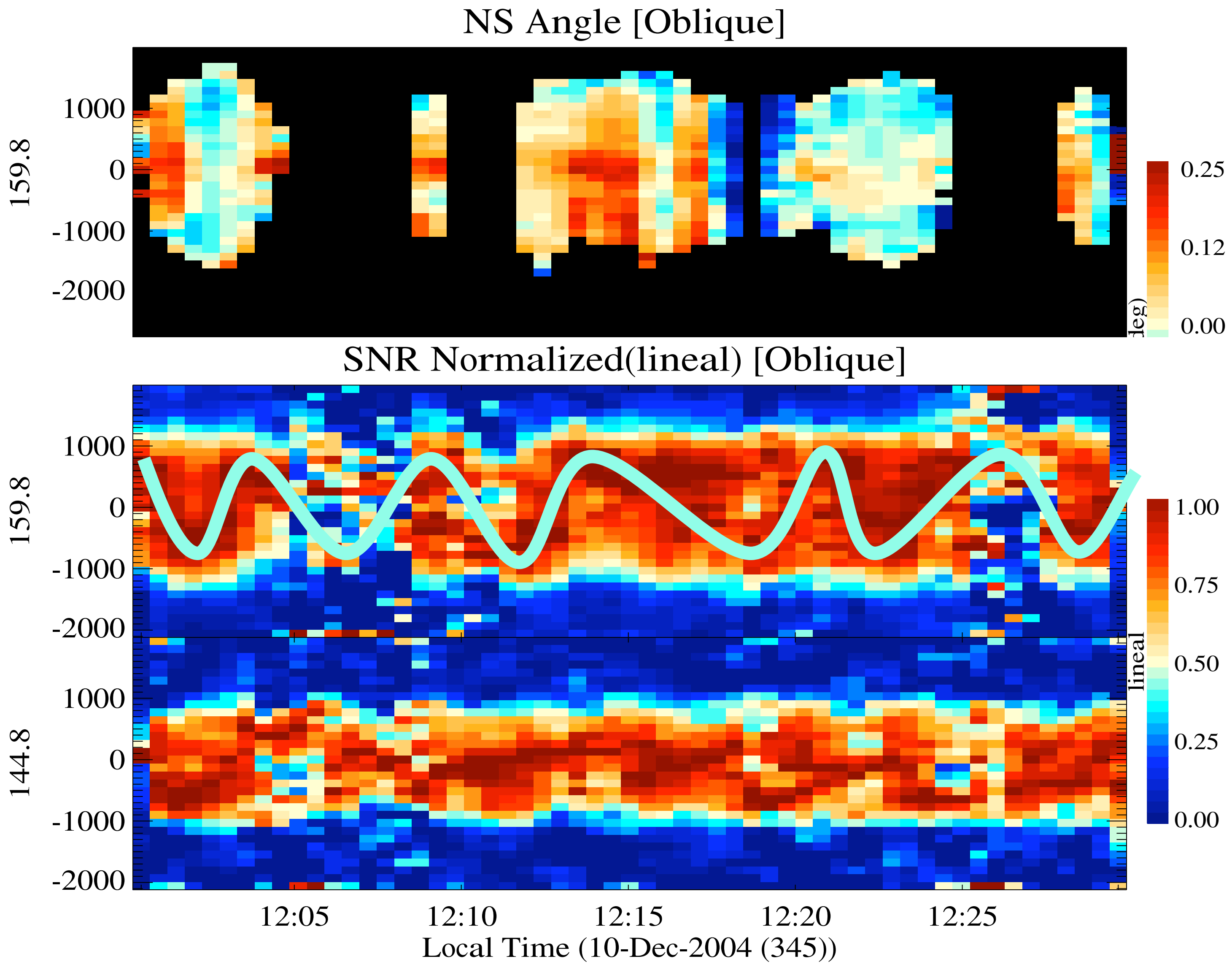
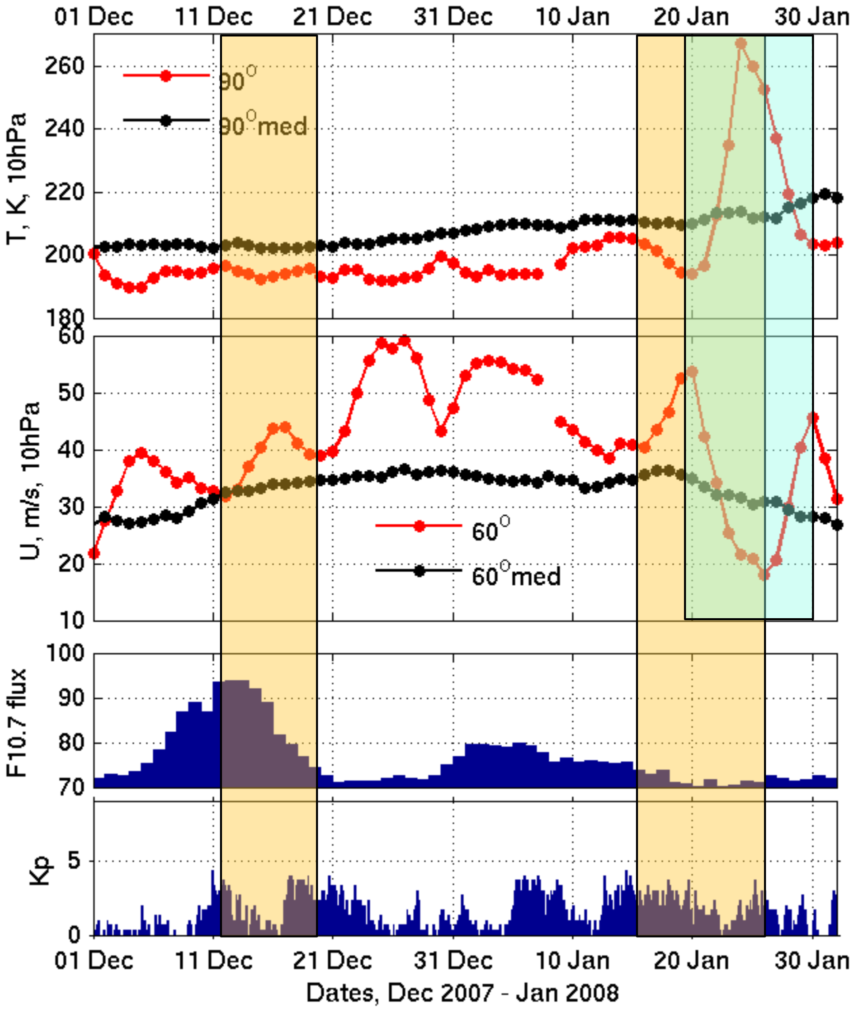


- Above 150 km: Spectra is wider and with an oscillating peak with a period ~5-10 min.
- Below 150 km: Spectra is narrower, peak is not well defined.
- Spectra structure appear to be associated to changes in location of the scattering center.

Sudden Stratospheric Warming and the Equatorial Ionosphere

SSW Jan 2008: SSW Main parameters

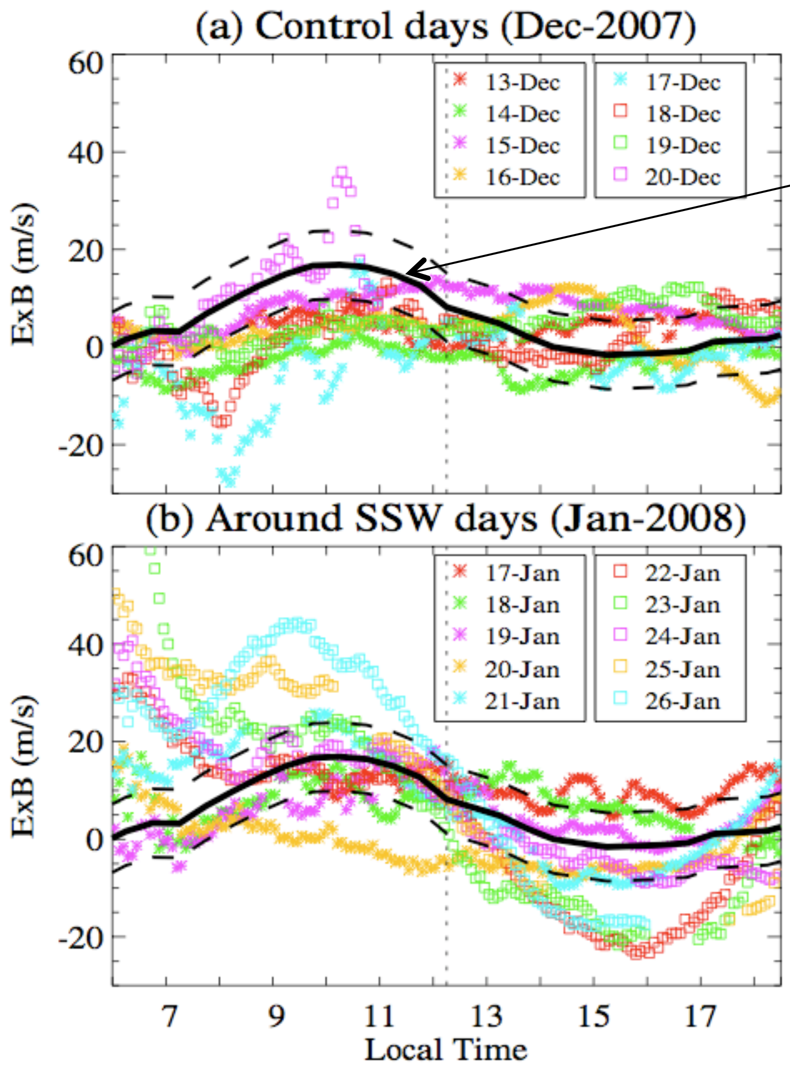


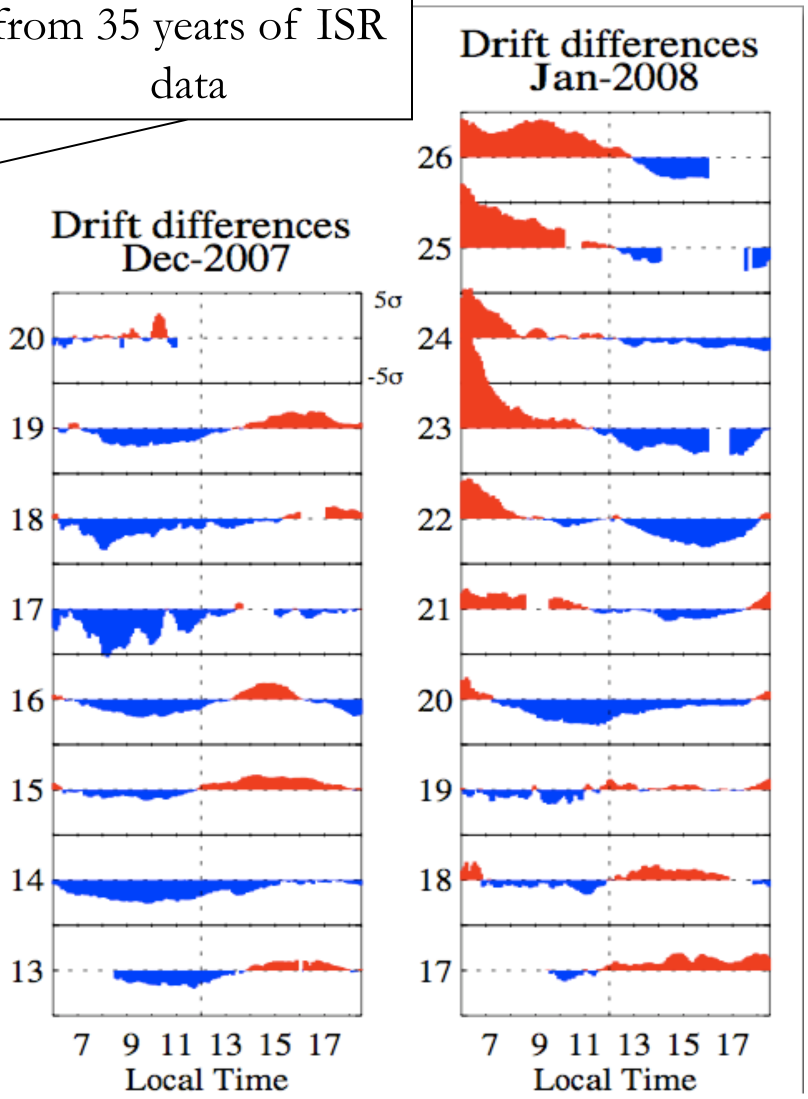
- Minor SSW event. Westerly winds slowed down
- One of the largest temperature increases in the last 30 years.
- Low solar flux (close to 70)
- Magnetically quiet conditions
- Many ground-based instruments operated 8-10 days in December 2007 and 10-14 days in January 2008.

[from *Chau et al.* 2009]

SSW Jan 2008: ExB Daytime Drifts

Average + variability from 35 years of ISR data





[from *Chau et al.* 2009]

SSW Jan 2008: Δ SSW vs Δ ExB

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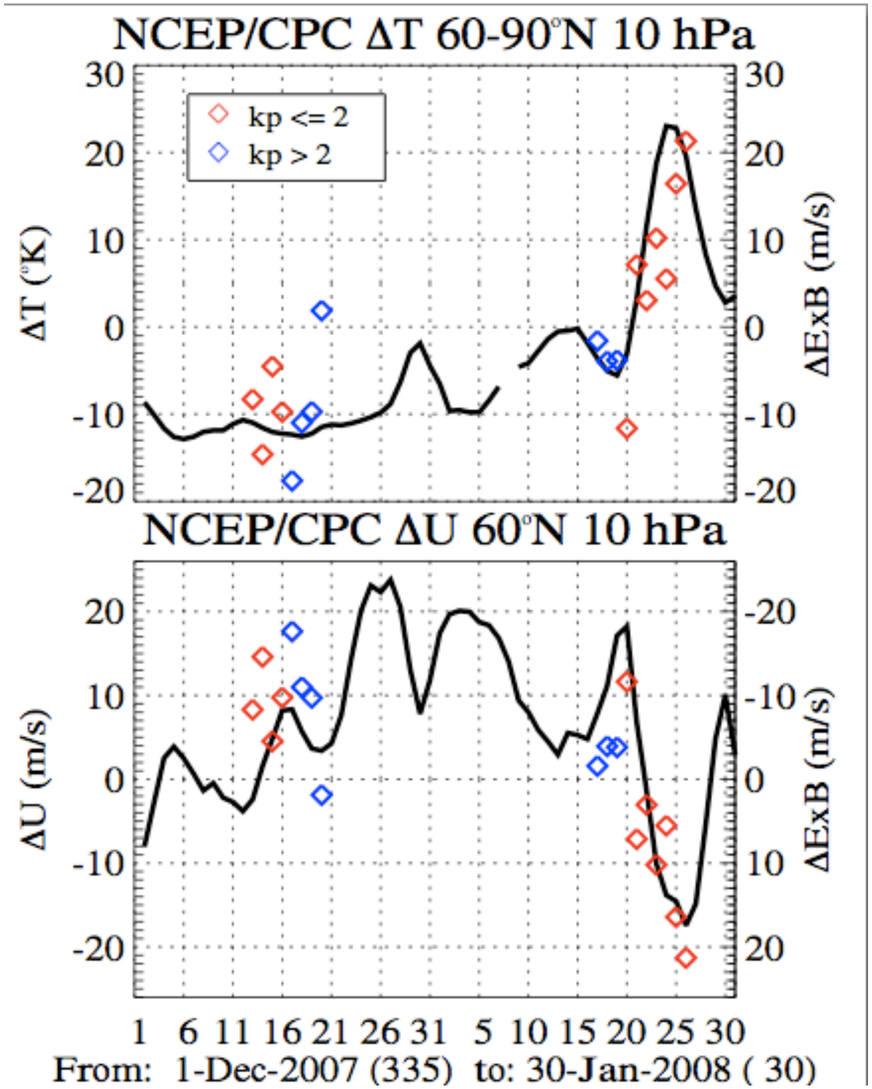


- Δ ExB: average morning ExB difference with respect to expected averages, after fitting a semidiurnal wave.
- Δ SSW: differences with respect to 30-year median values.
- High correlation/anticorrelation: Δ ExB vs. Δ T/ Δ U during SSW.
- Note the "persistence" of the ExB drift pattern during SSW period.

[from *Chau et al.* 2009]

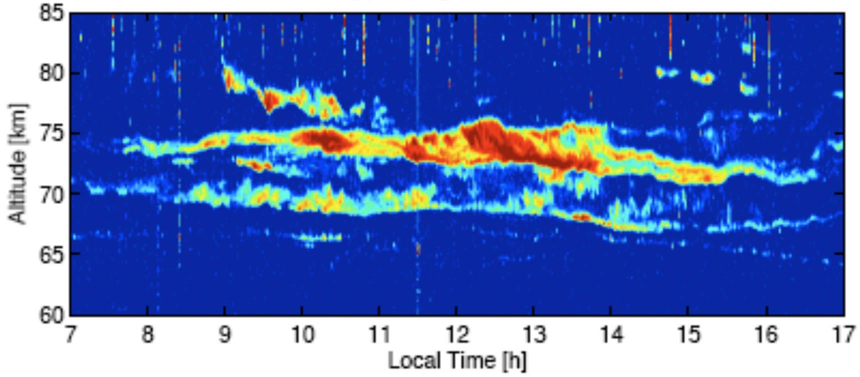
Perennial Equatorial Mesospheric Echoes (PEME)

PEME: Main Characteristics

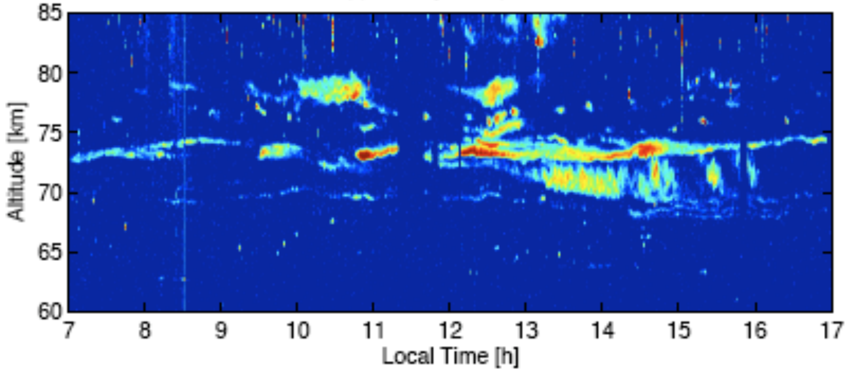
- Daytime occurrence, between 60-85 km, with preferred occurrence around 70-75 km.
- Mesospheric dynamics and turbulence are obtained from these echoes.
- RCS much weaker than PMSE and PMWE
- Rich temporal and altitudinal structure obtained from 3-m irregularities.
- Dependence on solar flux and X flares, indicate that high electron densities and strong density gradients enhance the strength of the echoes.

PEME: Fine structure

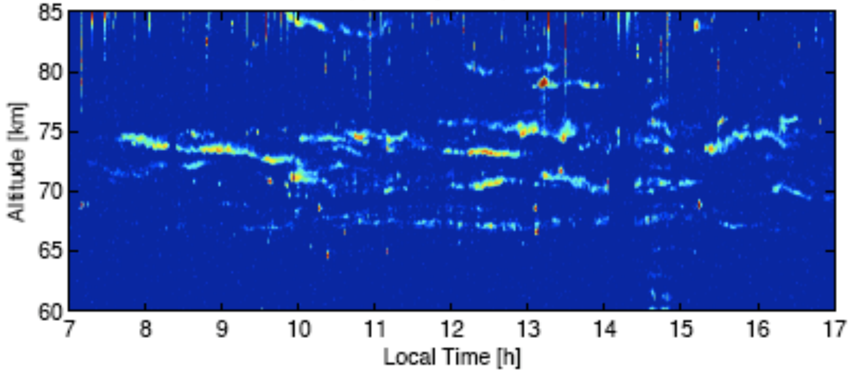
SNR Map, 27 May 2003, South Beam



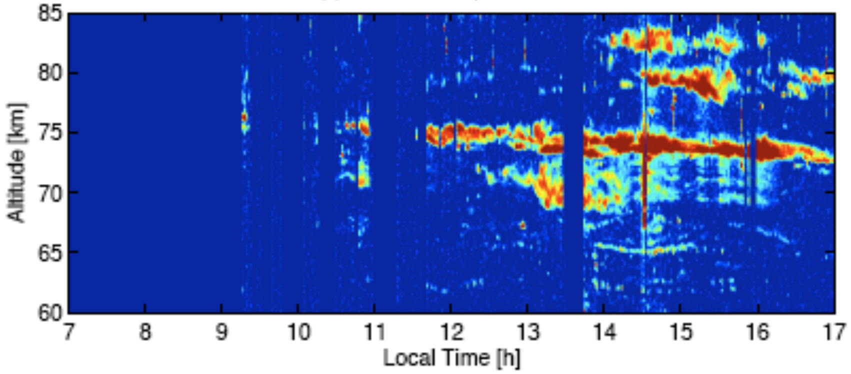
SNR Map, 28 May 2003, South Beam



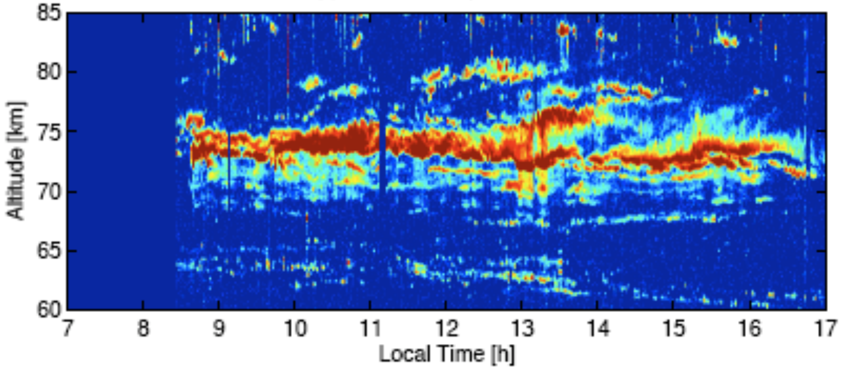
SNR Map, 29 May 2003, South Beam



SNR Map, 13–Jul–2004, Off–vertical Beam



SNR Map, 14–Jul–2004, Off–vertical Beam



[from *Sheth et al.* 2006]

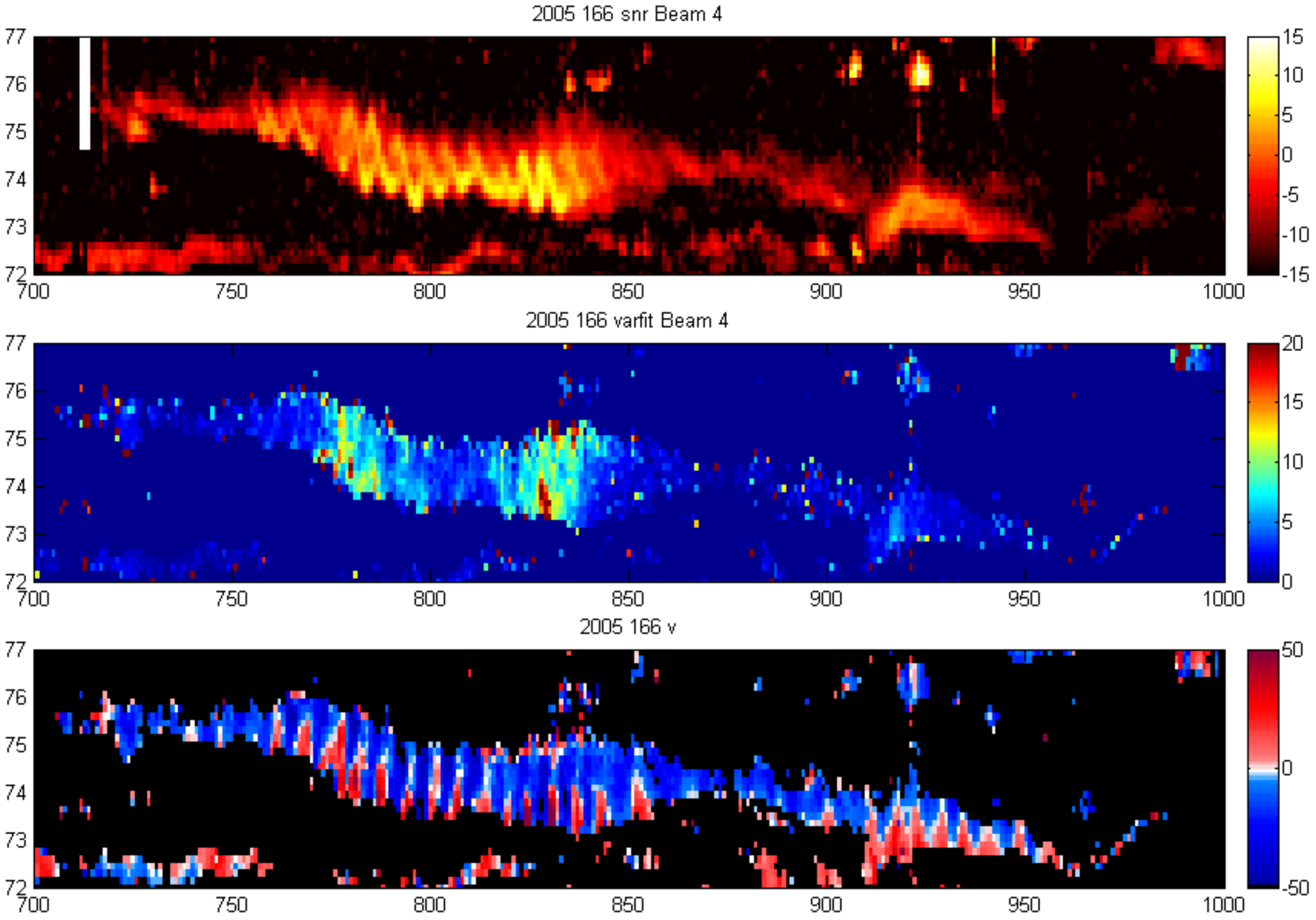
PEME: KHI (1)

[from *Lehmacher et al.* 2007]

SNR (dB) vs. altitude(km), time (min)

Spectral Width, Variance (m^2/s^2)

Meridional wind (m/s)



High resolution mesospheric echoes show evidence for KHI, braided structures with enhanced edges (top); turbulent fluctuations are intermittent (middle); layers are often strongly sheared (bottom). Observations: 8x3 days in 2005 and 2006.

PEME: KHI (2)

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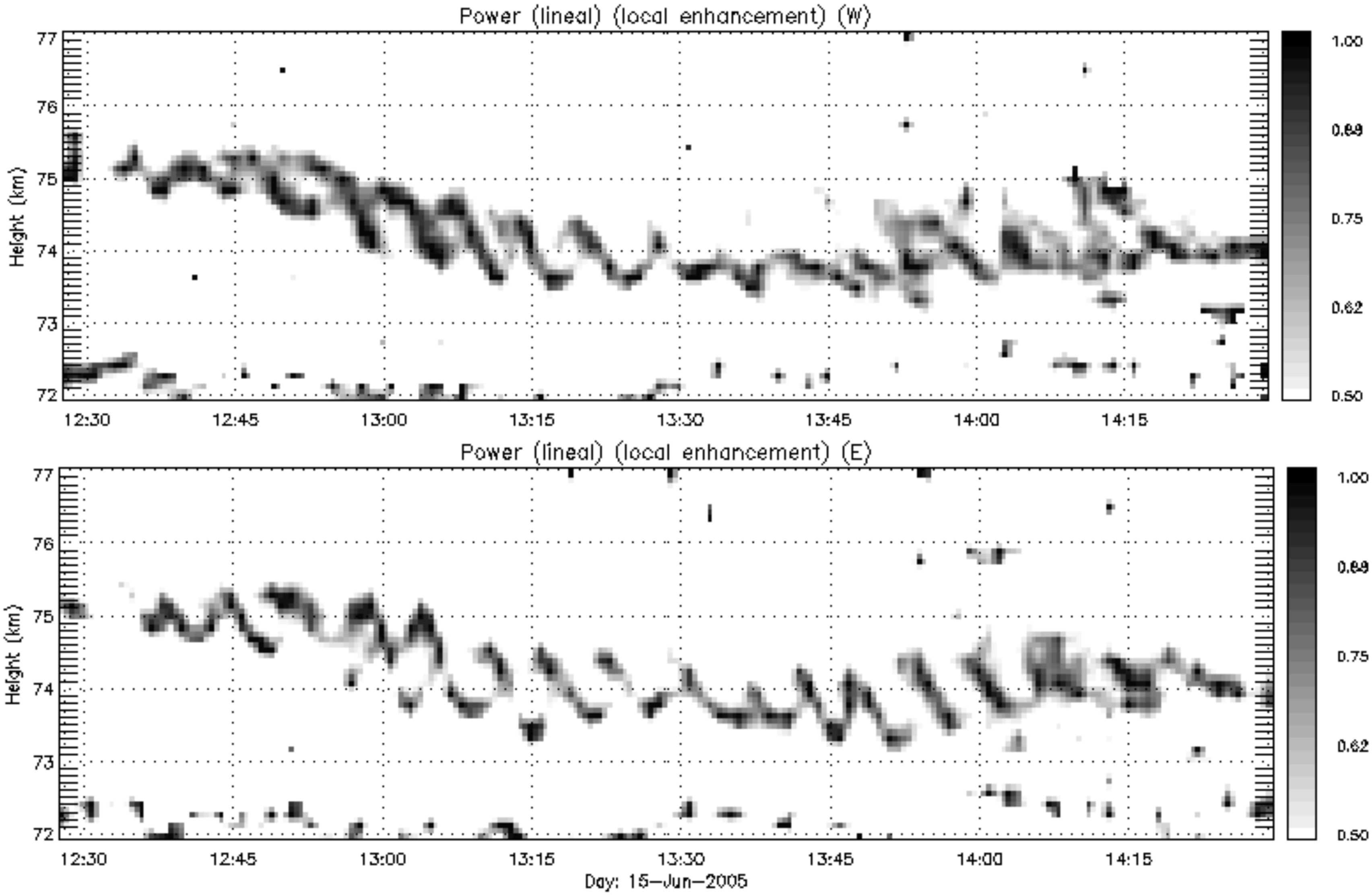


PEME: Turbulence

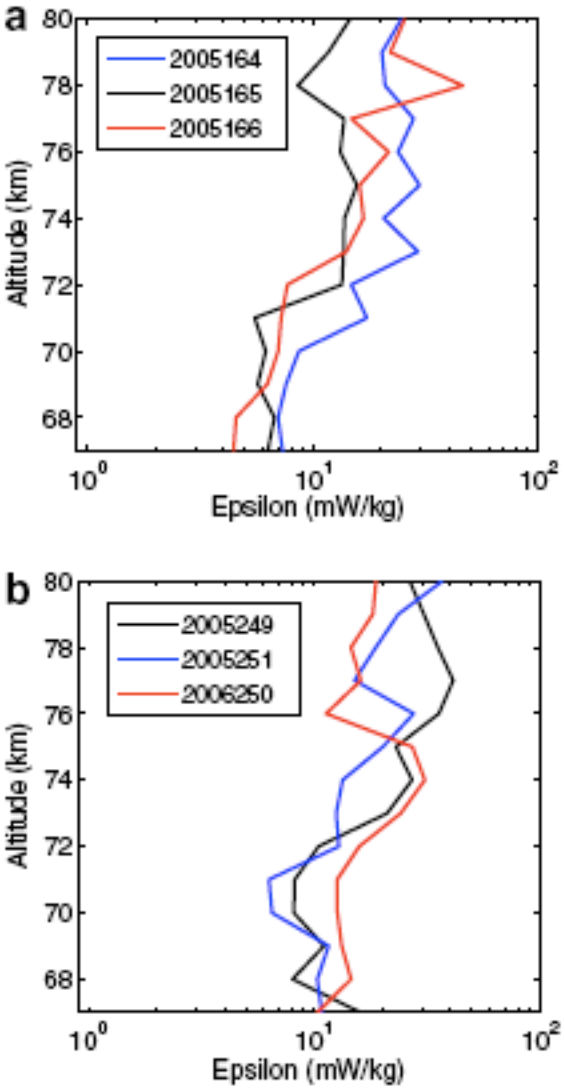
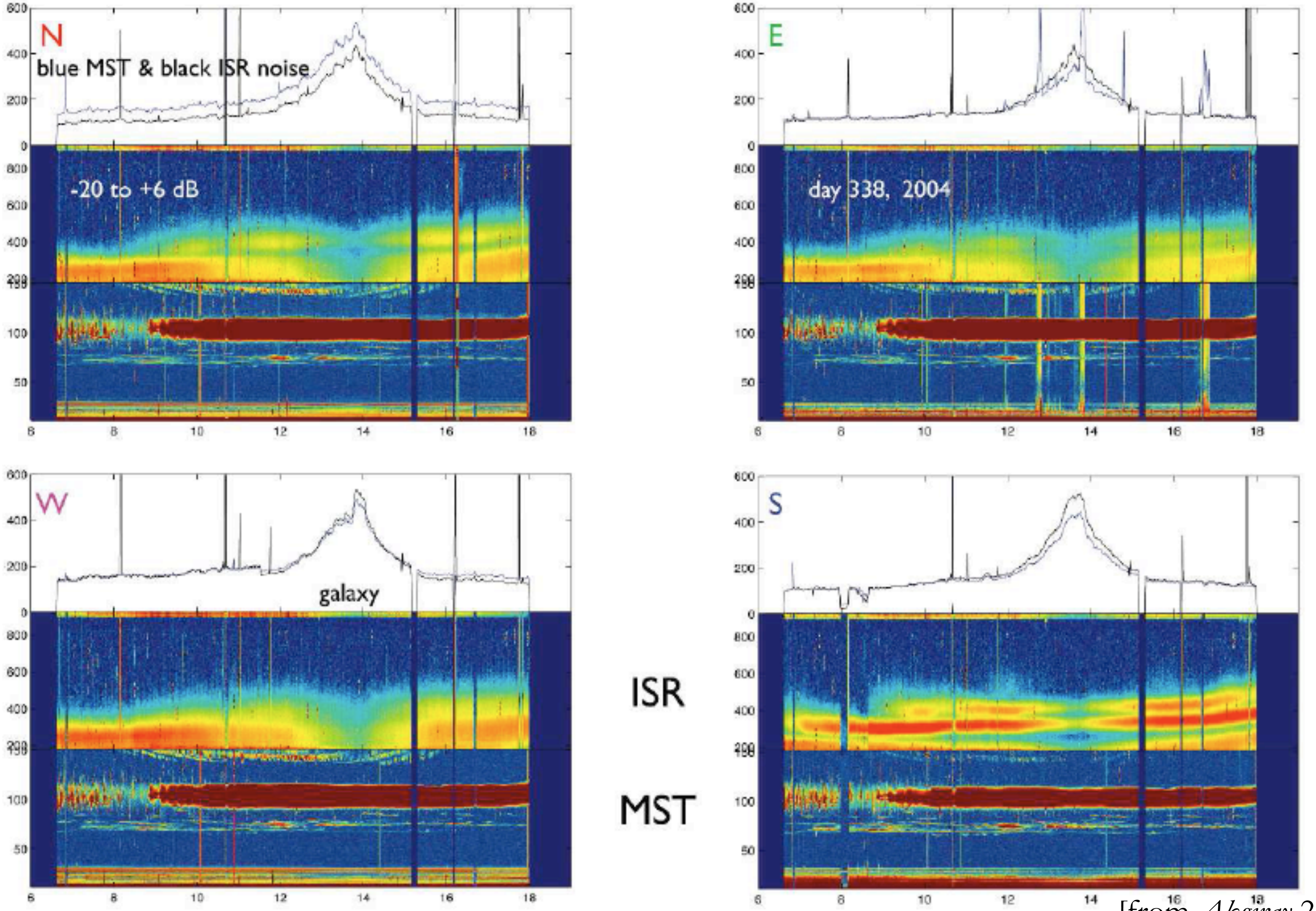


Fig. 5. Energy dissipation rates ε medians. (a) Energy dissipation rates ε daily medians for June 2005. (b) Energy dissipation rates ε daily medians for September 2005 and 2006.

- ε from spectral widths. A small beam broadening effect has been removed from the observed spectral widths.
- The daily median energy dissipation rates ε increase from 5 to 30 mW/kg between 67 and 80 km, and the eddy diffusivities increase from 3 to 20 m2/s result at Japan and India.
- The energy dissipation rates are about the same magnitude as the ε estimates for low-latitudes from a global model and are larger than the averages from rocket observations at high-latitudes.

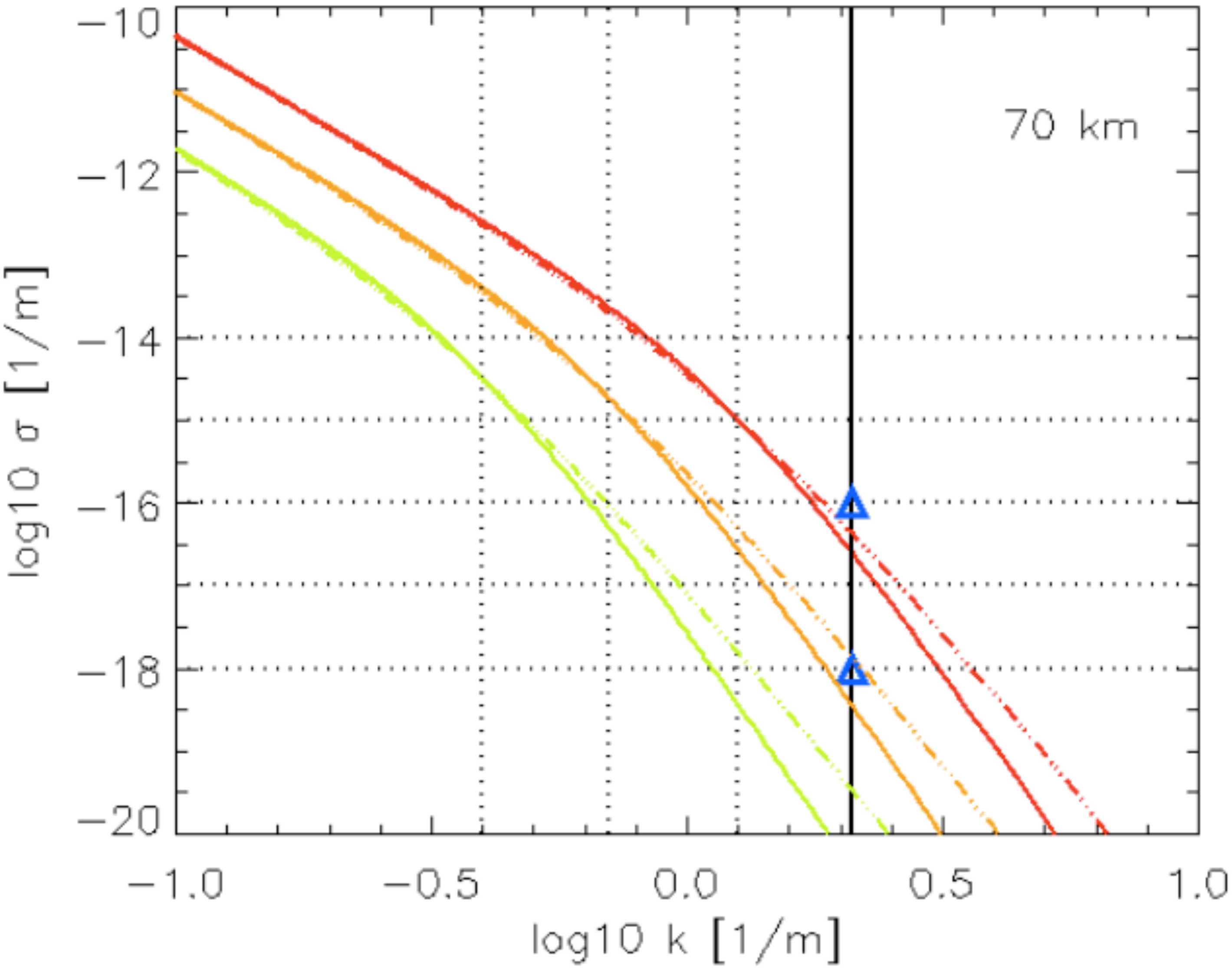
[from *Guo et al.* 2007]

PEME: RCS (1)



[from *Akgiray* 2007]

PEME: RCS (2)



[from *Lehmacher et al.* 2009]

PEME: RCS (3)

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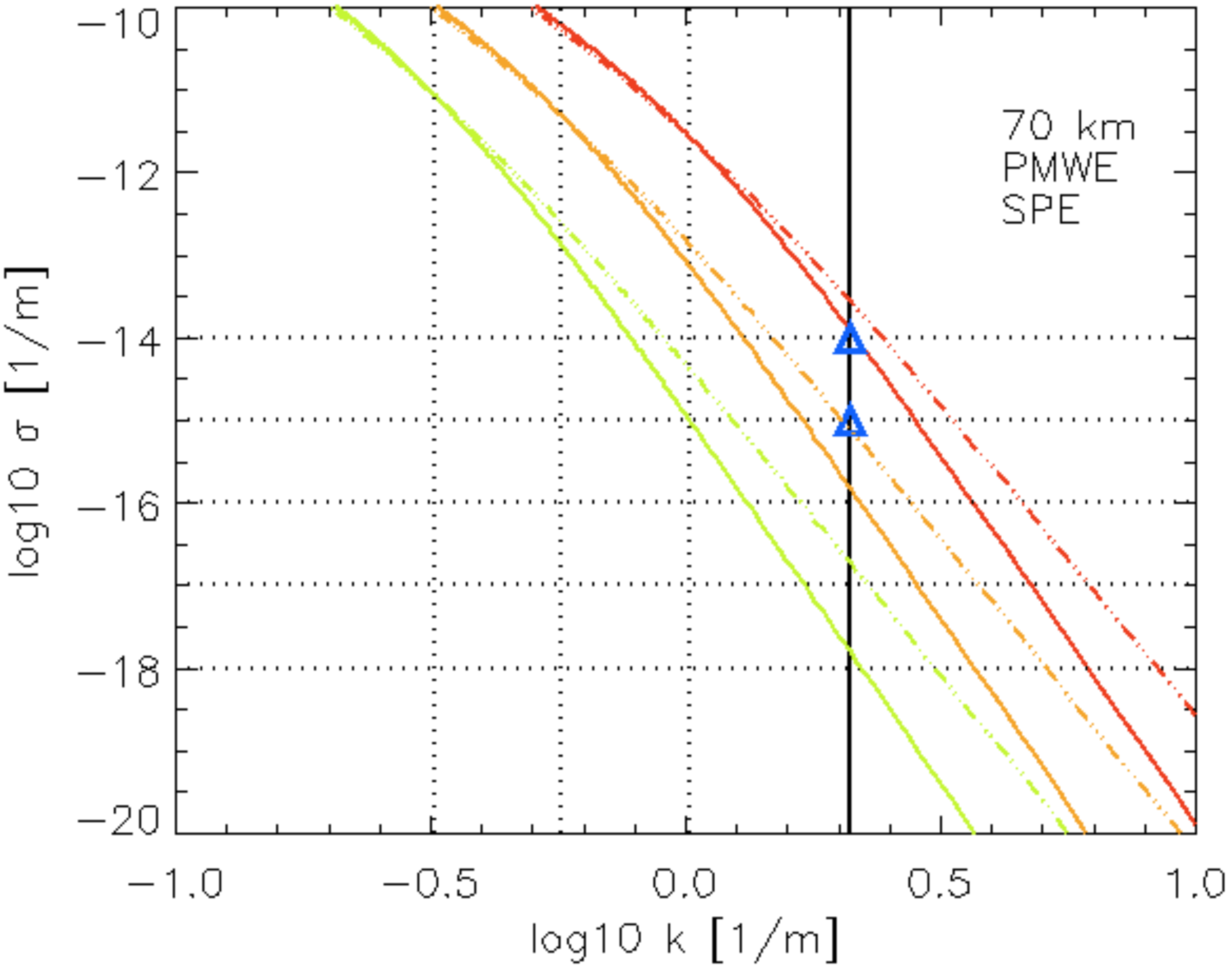

[from *Lehmacher et al.* 2009]

PEME: RCS (4)

- PEME RCS range from 10^{-18} to 10^{-16} m^{-1}, 3 orders of magnitudes smaller than RCS reported for PMWE during solar proton events and 6 orders of magnitude smaller than PMSE.
- For typical conditions, volume scattering coefficients for stationary, homogeneous, isotropic turbulence at 3 m are also in the range 10^{-18} to 10^{-16} m^{-1}.
- Theoretical values are still a matter of order-of-magnitude estimation, since the Bragg scale of 3 meters is near or inside the viscous subrange (turbulence spectrum is not well known).
- Steep electron density gradients can increase RCS significantly.
- For thin layers with large RCS and narrow spectra, isotropic turbulence theory fails and scattering or reflection from anisotropic irregularities maybe the cause, as suggested by numerical simulations.

[from *Lehmacher et al.* 2009]

PEME: Some open questions

- What are the scattering mechanisms in aspect-sensitive layers and near the edges of layers?
  - As far as we know only one rocket experiment has reported sharp gradients density gradients in the 70-75 km region [*Smith and Klaus*, 1975].
- Is there "enhanced" electron diffusion in this region?
  - A heater experiment may be helpful with that. There is certainly a lot of water in the equatorial mesosphere and therefore also large water cluster ions.
- Are there mesospheric aerosol layers?
  - Rocket experiments with sensitive particle detectors

Lower Atmospheric Kelvin Helmholtz Instabilities

KHI Billows and turbulence

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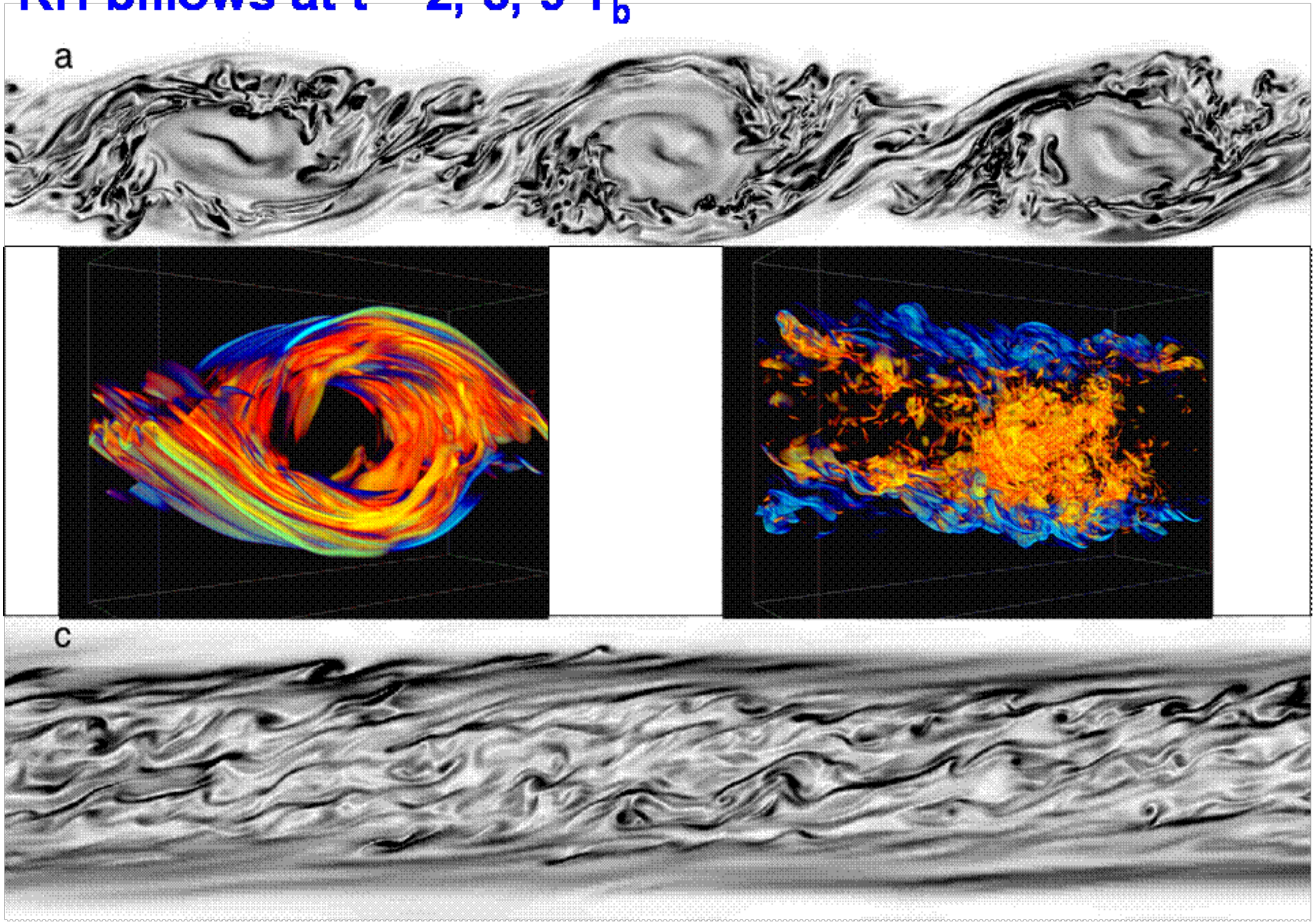
KH billows at t ~ 2, 5, 9 T_b

Fritts et al., 2007



SOUSY: High resolution ST measurements

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[*Woodman et al.*, 2007]