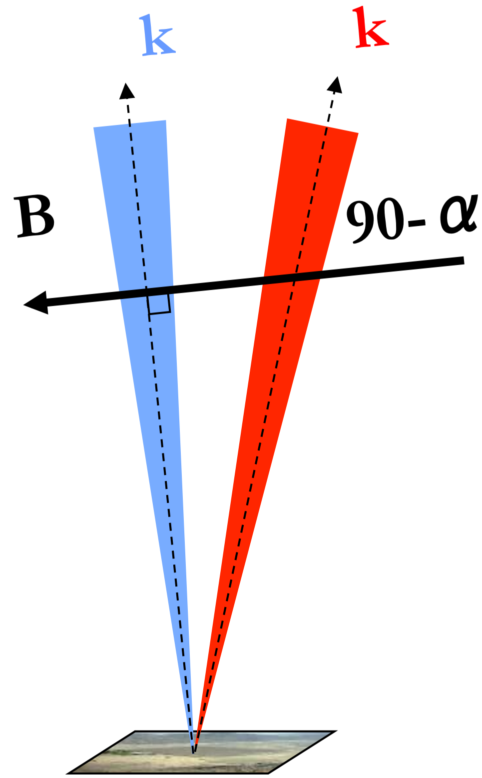
Radar Techniques at the Jicamarca Radio Observatory for studies of the Equatorial Atmosphere/Ionosphere



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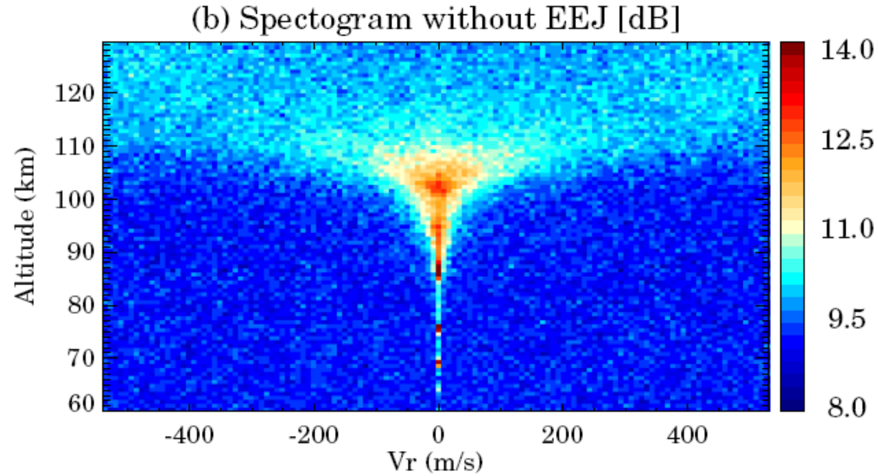
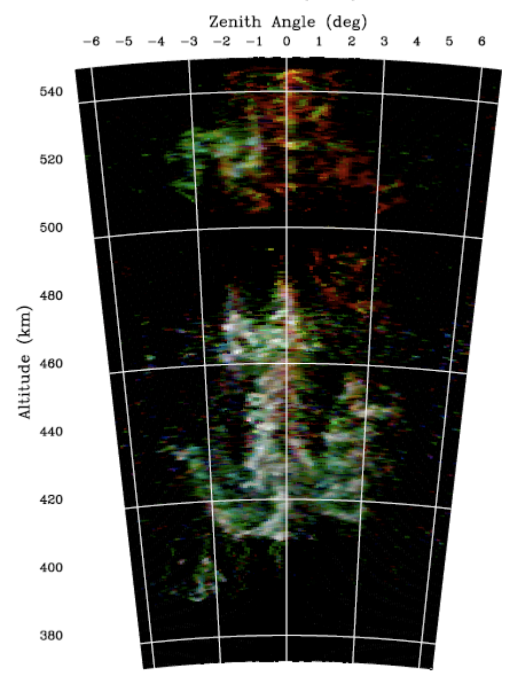
Oulu University – Dec 4, 2009

Outline

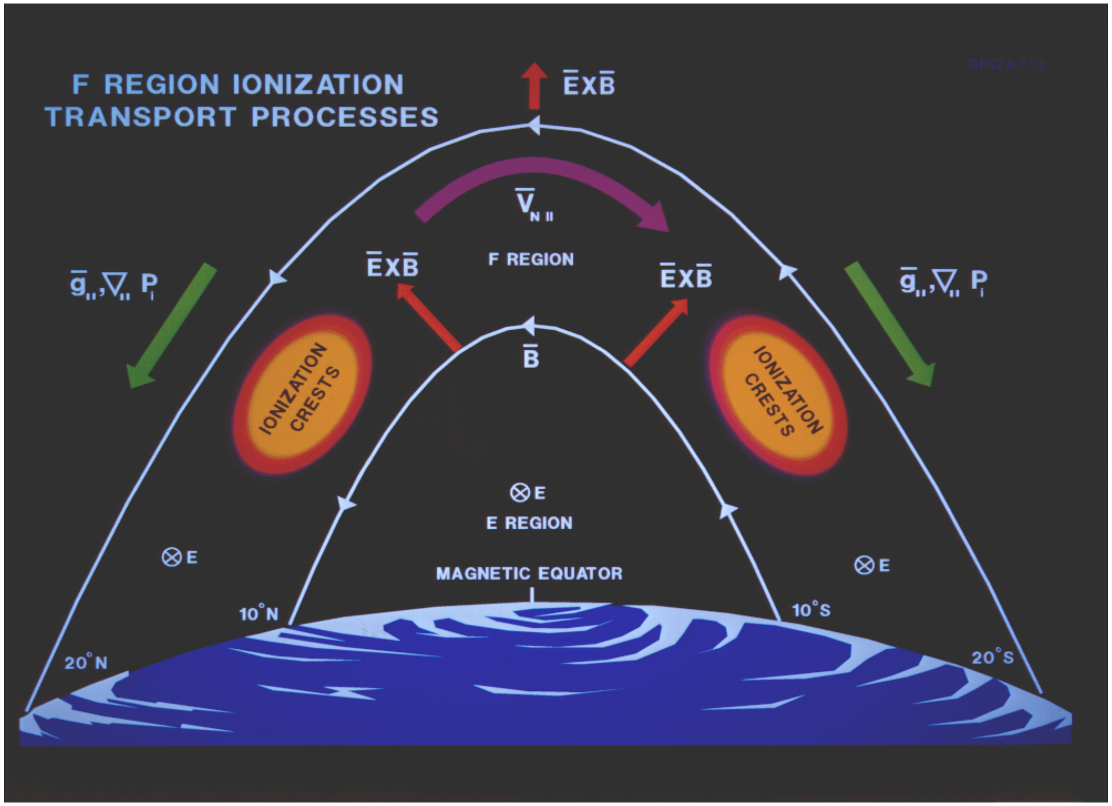
- The Equatorial Ionosphere
- The Jicamarca Radar
- Incoherent scatter techniques
  - Oblique vs. Perpendicular Modes
  - Pulsing schemes
- Coherent scatter techniques
  - MST Technique
  - Radar Interferometry
  - Aperture synthesis radar technique
- Irregularity comparison: in-situ vs. Radar

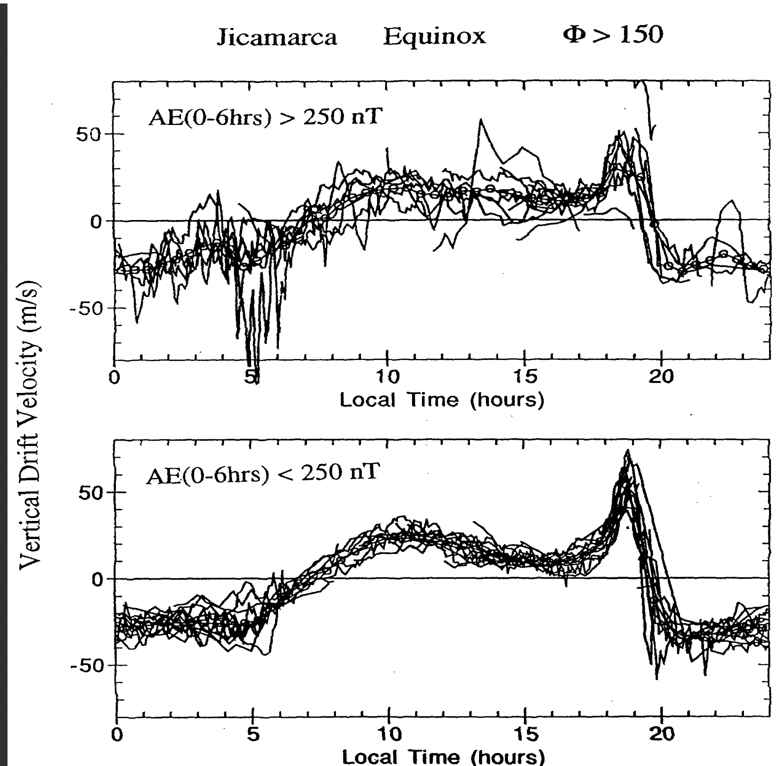




Equatorial Ionosphere

Radio Observatorio de JICAMARCA Radio Observatory





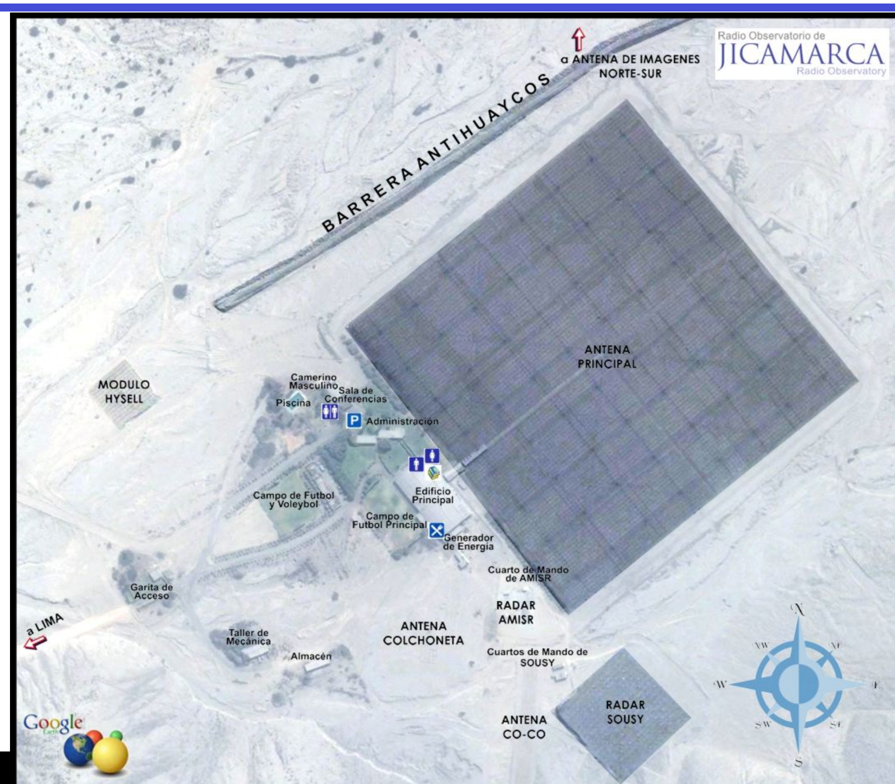
[from *Fejer et al*, 1999]

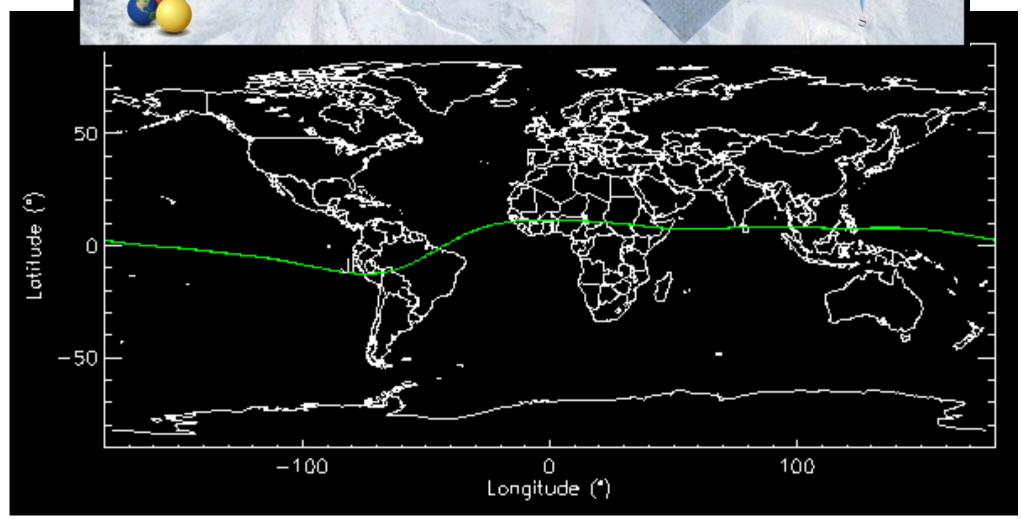
- **B** field is nearly horizontal
- Daytime:
  - *E*-region E is eastward
  - Off-equatorial E maps to F above mag. Equator -> Upward ExB
  - Formation of Appleton Anomaly

- 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.

The 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 1°).

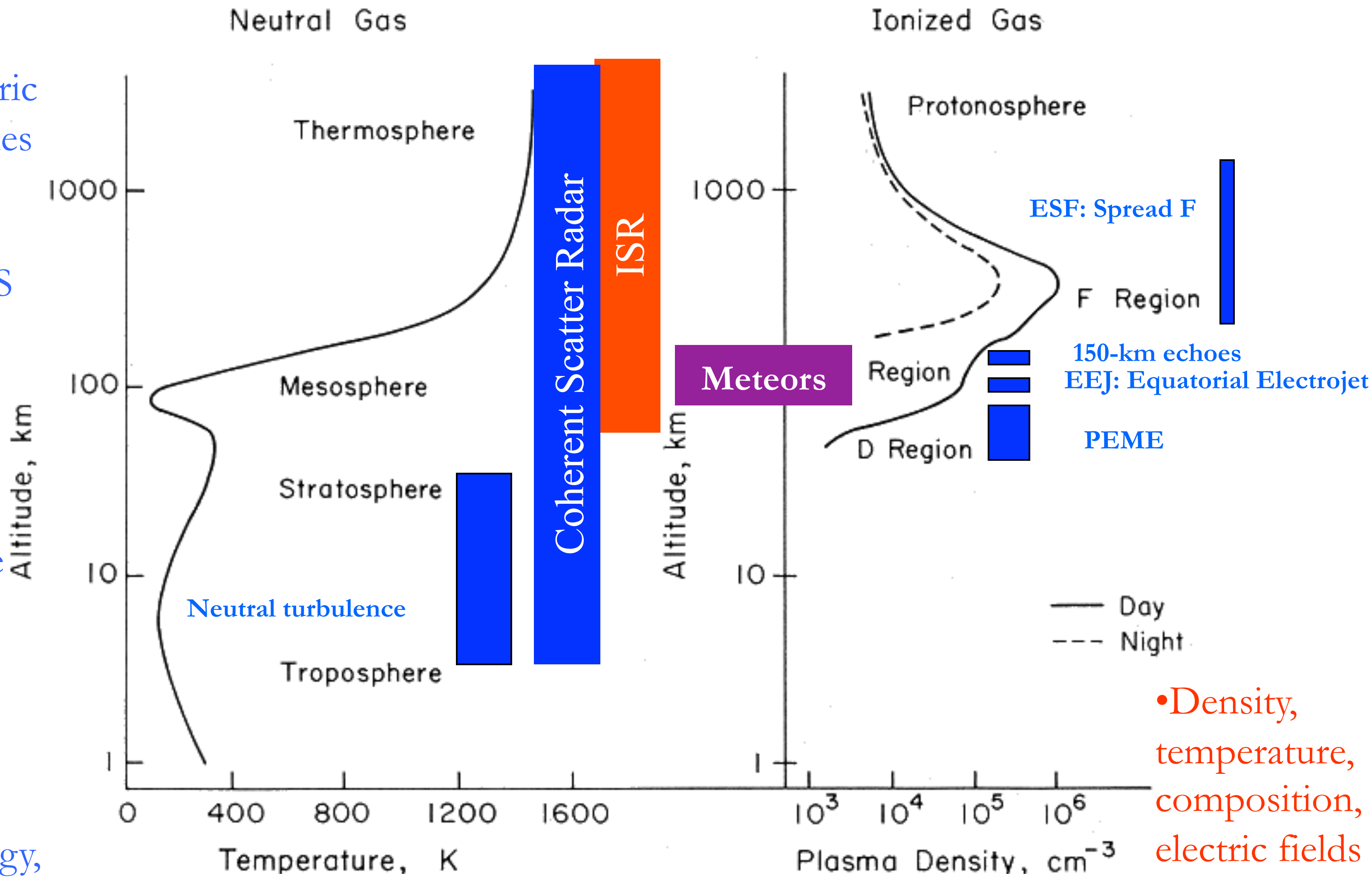




¿What do we study at Jicamarca?

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

Equatorial Irregularities (1)
RTIs above 100 km

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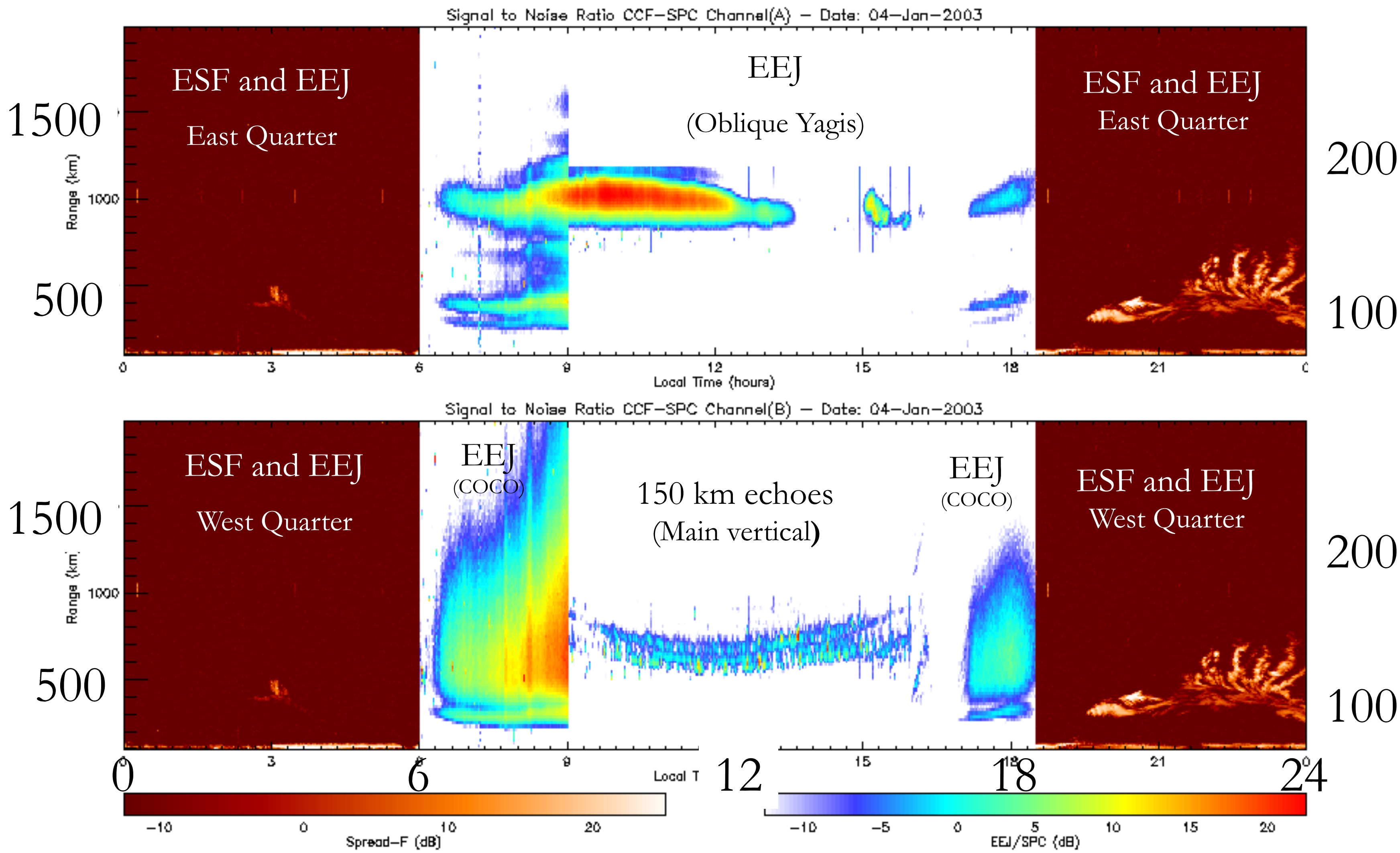
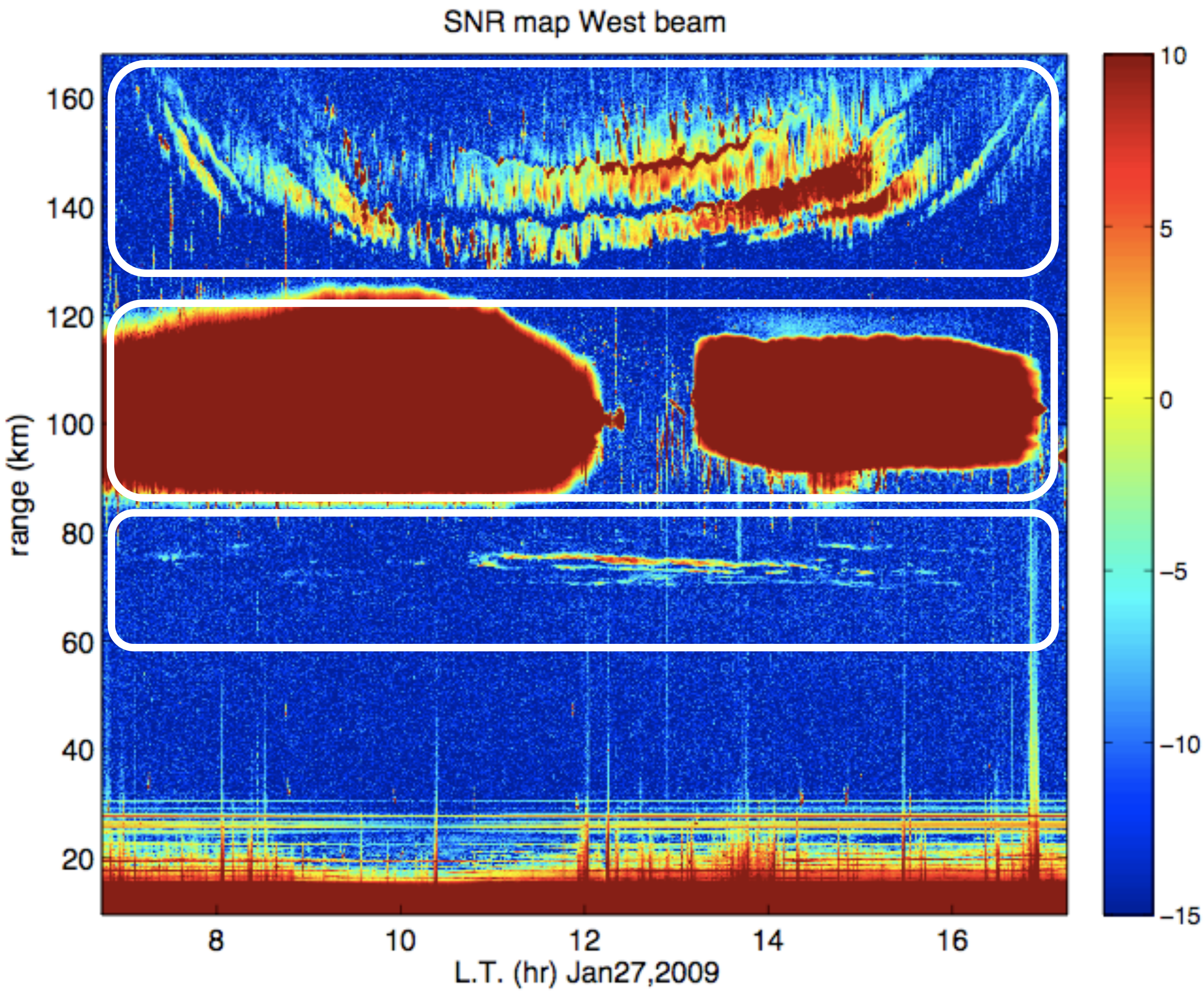


ESF: Equatorial Spread F (nightime)

150-km echoes: Daytime

EEJ: Equatorial Electrojet (all day)

Equatorial Irregularities (2) Below 200 km



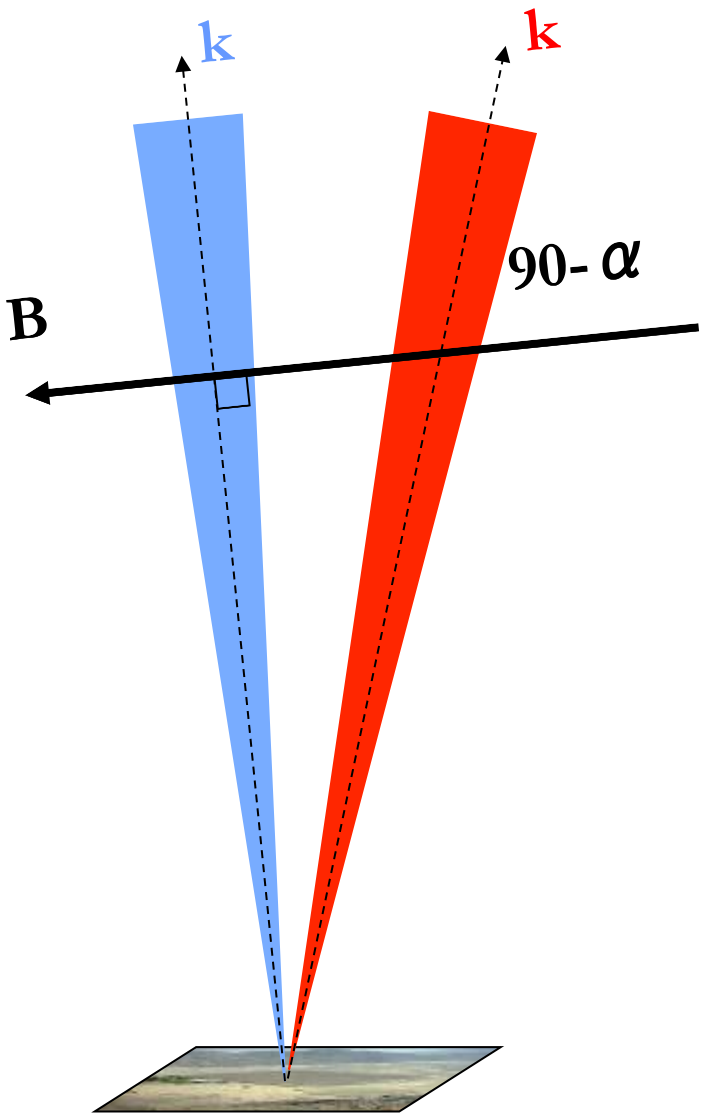
- ExB drifts from 150-km first moment.
- Plasma physics from EEJ spectra
- Plasma physics and lower thermosphere winds from non-specular meteor trails
- Mesospheric winds from mesospheric echoes

Jicamarca System Peculiarities

- Antenna modularity (Radar Interferometry, Imaging, Spaced Antenna, Antenna Compression, multi-beam experiments).
- Antenna polarization (Faraday rotation, simultaneous multi-beam experiments)
- Radar Frequency (coherent scattering, Faraday Rotation, high skynoise)
- Location (variety of atmospheric/ionospheric targets, transverse and longitudinal propagation modes)
- In-house hardware and software development (variety of pulse compression schemes, frequency domain interferometry, aperiodic pulsing, multi-pulse schemes)

Incoherent Scatter Techniques

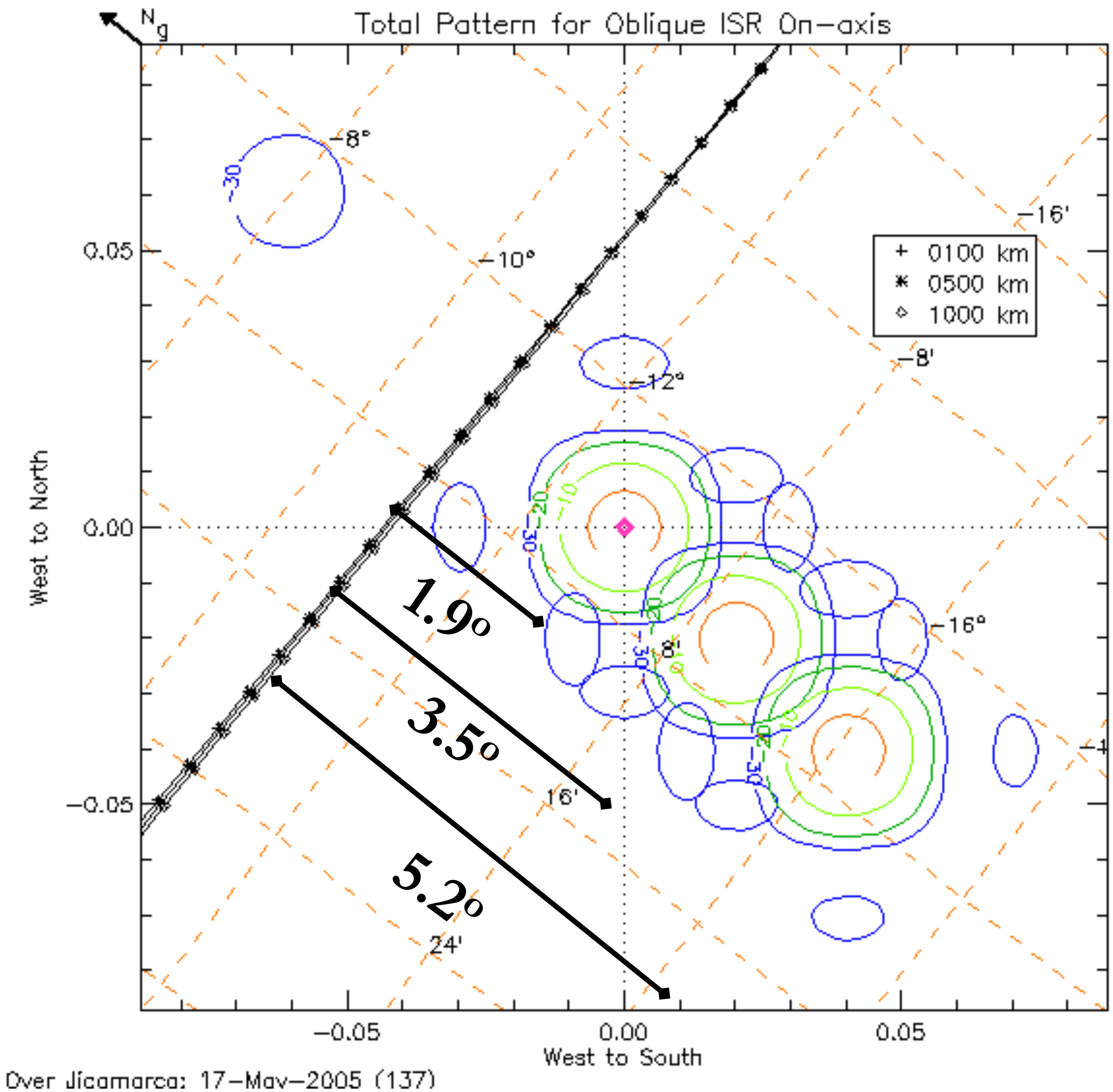
Oblique vs. Perpendicular ISR: Geometry



- 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

Radio Observatorio de JICAMARCA Radio Observatory



- Three standard beam positions are used:
  - On-axis (α = 1.9°)
  - "4.5" (α = 3.5°)
  - "6.0" (α = 5.2°)
- 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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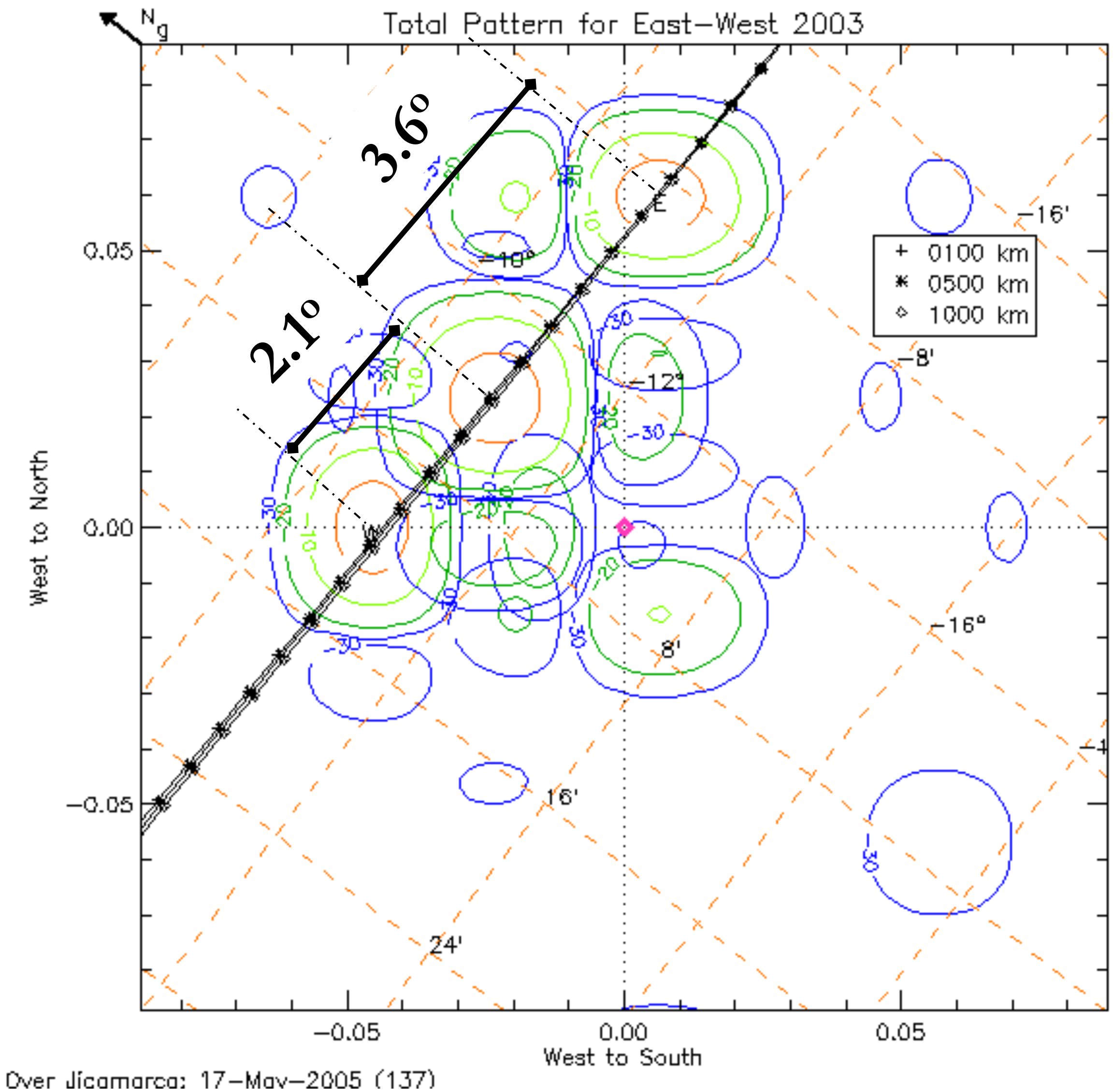

- Three standard beam positions are used:
  - Vertical (both polarizations)
  - "East" (3.6° with respect to vertical). One linear polarization.
  - "West" (~2.1°). The other linear polarization
- Maximum antenna gain is obtained with "Vertical" and less with "East".
- Either Vertical or East-West modes 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

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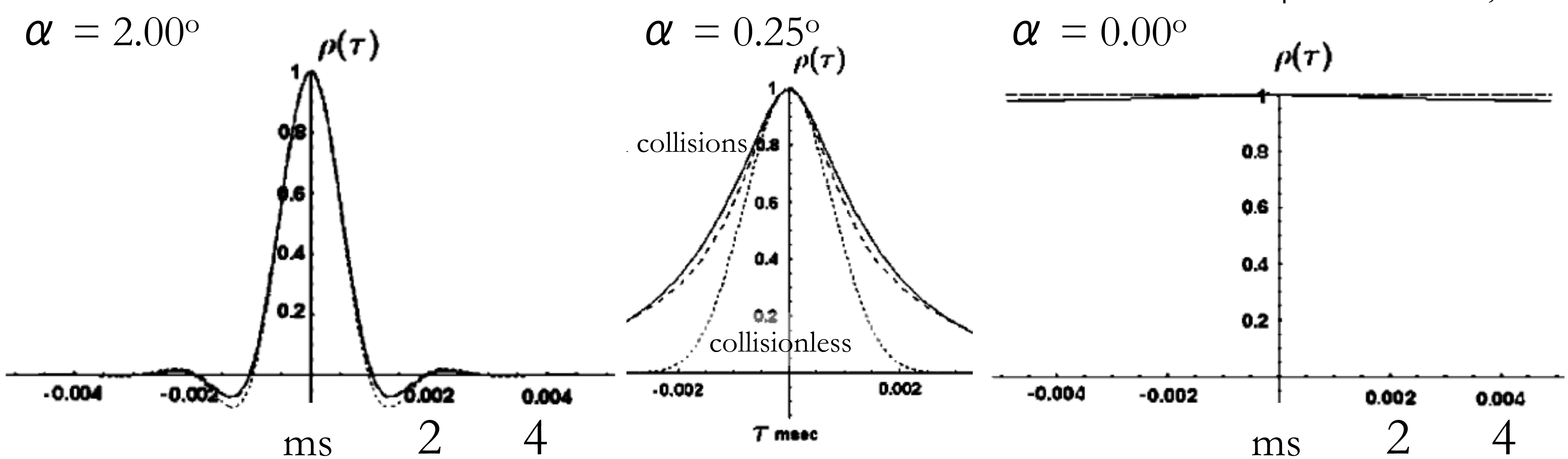
[from *Woodman*, 2004]



<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: α = 0.334° (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

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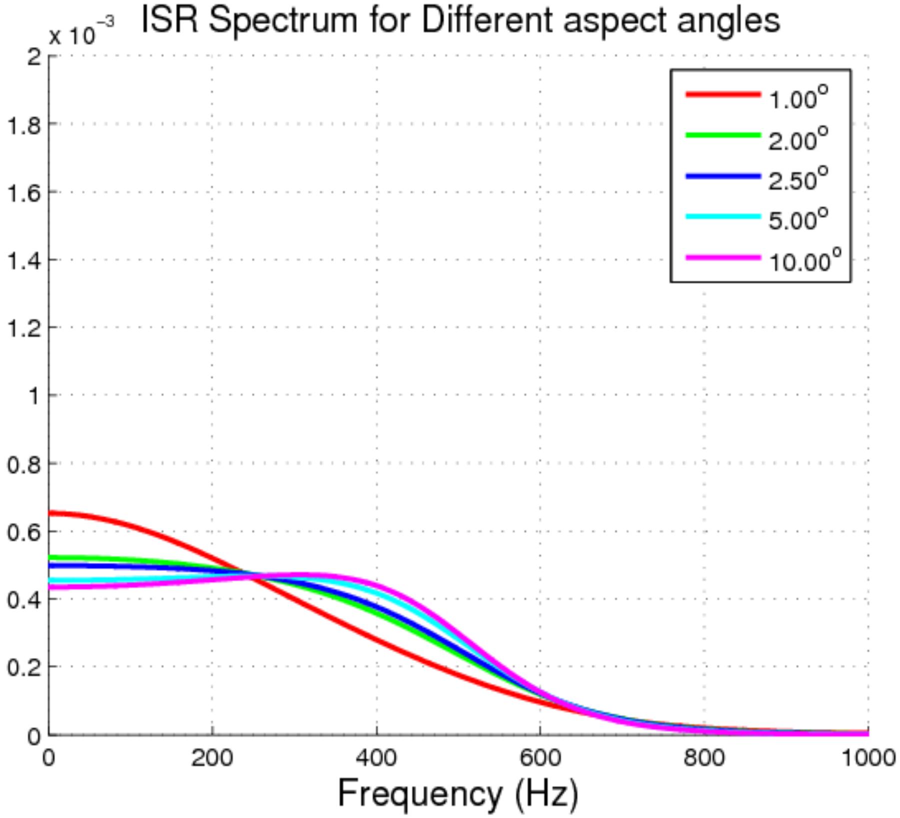

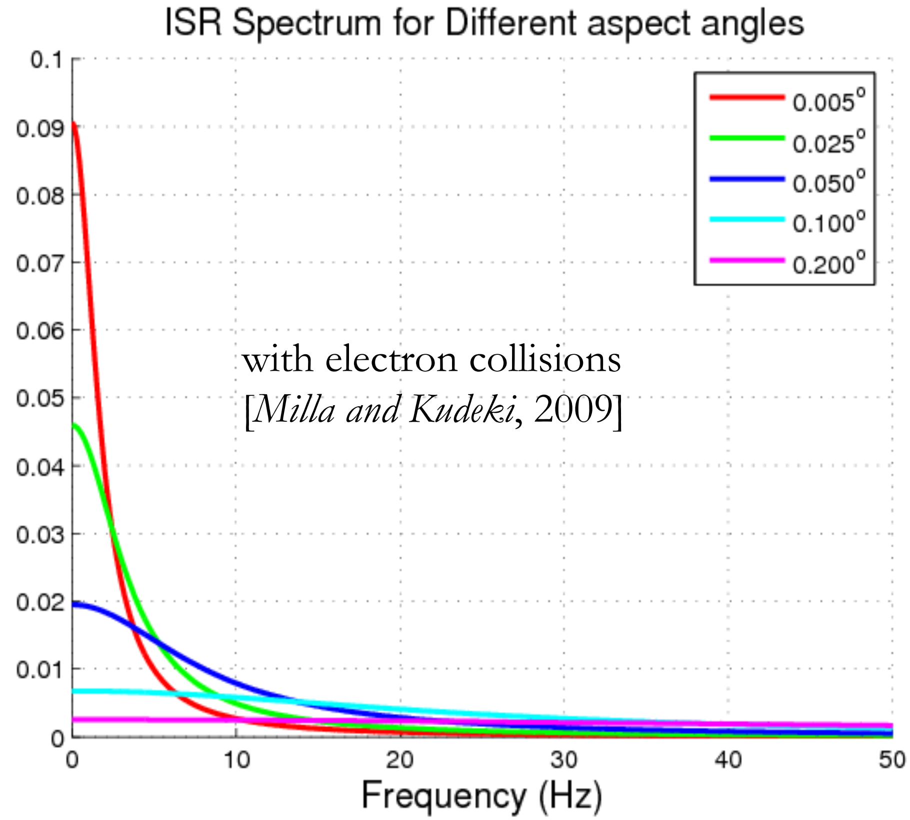

<u>Oblique</u>

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

<u>Perpendicular</u>

- 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

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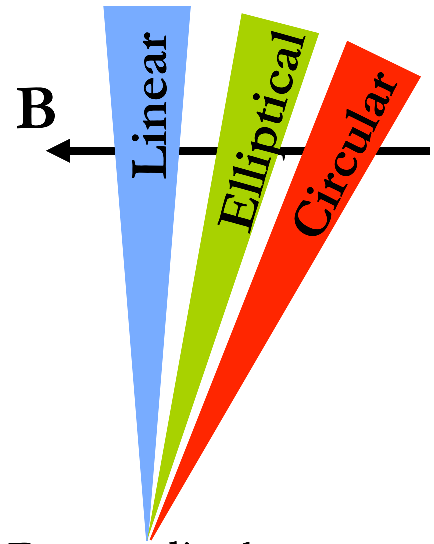
- Faraday "rotation" arises from the difference between the indexes of refraction corresponding to the two characteristic modes of a magnetoionic medium.
- Phase difference between these modes of propagation is proportional to the integrated electron density.
- Given Jicamarca's 50 MHz frequency (the 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 $\alpha > 0.4^{\circ}$.
- Two-circular polarizations are transmitted and received.
- Small "cross-talk" due to elliptical modes need to be corrected for $\alpha < 2.0^{\circ}$ We do this correction by flipping every other pulse.

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

[from *Farley*, 1969]

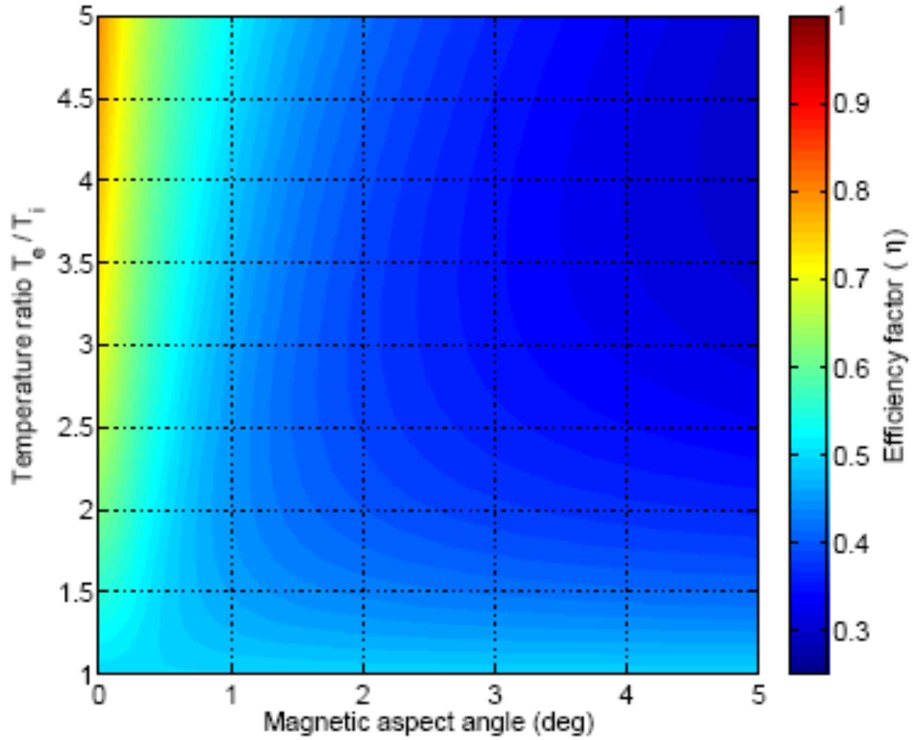
Perpendicular

- 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).

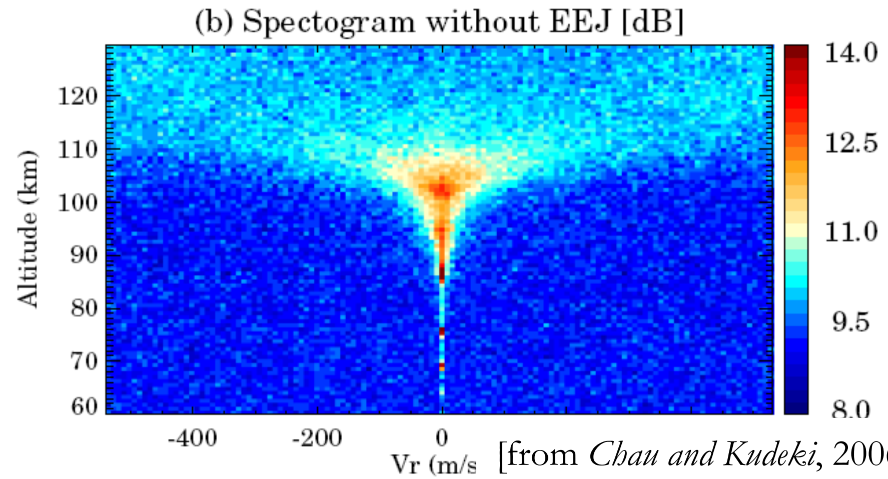


(a) [from *Milla and Kudeki*, 2006]

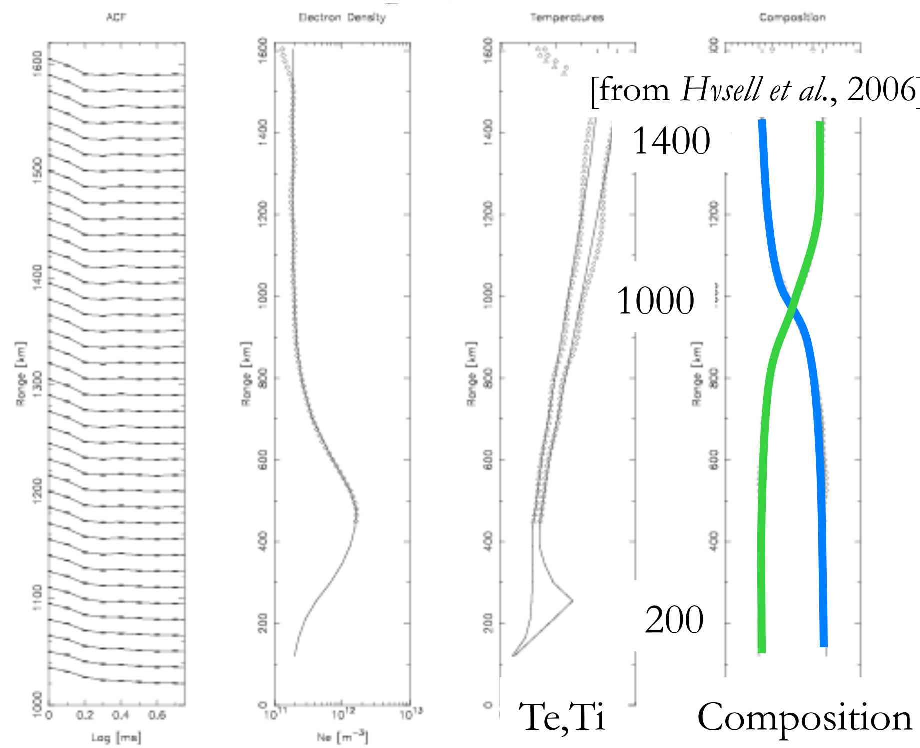
$$P_s(h) = K_s N_e(h) \sigma_{ne}(h) / h^2$$

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]

Perpendicular ISR Examples (1): Pulse-to-pulse Spectral Analysis

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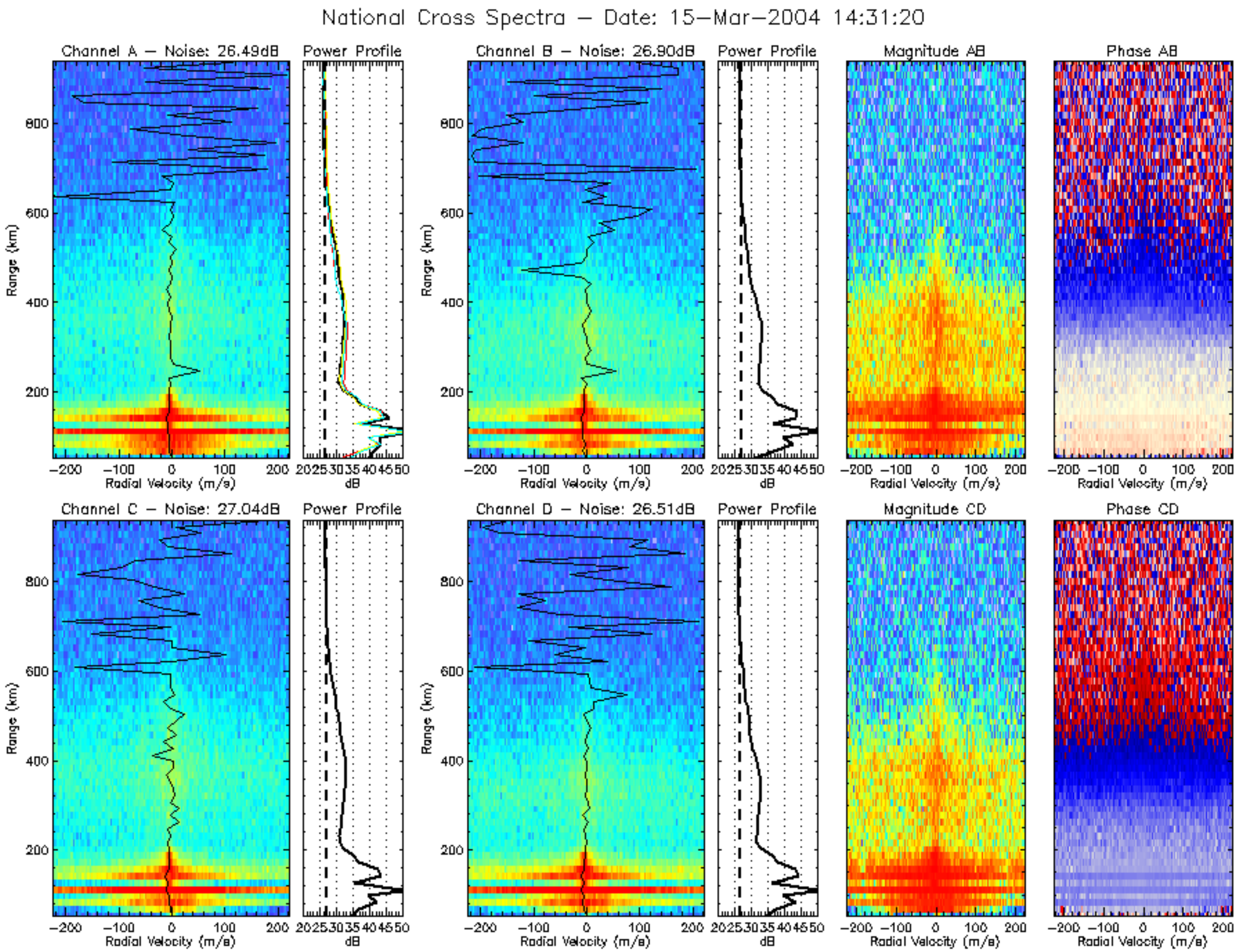
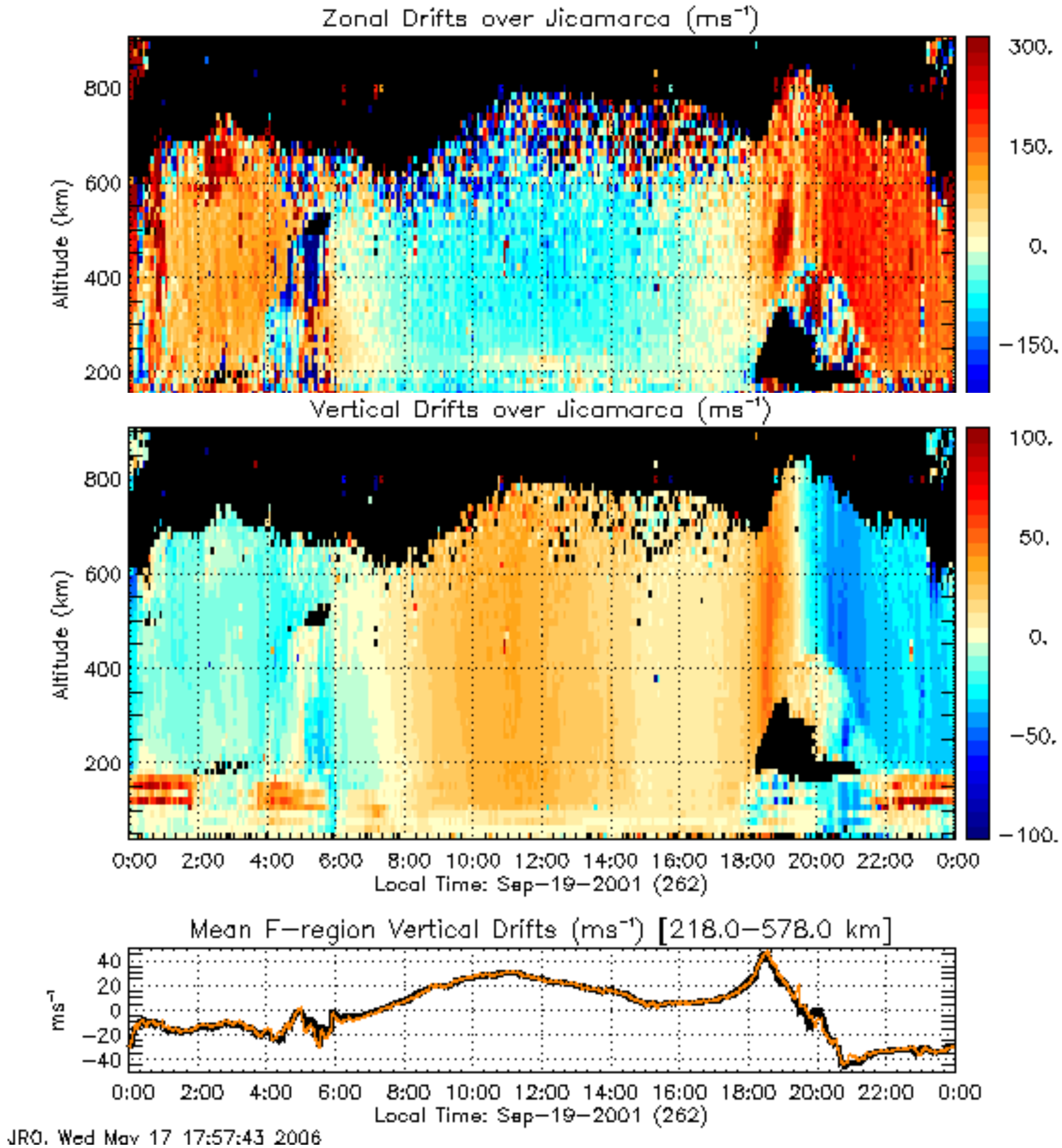


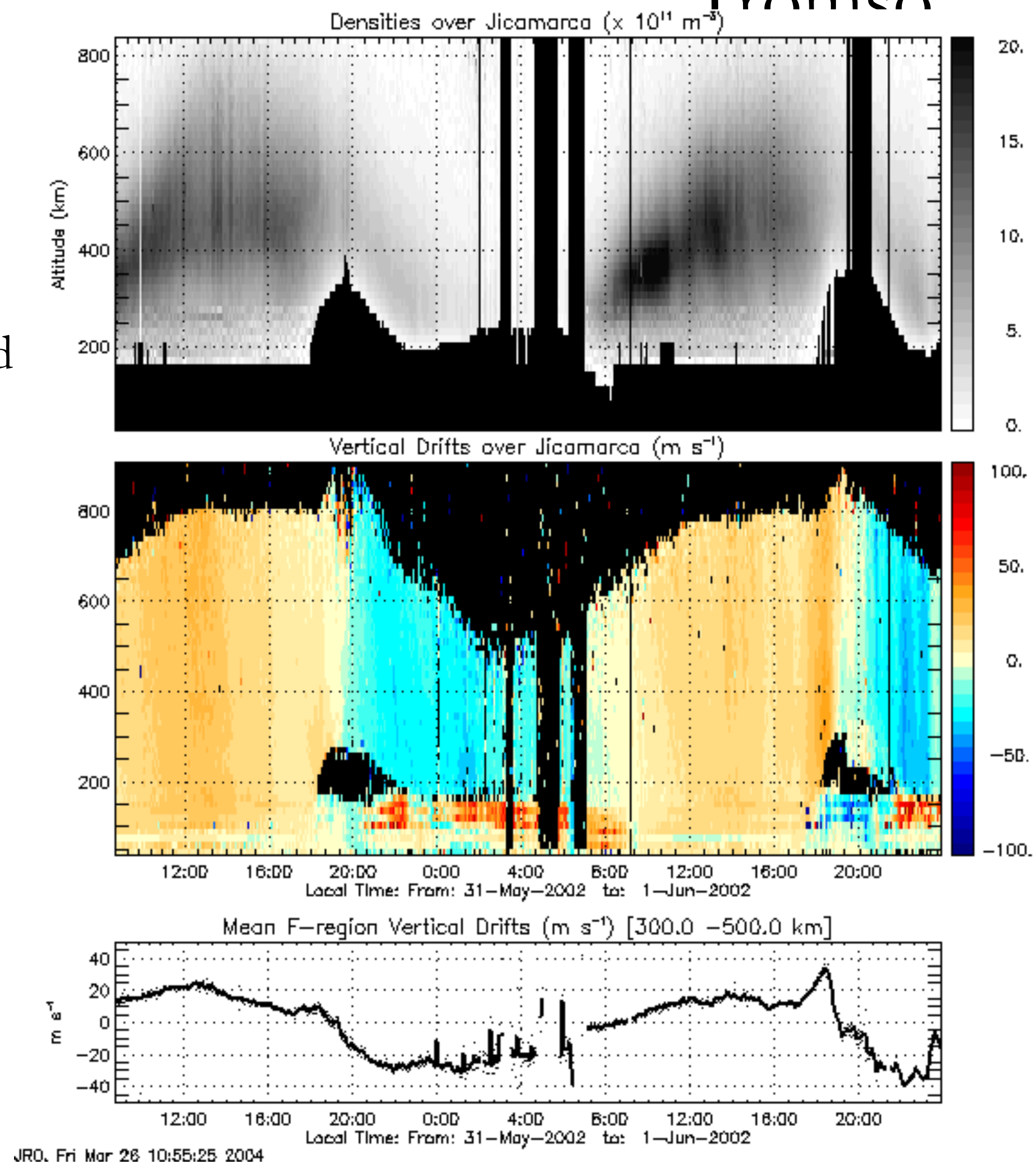
Perpendicular ISR Examples (2)

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



Perpendicular ISR Examples (3): Density Vertical Drift (DVD)

- Simultaneous measurements of vertical drifts and densities.
- Absolute densities are obtained from the differential phase of the normal modes of propagation and extended in altitude from power.
- Recently a new mode have been tested, combining East-West beams with differential phase measurements (DEWD).



[*Kudeki et al.*,2003]
[*Feng et al.*, 2004]

ESF Vortex

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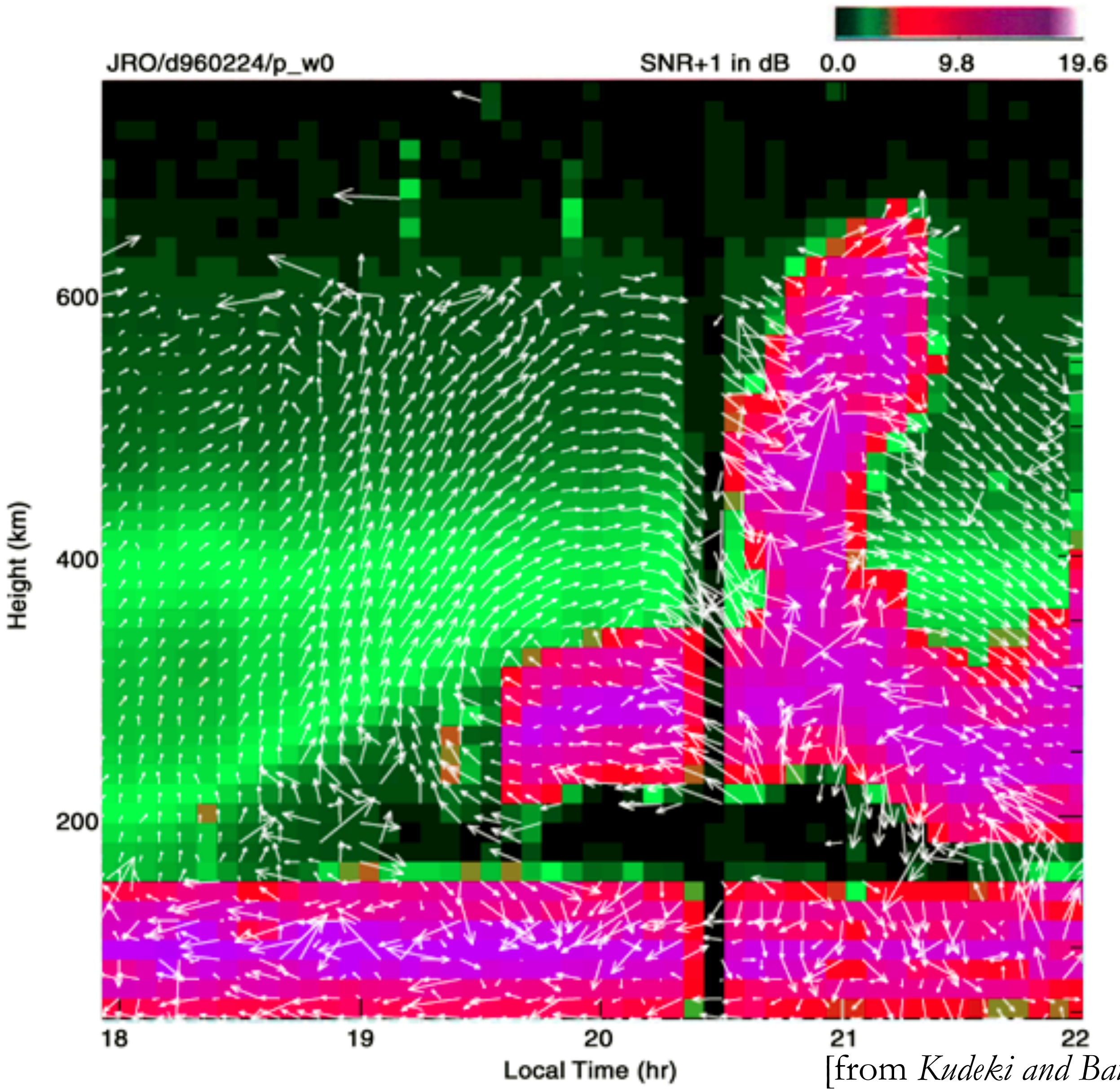

[from *Kudeki and Batthacharyya*, 1999]

Oblique ISR Examples (1): Faraday Double Pulse

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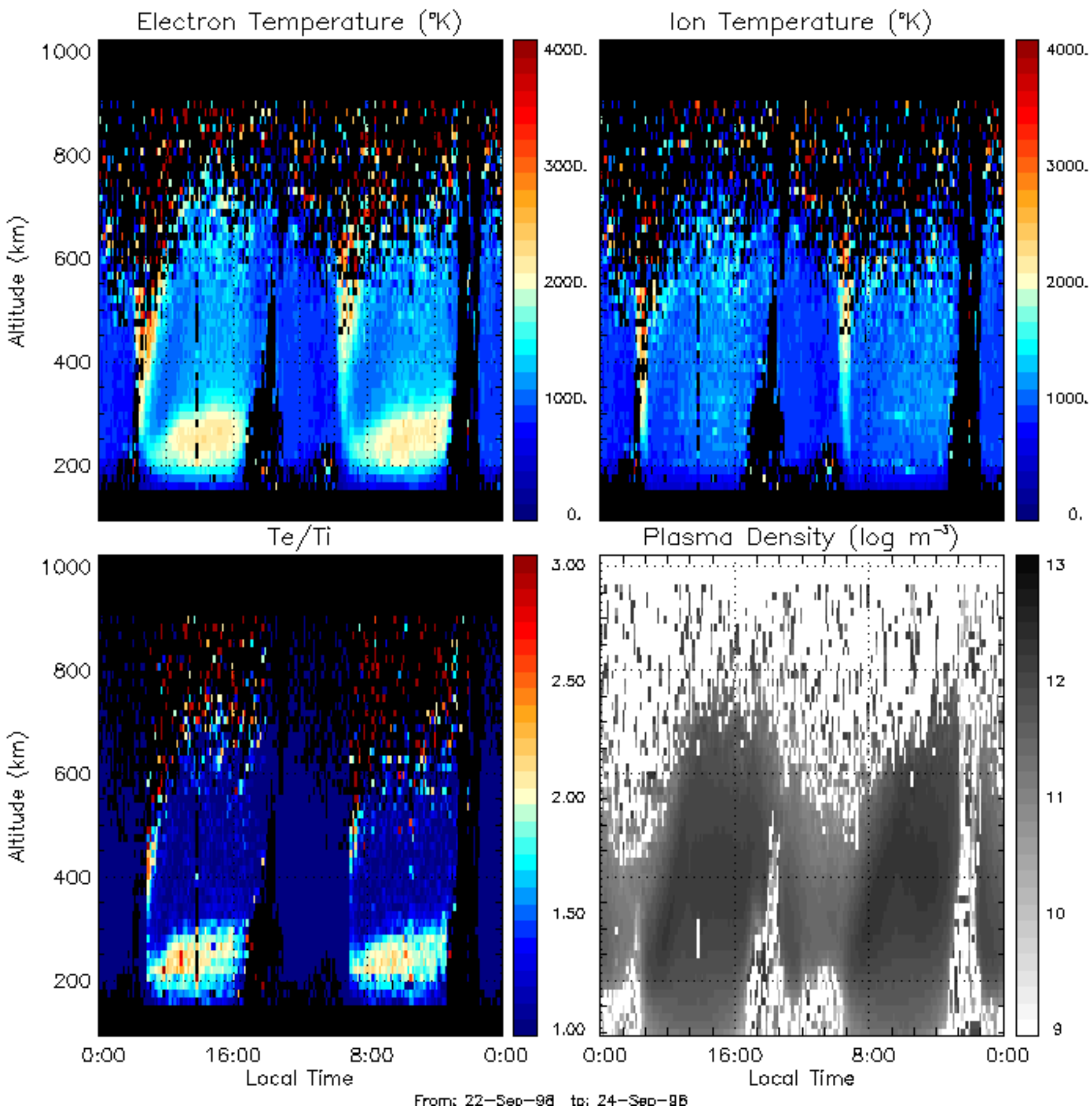
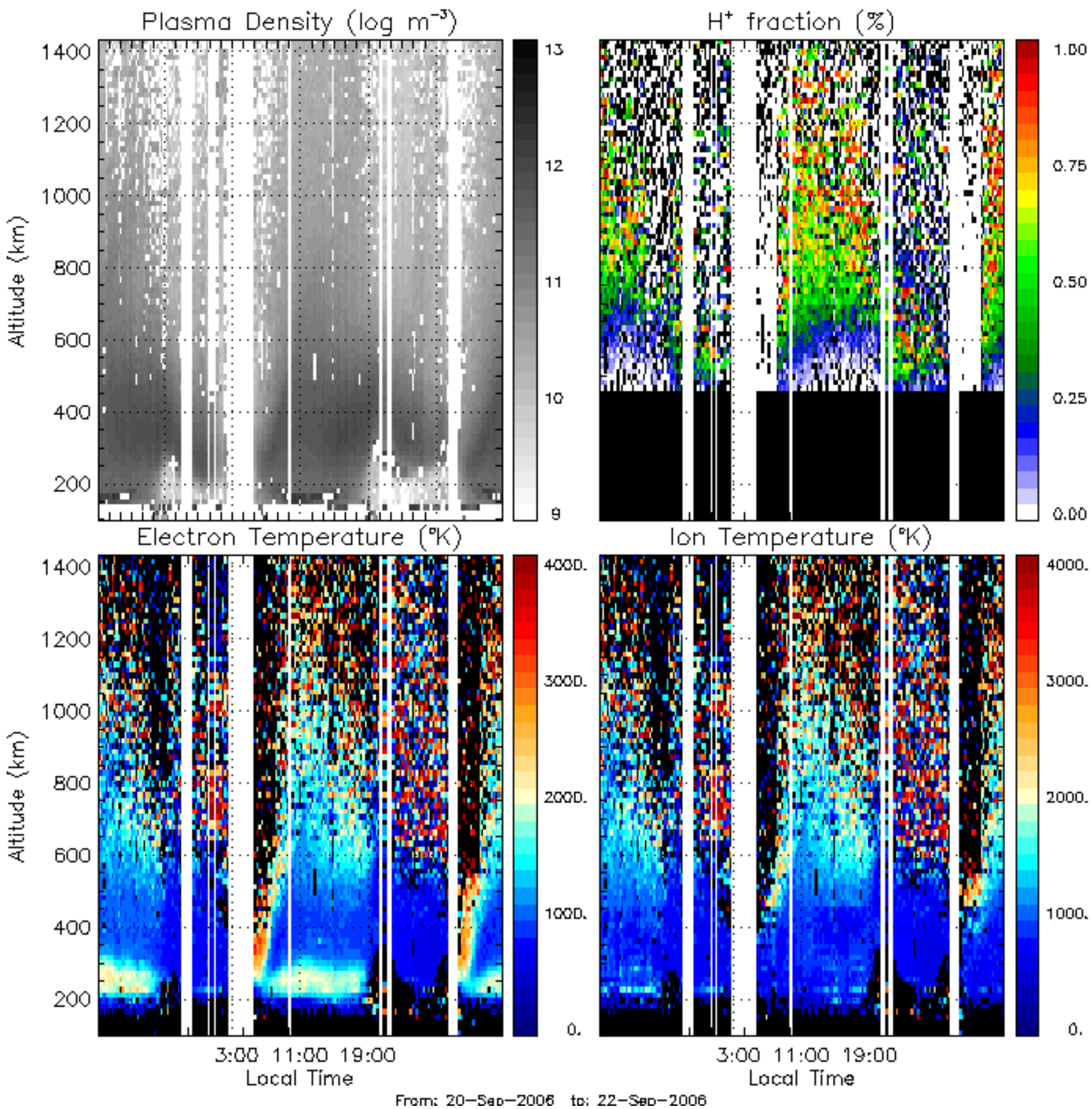


- This is the traditional mode (since 1960's) to get:
-densities from Faraday rotation and power.
-Temperatures and Composition from ACFs obtained with Double Pulse sequences.
- This mode doesn't use the available duty cycle.
- Composition is hardly obtained.
- After *Sulzer and Gonzalez* [1999] work, temperatures estimates have been improved and the data reanalyzed since 1996.
- e.g., This mode is ideal for studying the Midnight temperature maximum (MTM).

[*Farley*, 1969]

Oblique ISR Examples (2): Hybrid 1 Faraday DP – Alternating codes



•This modes combines the Faraday DP mode with an alternating code mode [e.g., *Hysell*, 2000]. Allowing us to use the available duty cycle. It provides:

-Density and temperatures below 500 km from Faraday Double Pulse

-Density, temperatures and composition above 500 km.

•Altitudinal coverage it is better at the expense of bottom side temperature estimates with slightly less accuracy.

•Very good for removing satellite clutter from raw voltages.

Oblique ISR Examples (3): Hybrid 2 Faraday DP – Long Pulse – Full Profile

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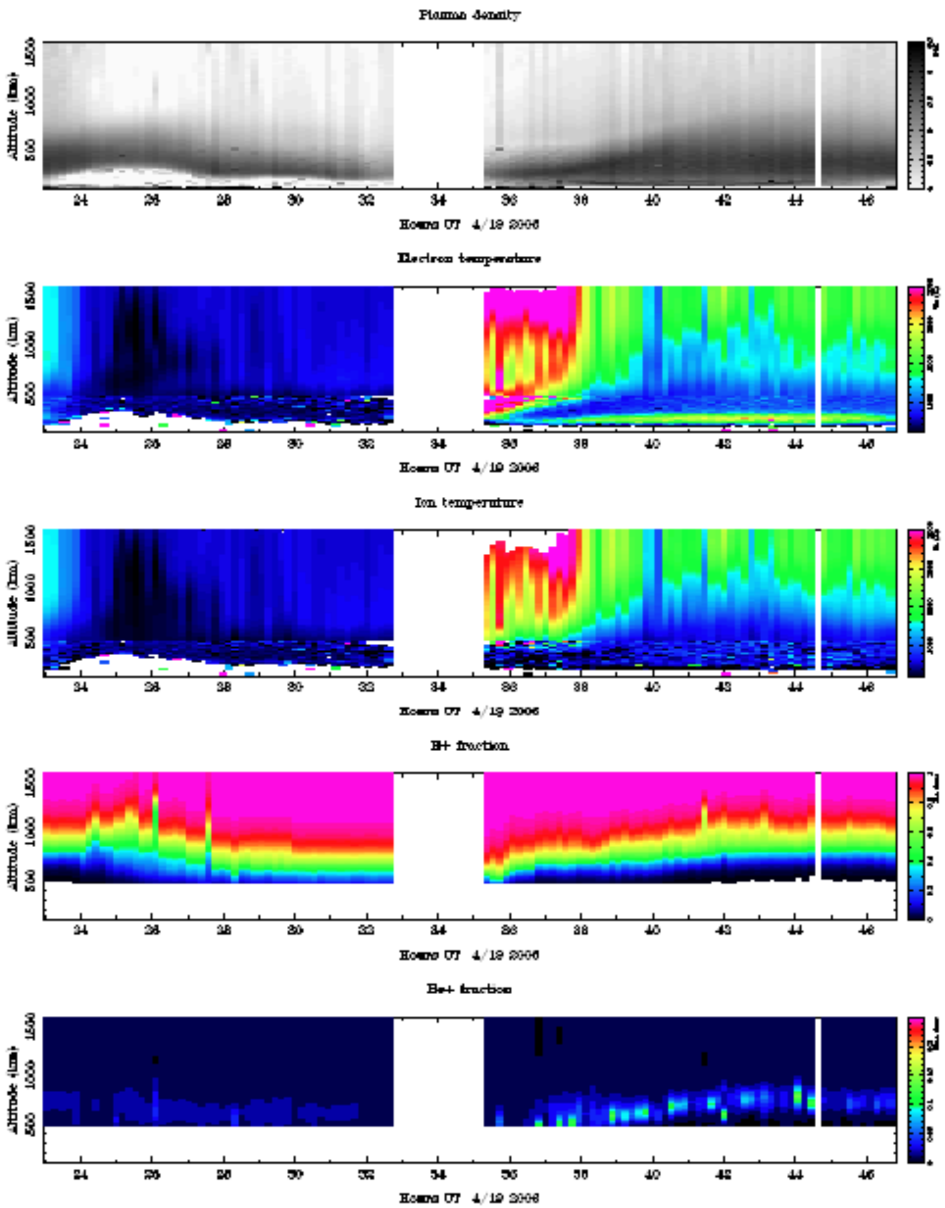


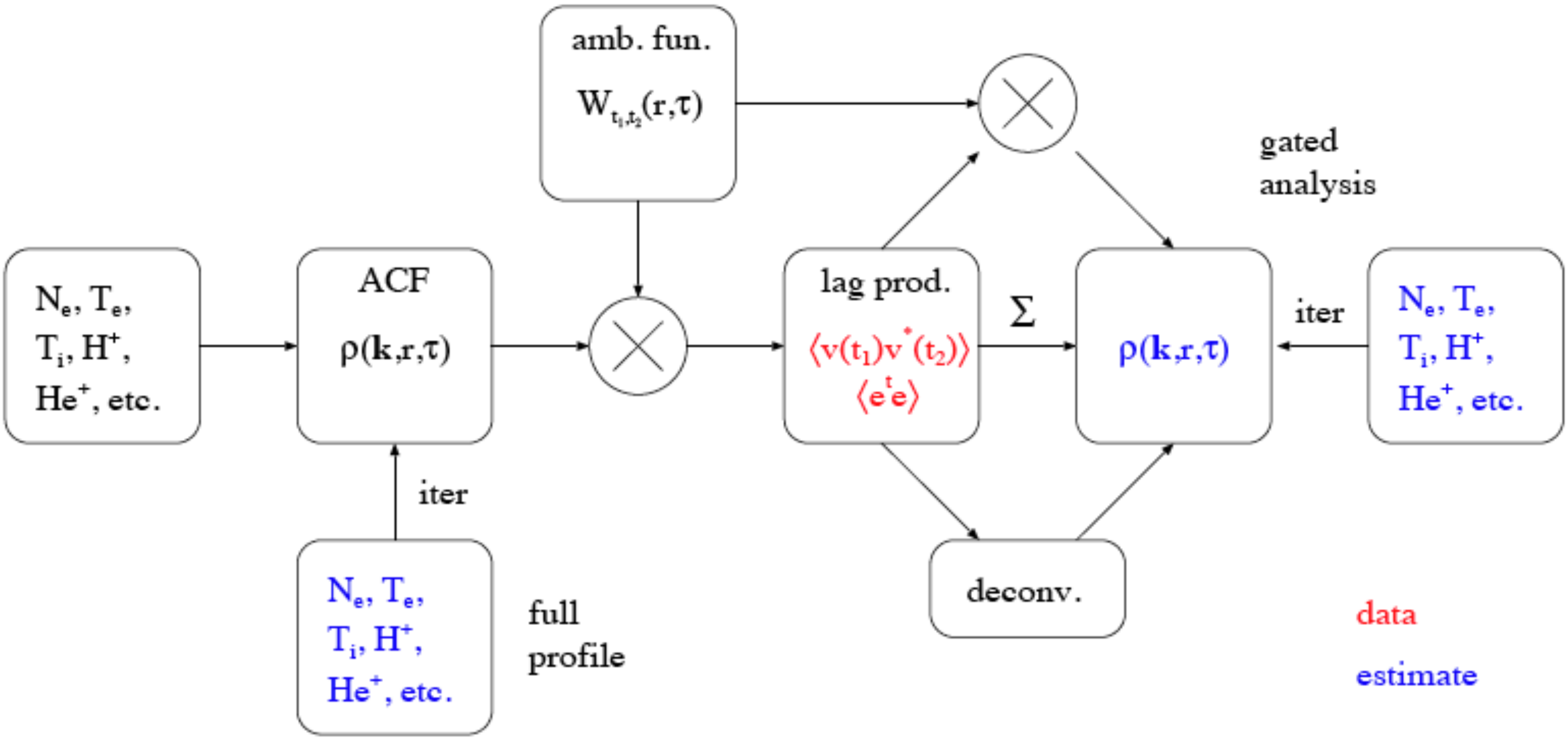
- This modes combines the Faraday DP mode with a long pulse mode, again allowing use of the available duty cycle.
- Altitudinal coverage it is better than previous two modes at the expense of less altitudinal resolution in the topside.
- Similarly it provides:

-Density and temperatures below 500 km

-Density, temperatures and composition above 500 km.

[*Hysell et al.*, 2008]

Full Profile: Block Diagram



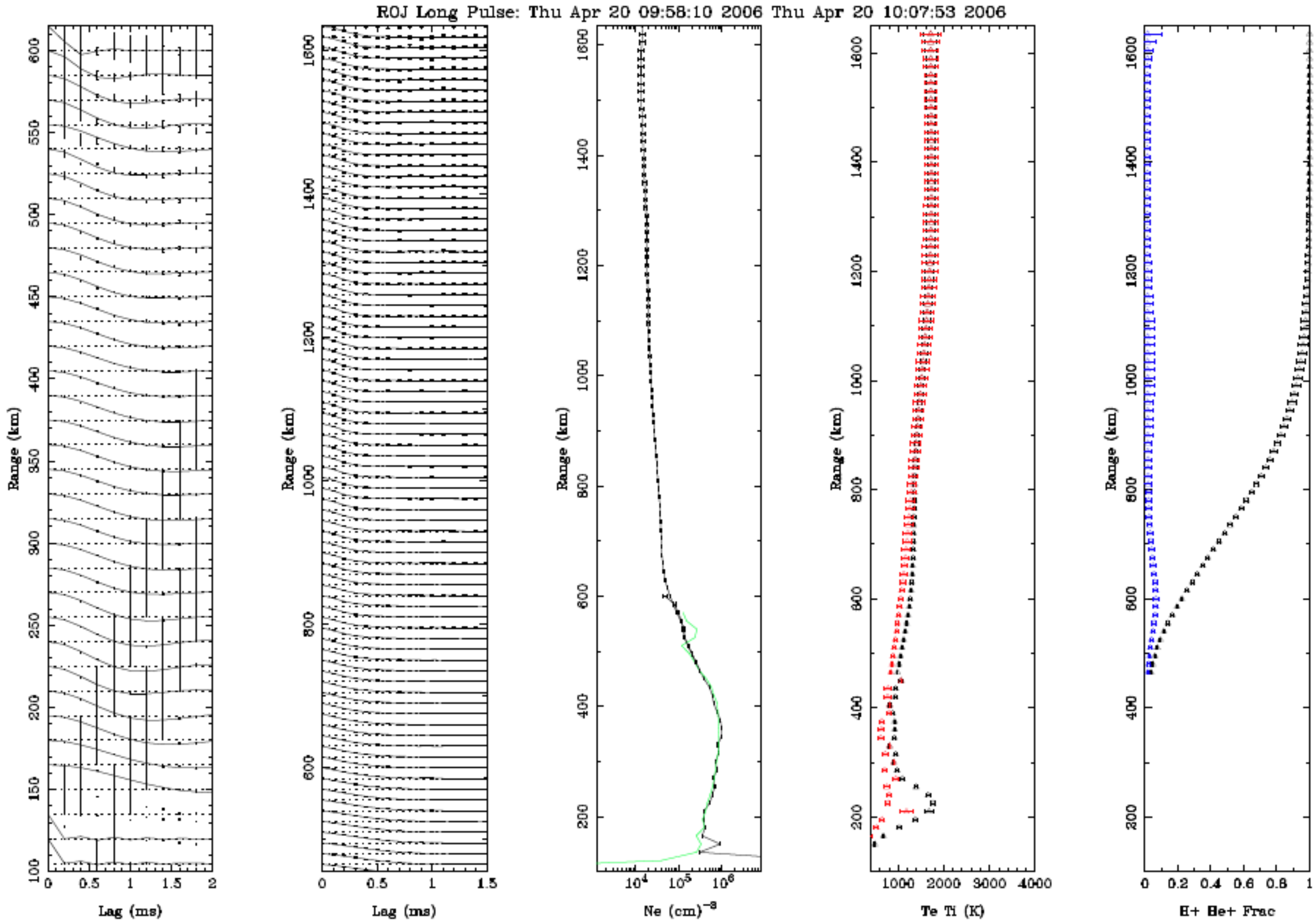
[*Hysell et al.*, 2008]

Full profile: Metodology

- Problem is to find density, temperature, and composition of ionosphere consistent with lag-product measurements within confidence limits.
- Strategy is to solve the forward problem, iterate using nonlinear damped least squares methodology.
- Discretization: parameterize temperature, composition curves by finite number of points (20) and fill in using cubic spline interpolation.
- Problem is mixed determined (no exact solution, many statistically acceptable solutions) and poorly conditioned (solutions to noisy data problem typically very oscillatory).
- Regularize by introducing prior information to cost function (temperature ratio, temperature and [H+] roughness, positive compositions).

[*Hysell et al.*, 2008]

Full-profile example (10 LT)

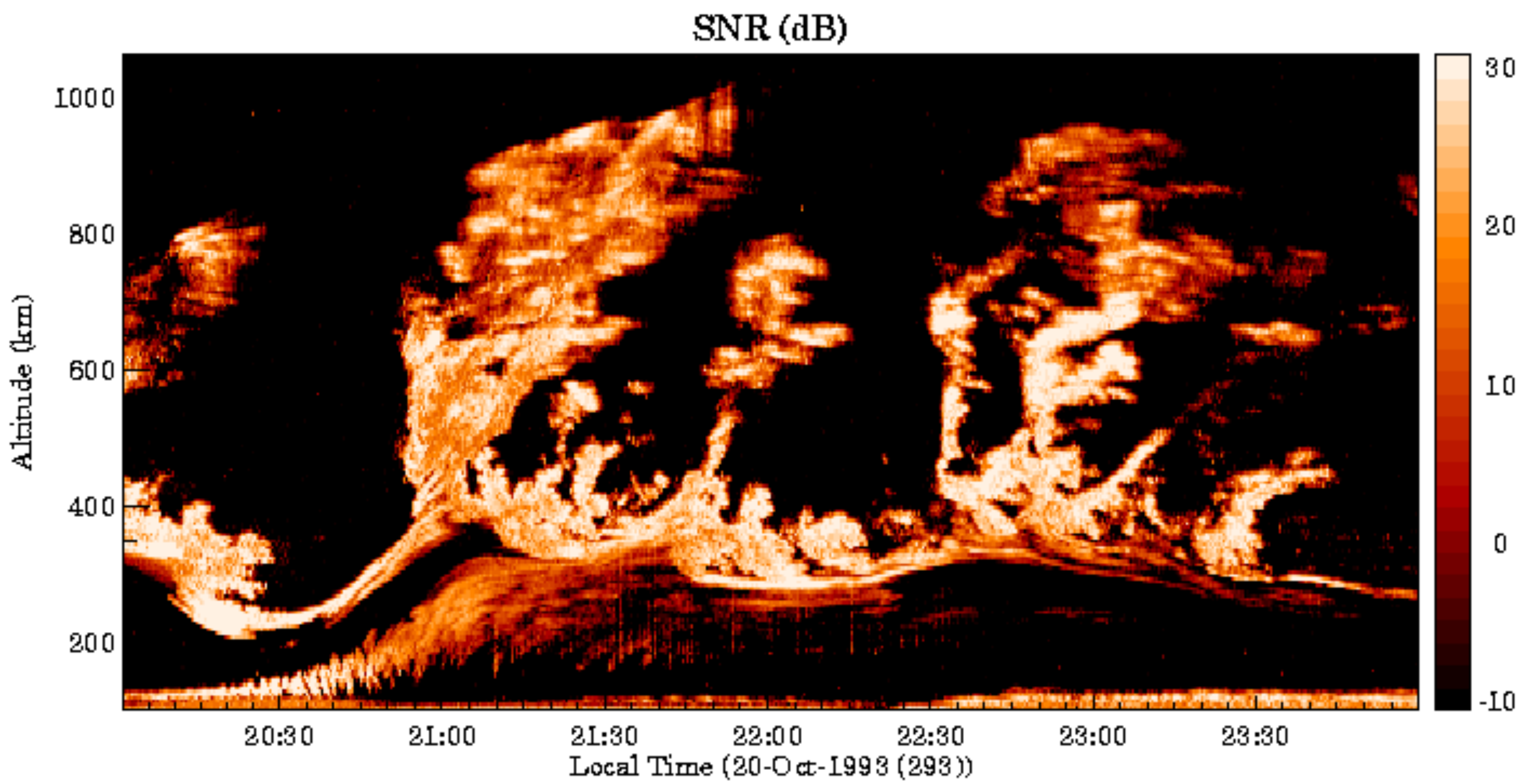


Coherent Scatter Techniques

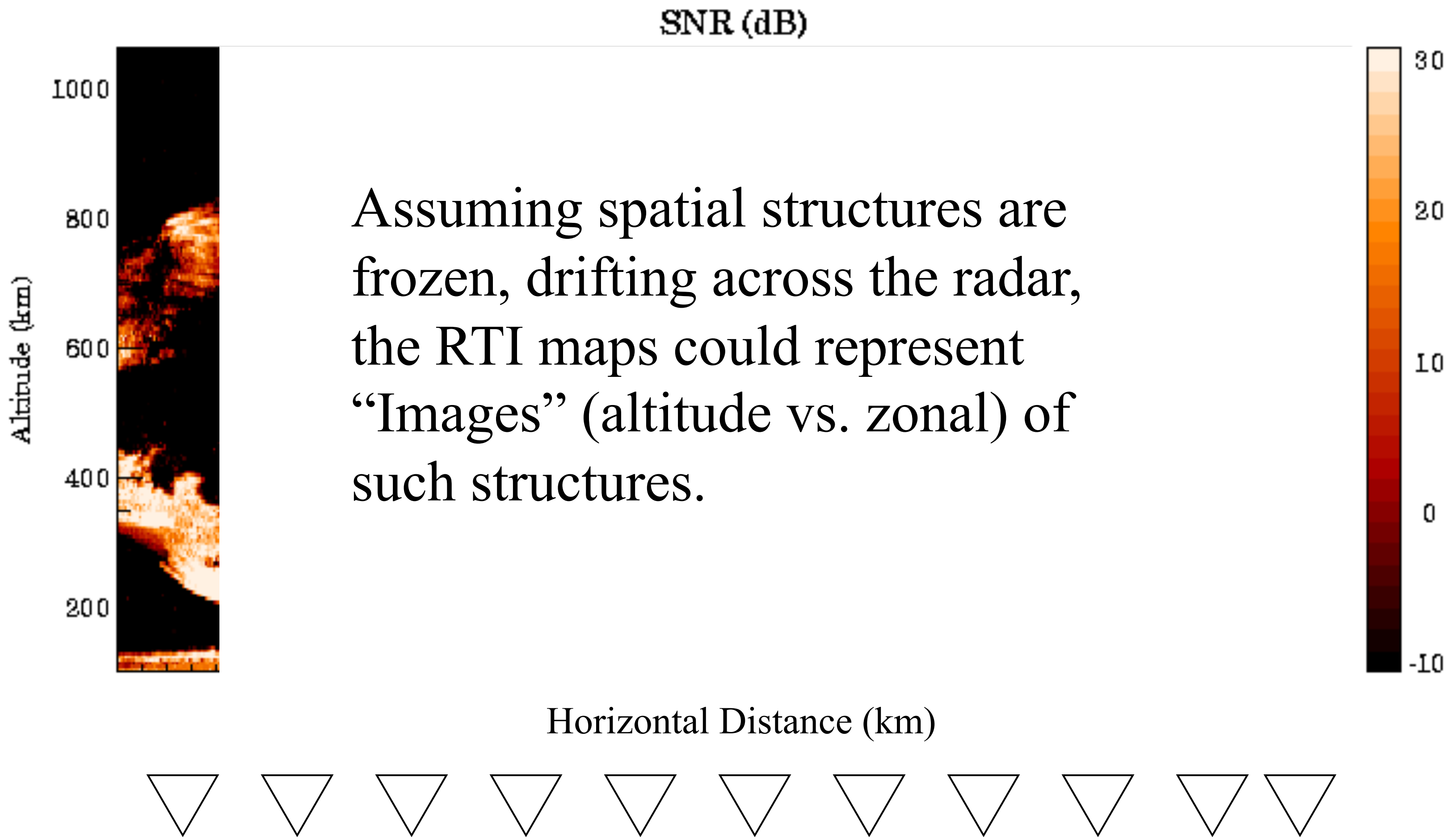
MST and Radar Interferometry

- MST technique
  - To measure neutral winds in the lower atmosphere
  - Improvements in hardware and software (rapid T/R switches, low power capabilities, coherent integrations, pulse compression, pulse-to-pulse analysis).
- Radar Interferometry
  - It uses two or three antennas depending if the target to study is field-aligned or not.
  - To measure target location and angular width (aspect sensitivity). From changes of location as function of time, we can infer horizontal drifts.
  - It has been applied to: EEJ, ESF, meteors, PMSE, sporadic E, lightning, …

Range-Time Intensity (RTI) maps

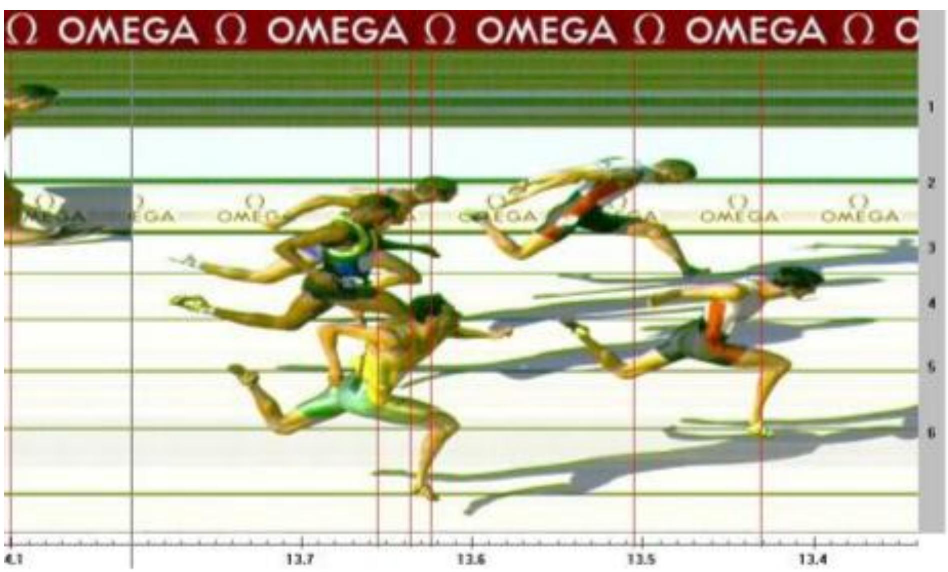


Range-Time Intensity plots as “Images”: Slit camera interpretation



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



- 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.

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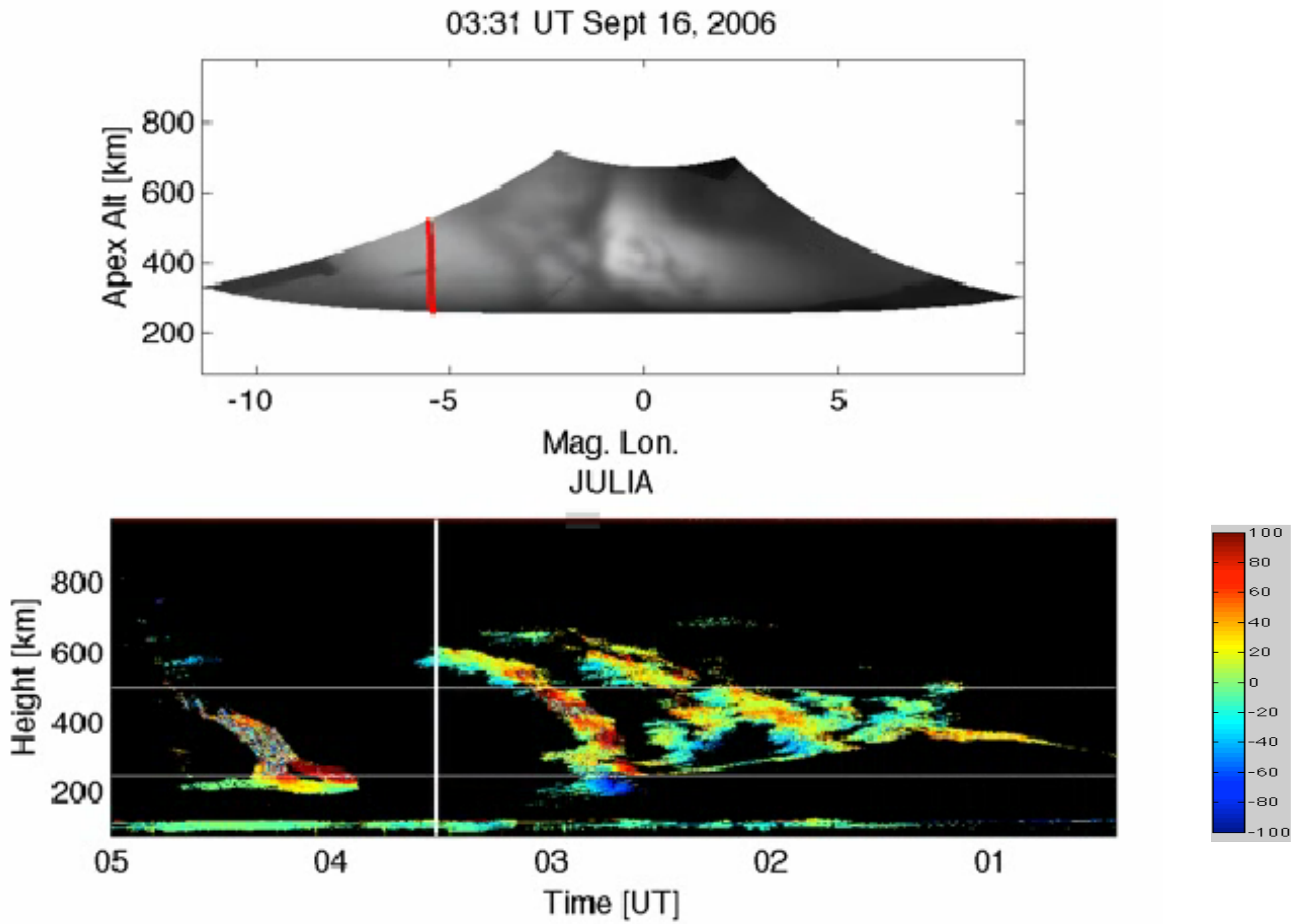
Radar "Slit" Camera vs. Optical "Airglow" Camera

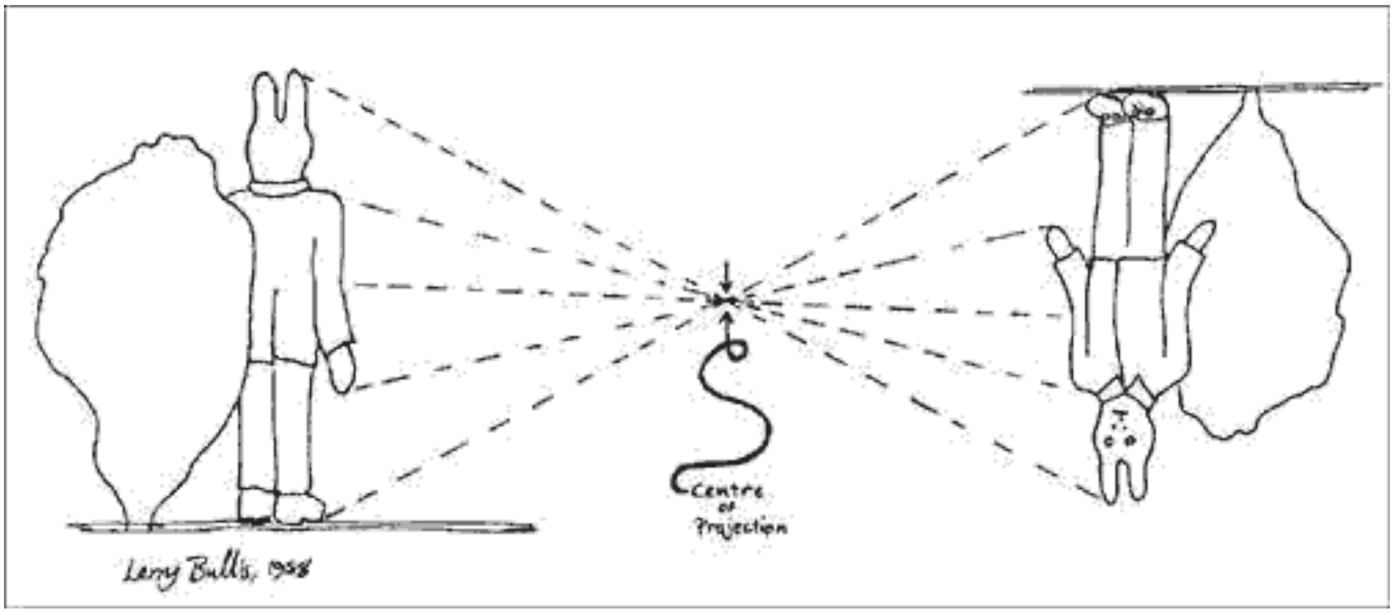


[*Courtesy of J. Makela*]

Atmospheric/Ionospheric Target

- In atmospheric applications, besides the problems of discriminating space-time features of moving structures across the beam, radar have finite beam widths and "irregularities" can appear, grow, dissipate, disappear, inside the beam!

Analogy with an Optical Camera (1)
The pin-hole camera

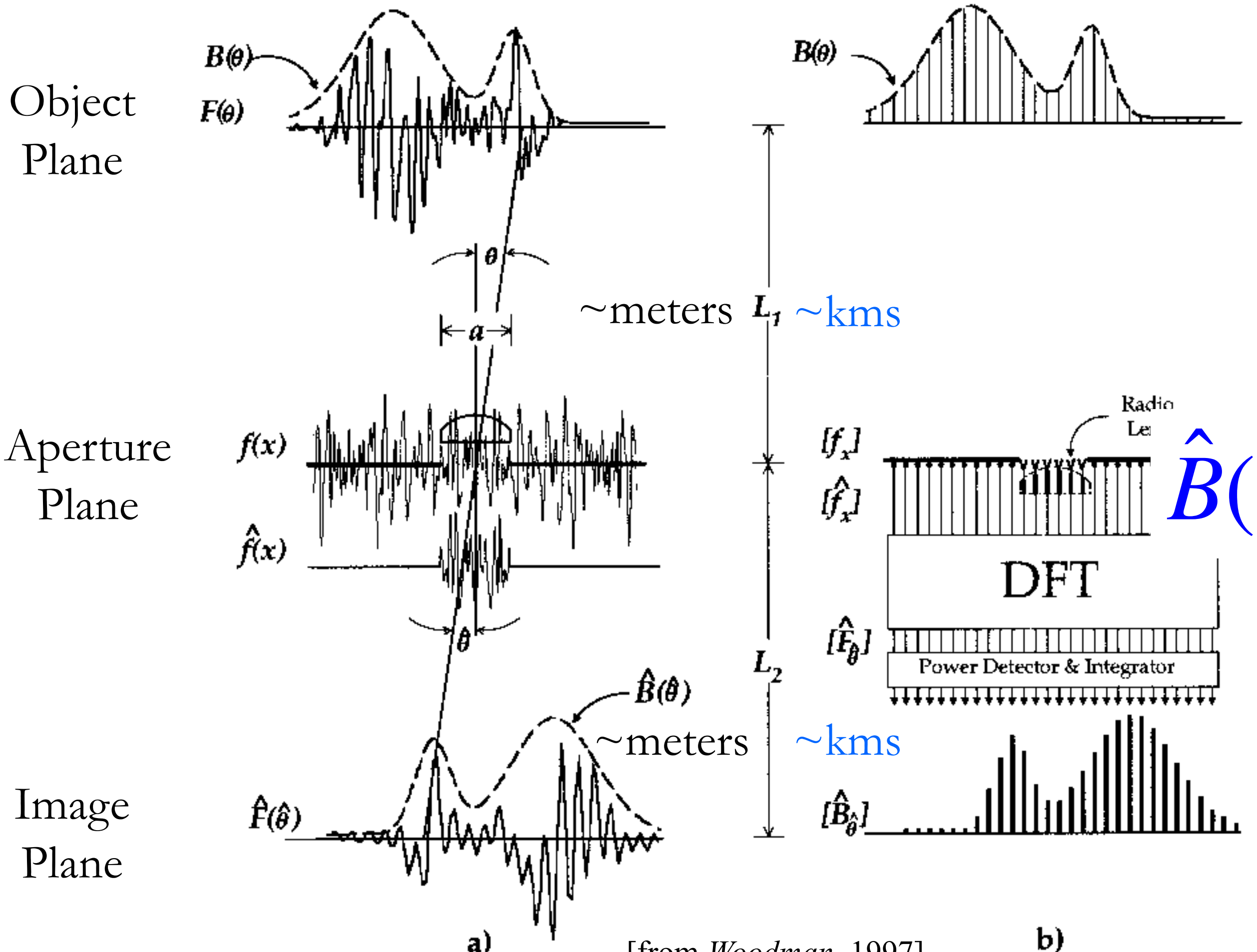


Object Aperture Image

Far field Far field

Optical wavelength ~ 500 nm

Analogy with an Optical Camera (2)
Fourier Operations



[from *Woodman*, 1997]

$B(\theta)$ True Brightness

$$B(\theta) \xleftrightarrow{Fourier} V(r)$$

$$\hat{B}(\theta) = A^2(\theta) * B(\theta)$$

$$\hat{B}(\theta) \xleftrightarrow{Fourier} \hat{V}(r)$$

$\hat{B}(\theta)$ Estimated Brightness

- •In radio astronomy: Camera without “flash”
- •In radar imaging: Camera with “flash”

Aperture Synthesis Radar Problem

Given:

$$\hat{V} = \mathbf{a} * \mathbf{a}^* \times \mathbf{M}\mathbf{B}$$

- find $\hat{B}$ that best agrees with B.
- where **a** can be an arbitrary complex vector, e.g.,
  - Truncation (like windowing in spectral analysis)
  - Gaps
  - Focusing (needed for near-field applications)

Ionospheric Radar Imaging: Peculiarities of the target

Radio Observatorio de JICAMARCA Radio Observatory

- Spatially 3D.
- Changes with time in two different time scales:
  - short, that defines the "color" (frequency spectrum)
  - long, non-stationary scale.
- It is non stationary and non homogeneous, representing a stochastic process of 4 dimensions.
- Normally, once has a small number of independent samples to average.
- Given these characteristics, how do we solve the problem?
  - Shall we do a simple Fourier inversion?
  - Are there any constraints or a priori information that we could consider? If so, how?

Aperture Synthesis Radar Imaging Algorithms

Radio Observatorio de JICAMARCA Radio Observatory

- Beamforming or Non-parametric Methods. These methods do not make any assumption on the covariance structure of the data.
  - Fourier-based
  - Capon or Linear Constraint Minimum variance beam forming
- Parametric methods. These methods usually make use of a known functional form B, error covariances, or other *a priori* information.
  - **Maximum Entropy** [e.g., *Hysell and Woodman*, 1997; *Hysell and Chau*, 2006]
  - Model fitting. For example, a Brightness modeled by N anisotropic Gaussian blobs [e.g., *Chau and Woodman*, 2001]
  - Single value decomposition (SVD)+MUltiple SIgnal Classification (MUSIC) (developed for the localization of discrete scatterers)
- Other
  - CLEAN, RELAX (Super CLEAN) (from Radio Astronomy)
  - APES, variants of Capon, etc. (from high resolution spectral analysis)

Maximum Entropy Method (MaxEnt)

Radio Observatorio de JICAMARCA Radio Observatory

- Model-based inversion process where $B(\theta,\omega)$ is a positive definite function constrained to be consistent with the data ($\hat{V}(\mathbf{r},\omega)$) to a specified accuracy (based on self and statistical errors).

$$\hat{B}(\theta,\omega) \propto \frac{e^{-\lambda_j h_j(\theta)}}{\int e^{-\lambda_j h_j(\theta)} d\theta}$$

λ_j : Lagrange multiplier, one for each visibility measurement

$h_j(\theta)$: point-spread function of the interferometer

denominator: like the Gibbs canonical partition function

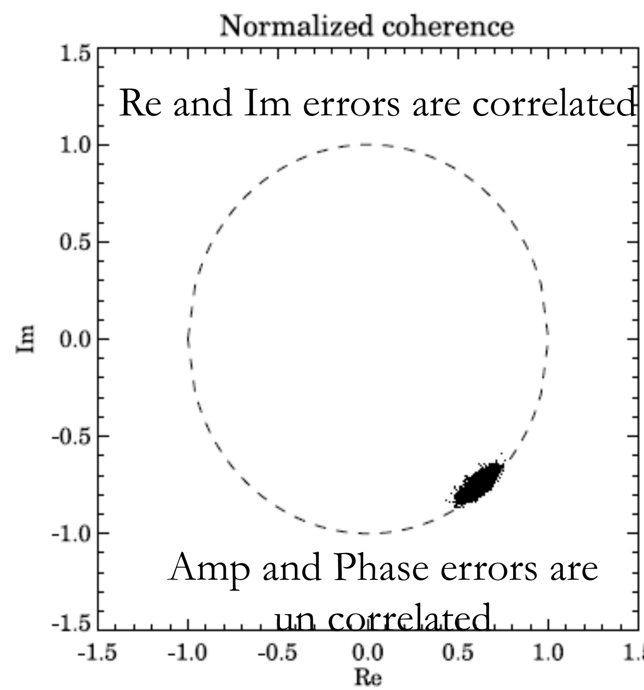
- By maximizing the Shannon Entropy ($S \propto B_j \log B_j$), including the constraints, one gets a well-posed set of N simultaneous non-linear equations for N Lagrange multipliers.
- The estimation problem is reduced to solve numerically the set of non-linear equations (e.g., Powell method).
- It is a method that "deconvolves" via regularization.

MaxEnt: Recent Improvements

- Use of a priori information,
  - Transmitting beam pattern (avoids estimating the image in a region that is not illuminated)
  - Different receiver beam patterns (allows the use of different receiver antenna sizes).
- Full-covariance matrix. Errors between Re and Im components and between baselines are no longer assumed to be uncorrelated.
  - Data and model need to be diagonalized.

[from *Hysell and Chau*,2006]

$$\delta^2 = \frac{1}{m}\left(\frac{S+N}{S}\right)^2 \Big[\rho_{13}\rho_{24}^* - \frac{1}{2}\left(\frac{S+N}{S}\right)\rho_{34}^*(\rho_{13}\rho_{23}^* + \rho_{14}\rho_{24}^*) - \frac{1}{2}\left(\frac{S+N}{S}\right)\rho_{12}(\rho_{13}\rho_{14}^* + \rho_{23}\rho_{24}^*) + \frac{1}{4}\left(\frac{S+N}{S}\right)^2 \rho_{12}\rho_{34}^*\left(|\rho_{13}|^2 + |\rho_{14}|^2 + |\rho_{23}|^2 + |\rho_{24}|^2\right)\Big]$$



How to display radar images (1)

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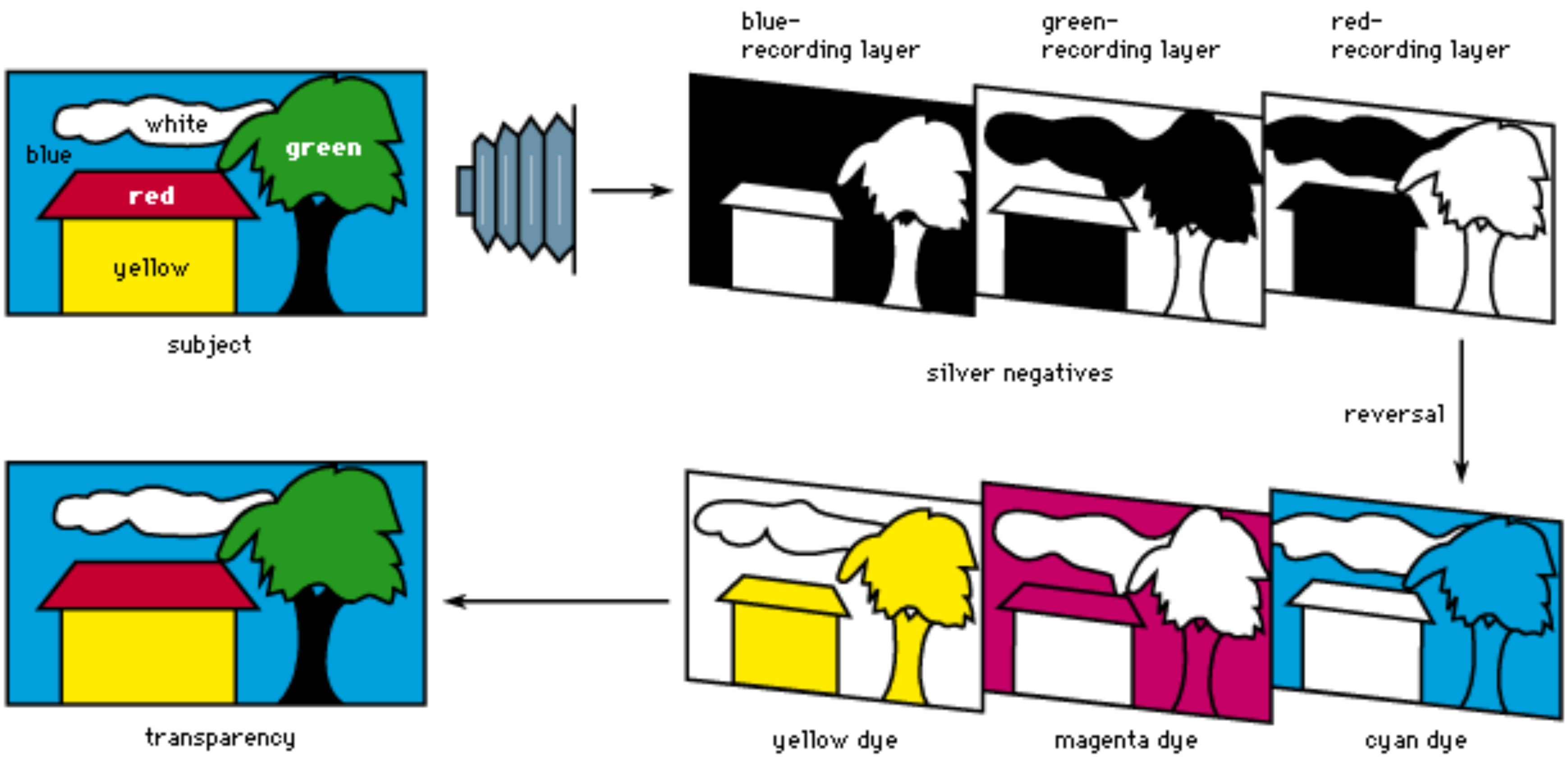

How to display radar images (2)

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- Recall that an angular image is obtained as a function of range and Doppler frequency, every integration time.
- To extend the optical analogy further, images are color-coded based on Doppler information.
- 8-bit images are obtained for each color: Red (R), Green (G), and Blue (B).
- The SNR of each Doppler interval is represented by the intensity of the respective color (0-255).
- A 24-bit true color image is obtained by combining the R, G, and B images.
- Movies are obtained by joining all images into standard movie formats (e.g., GIF animation, MPEG, AVI), resulting into a Radio Movie Camera!
- Lightness: SNR, Saturation: Spectral width, Hue: Doppler

How to display radar images (3)

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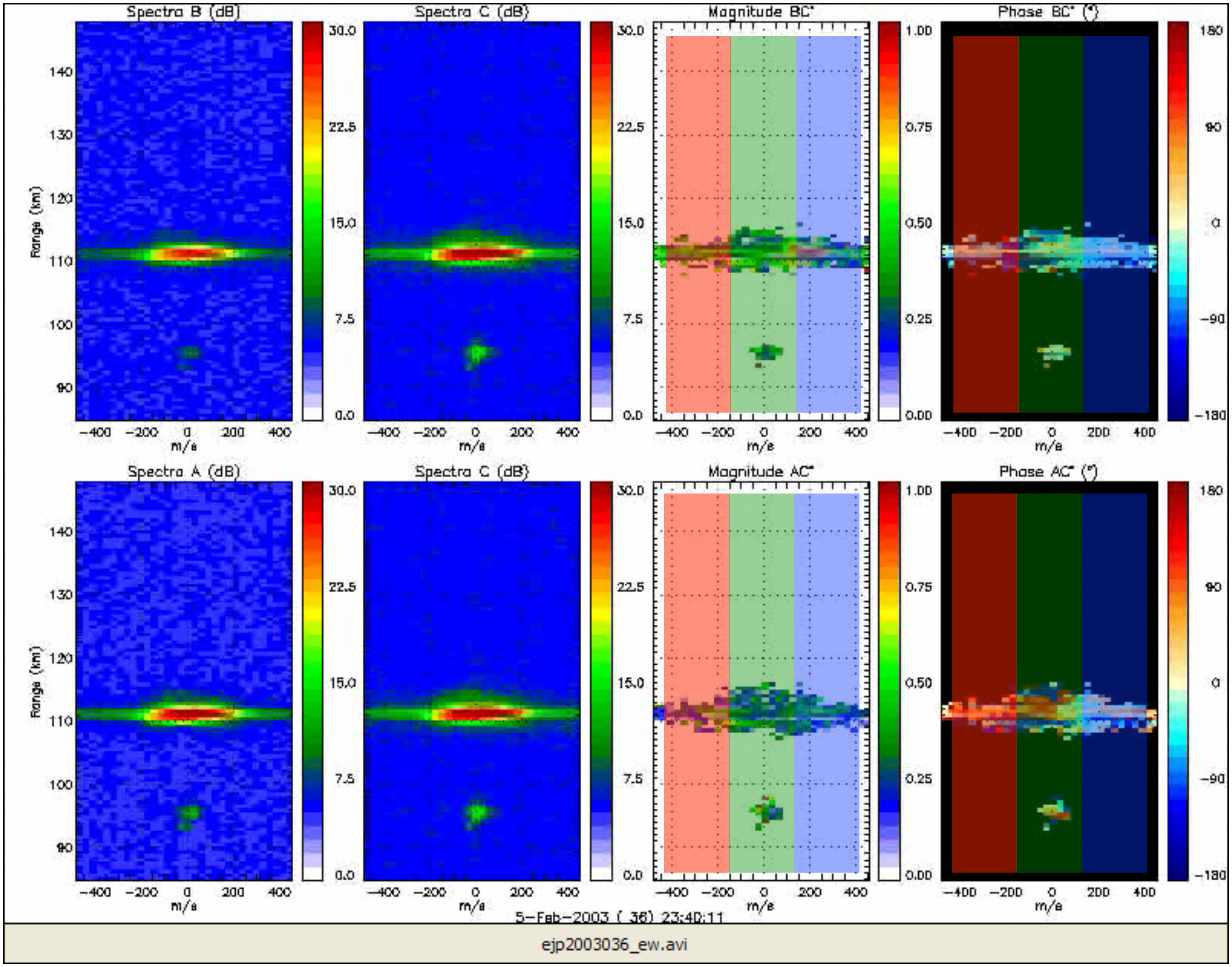

How to display radar images (4)

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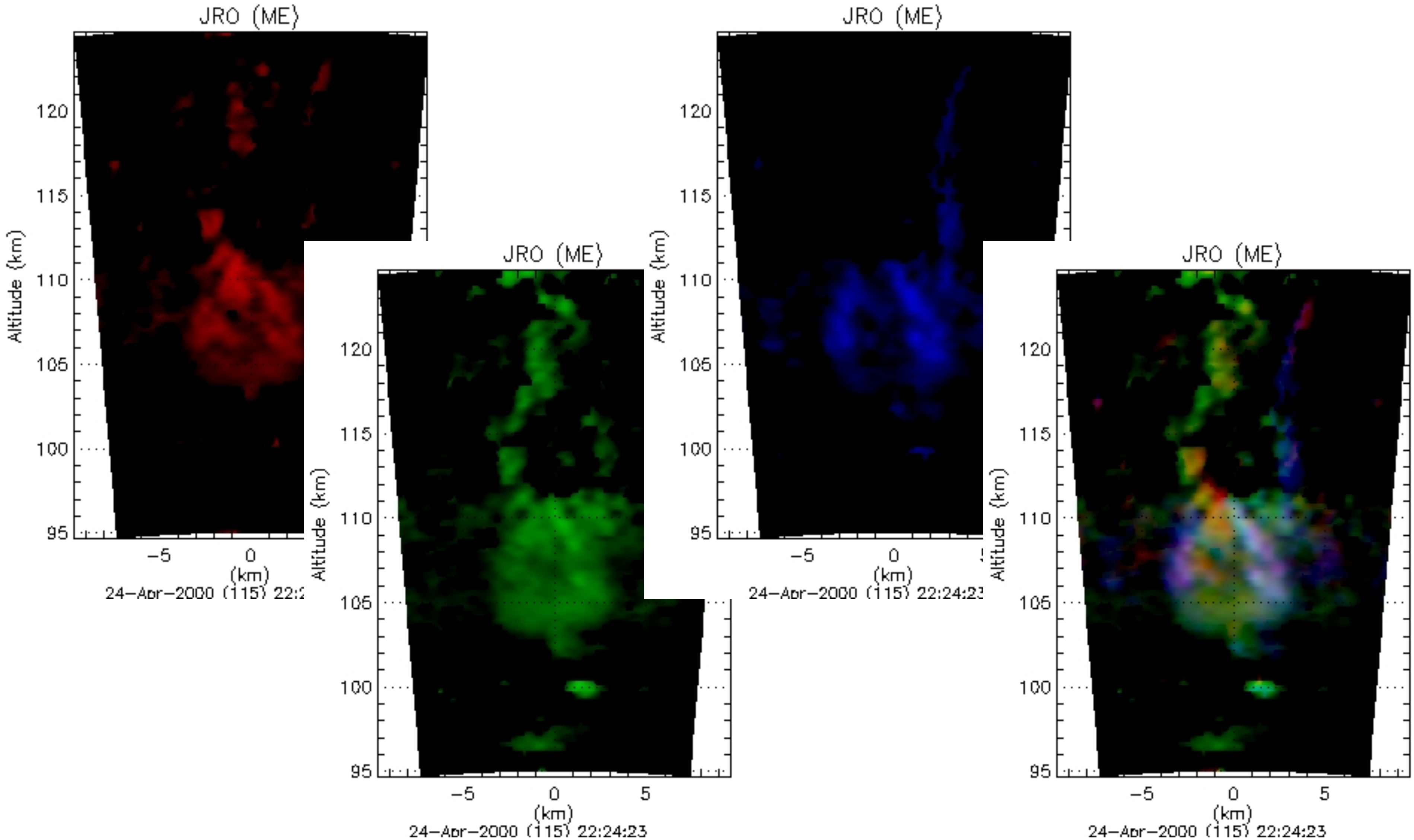

Latest examples of ESF Radar Imaging at Jicamarca

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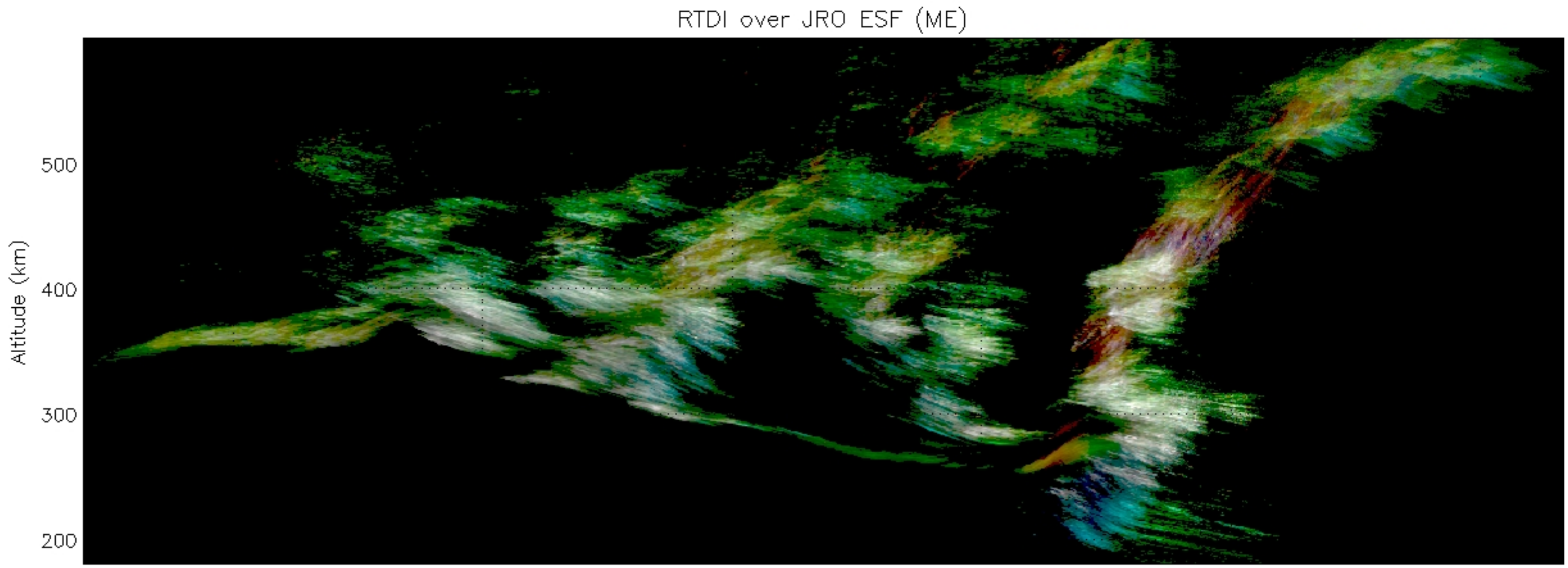
- Tx using two quarter antennas, phased to have a wide beam in the EW direction.
- 8 digital Rx channels for "imaging". A pair of modules can be used for single baseline interferometry.
- Automated phase calibration procedure, using beacon on the hill (relative). Absolute calibration from Hydra, meteor-heads, …
- 16-32 "colors" (FFT points)
- ESF images are obtained every 2 seconds and 300 m. The angular resolution is ~0.1-0.2^{o}

ESF RTDI: Slit camera interpretation



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.

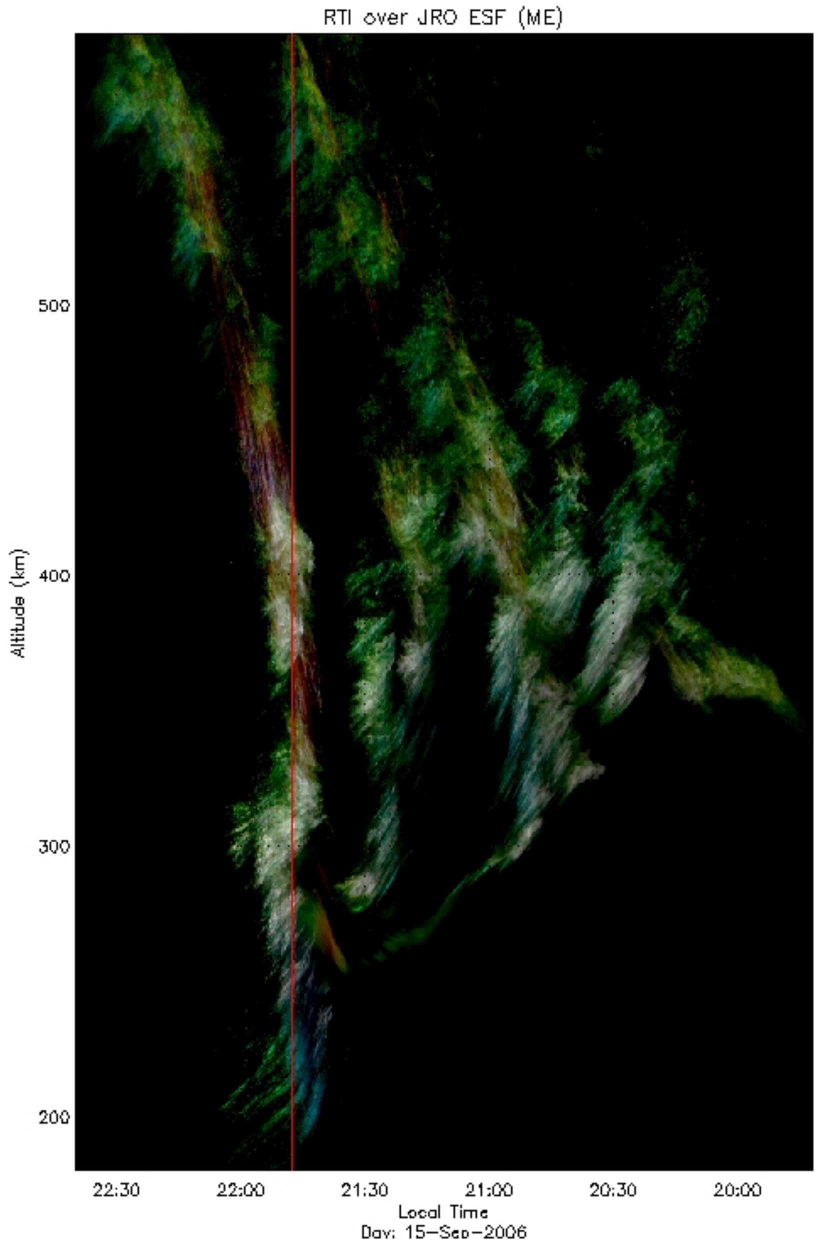
ESF RTDI + Imaging (1)

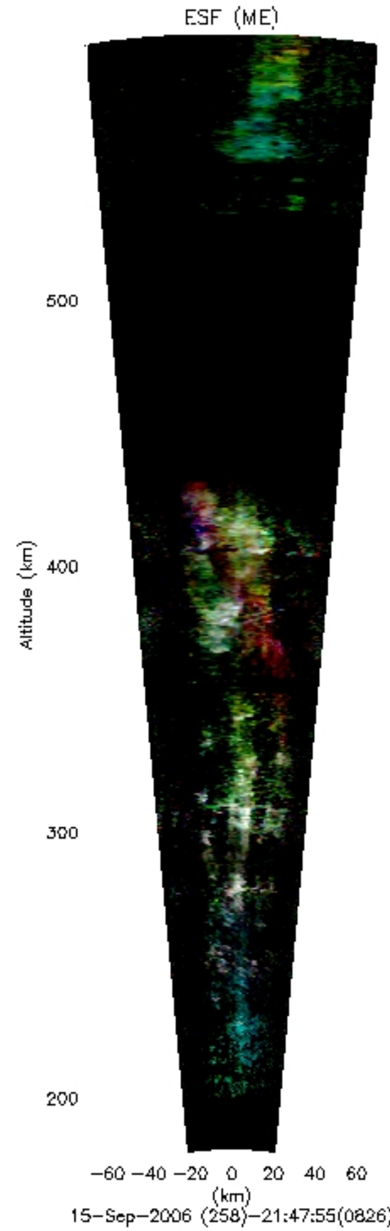
500

400

300

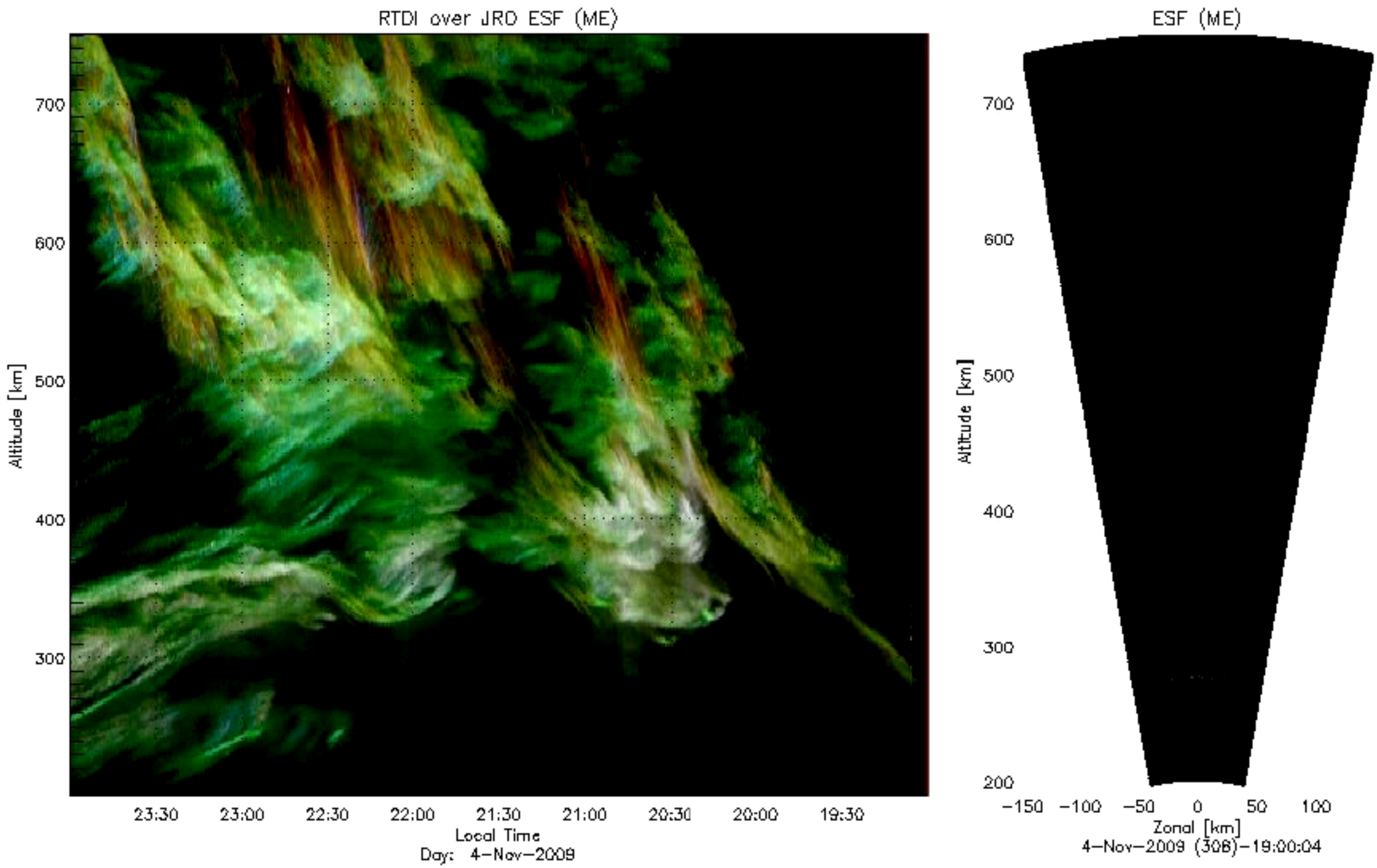
200



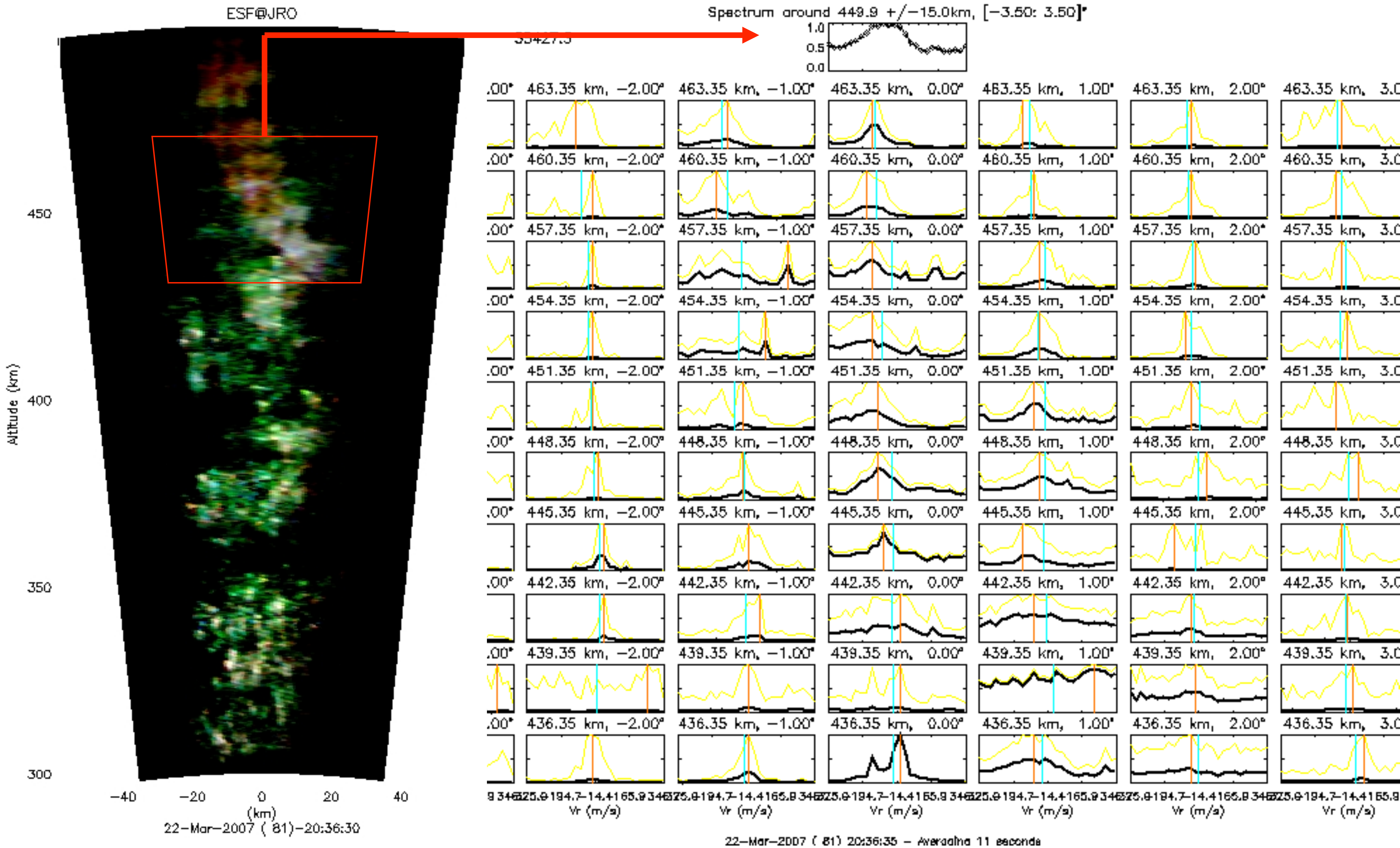


[from *Chau et al.*, 2008]

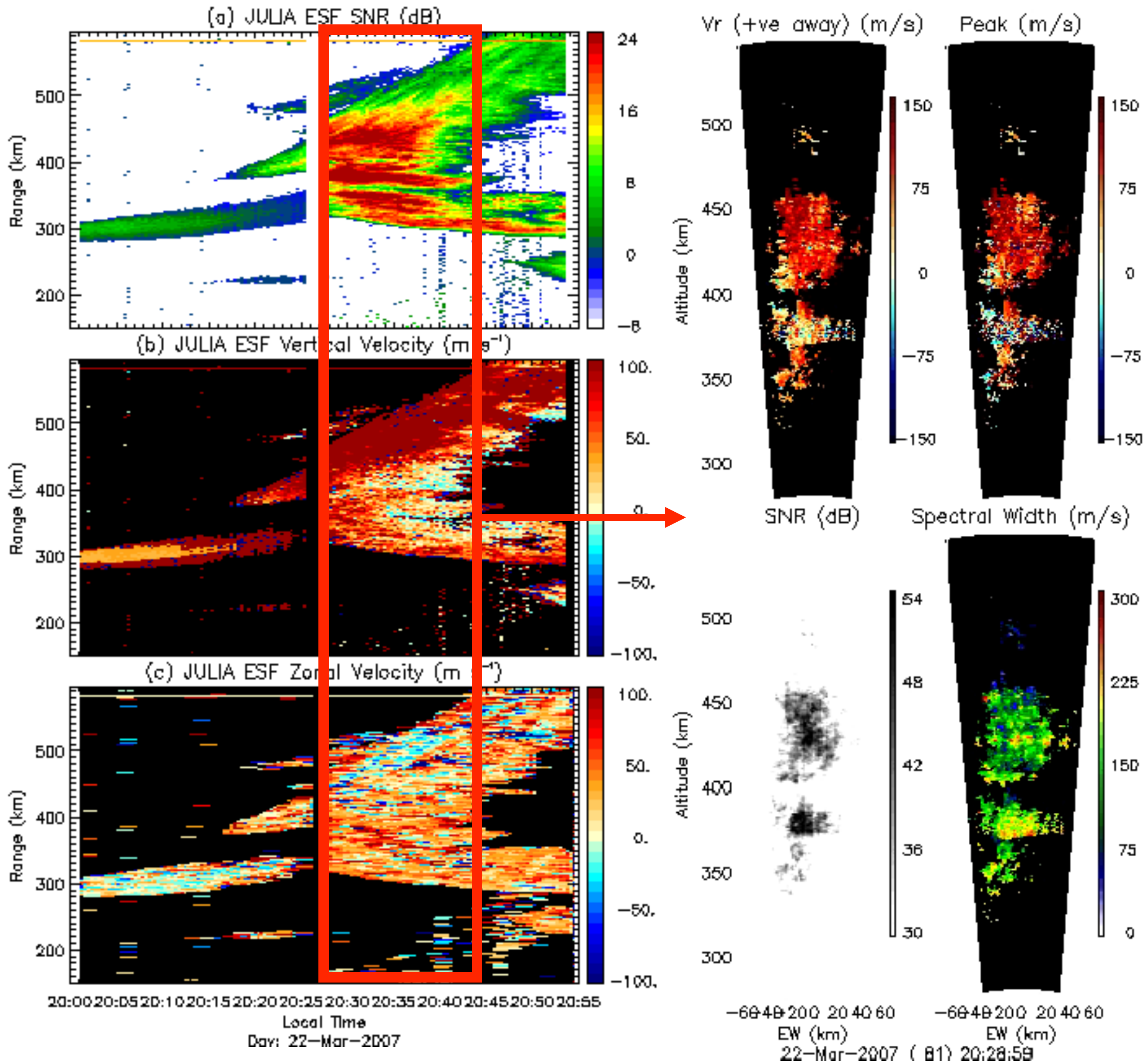
ESF RTDI + Imaging (1)



Spectra cuts from Imaging results



Multi-beam Radar Observations from "Imaging"



- JULIA-like parameters can be obtained from interferometry using a pair of antennas (SNR, mean vertical Doppler, zonal drift).
- Using imaging, we can get the spectra for different synthesized beams and range resolutions. In this example, each synthesized "scattering volume" is 0.2° and 600m obtained every 10 sec.
- Investigate the possibility of estimating the irregularity spectrum by measuring the radar Doppler spectrum with different averaging volumes [e.g., *Hysell and Chau*, 2004]

ESF Imaging experiment with IPP=600: Frequency aliased spectra

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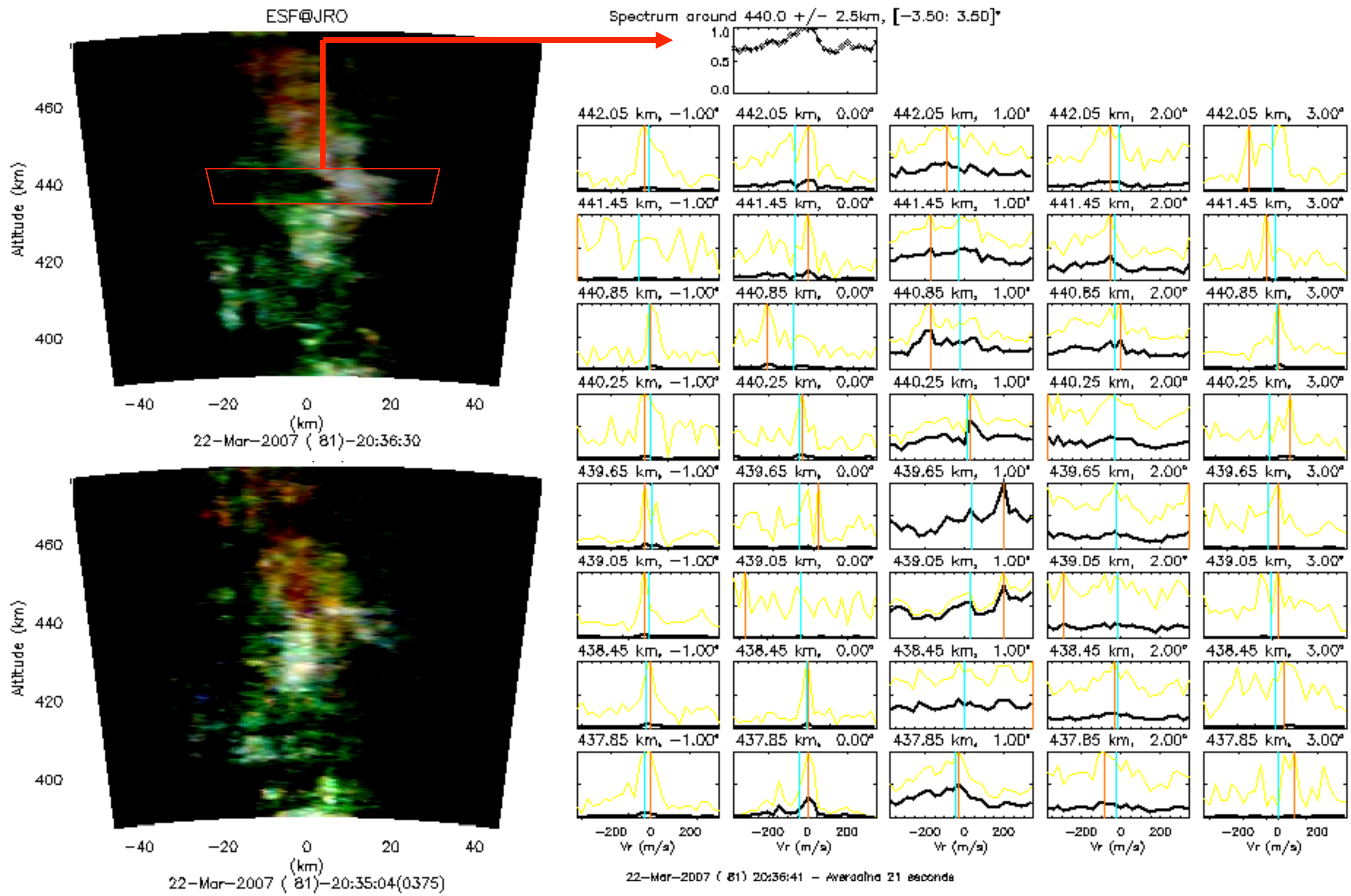
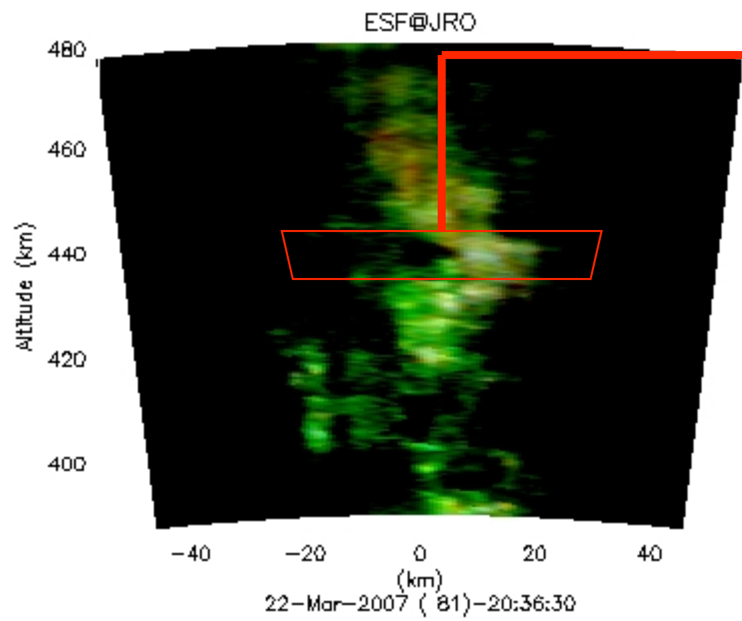
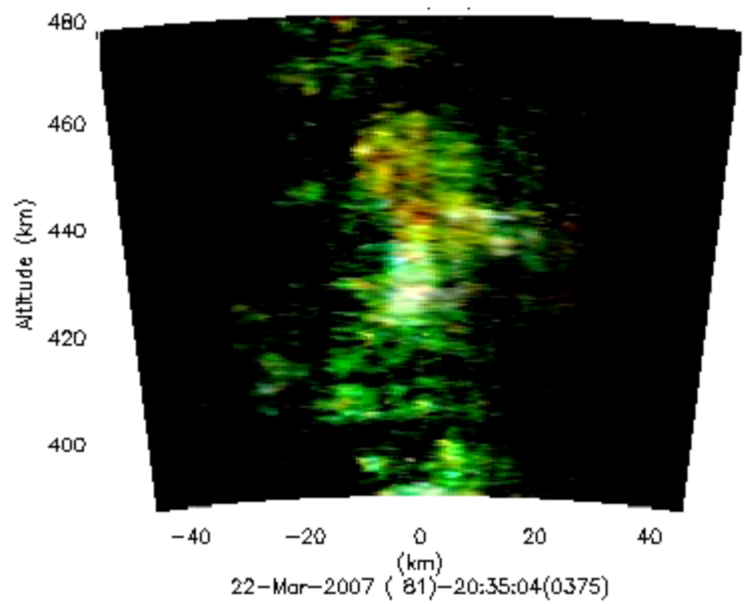
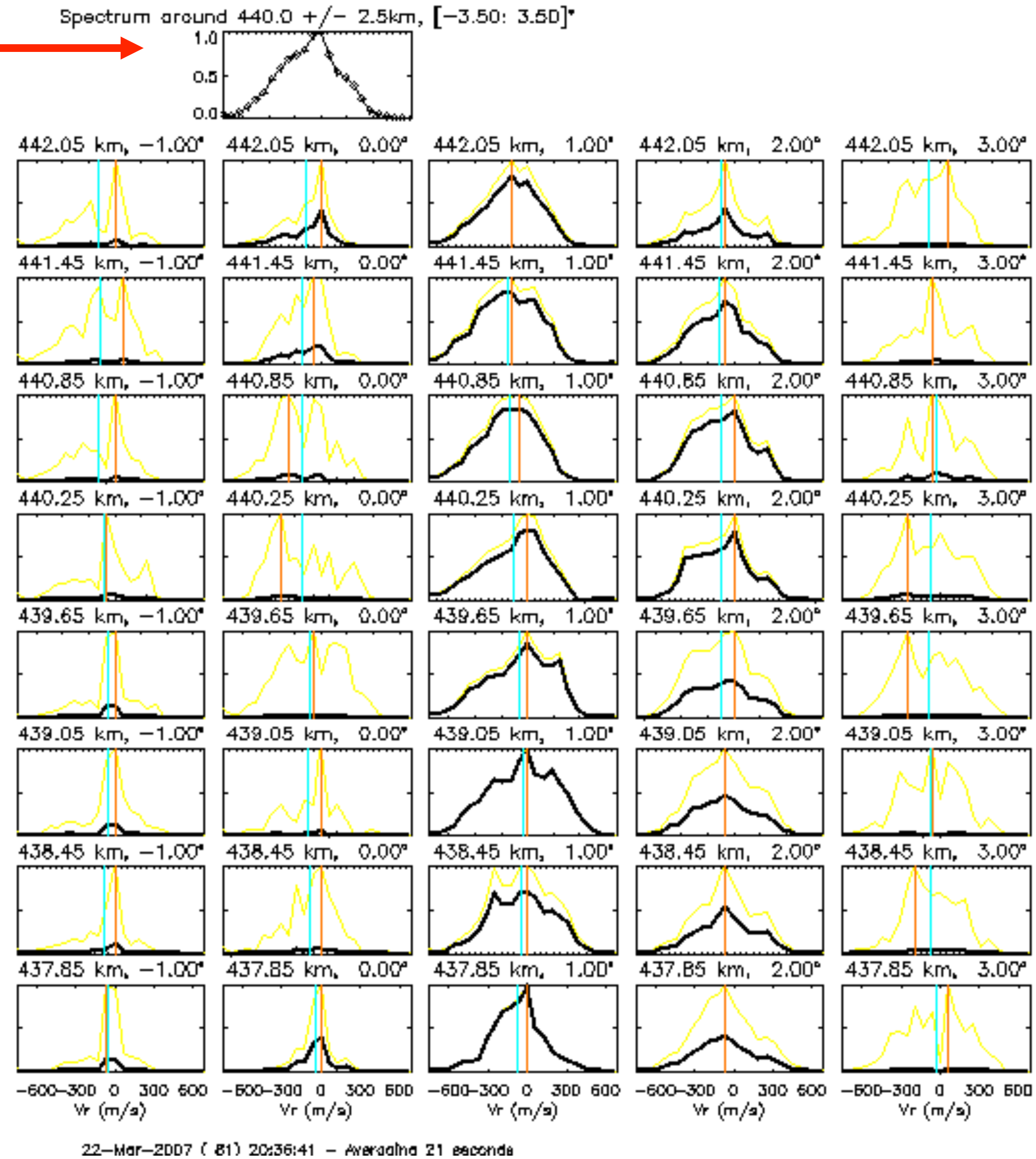


ESF Imaging experiment with IPP=300: Range aliased, but without frequency aliasing







Common volume: C/NOFS vs JRO

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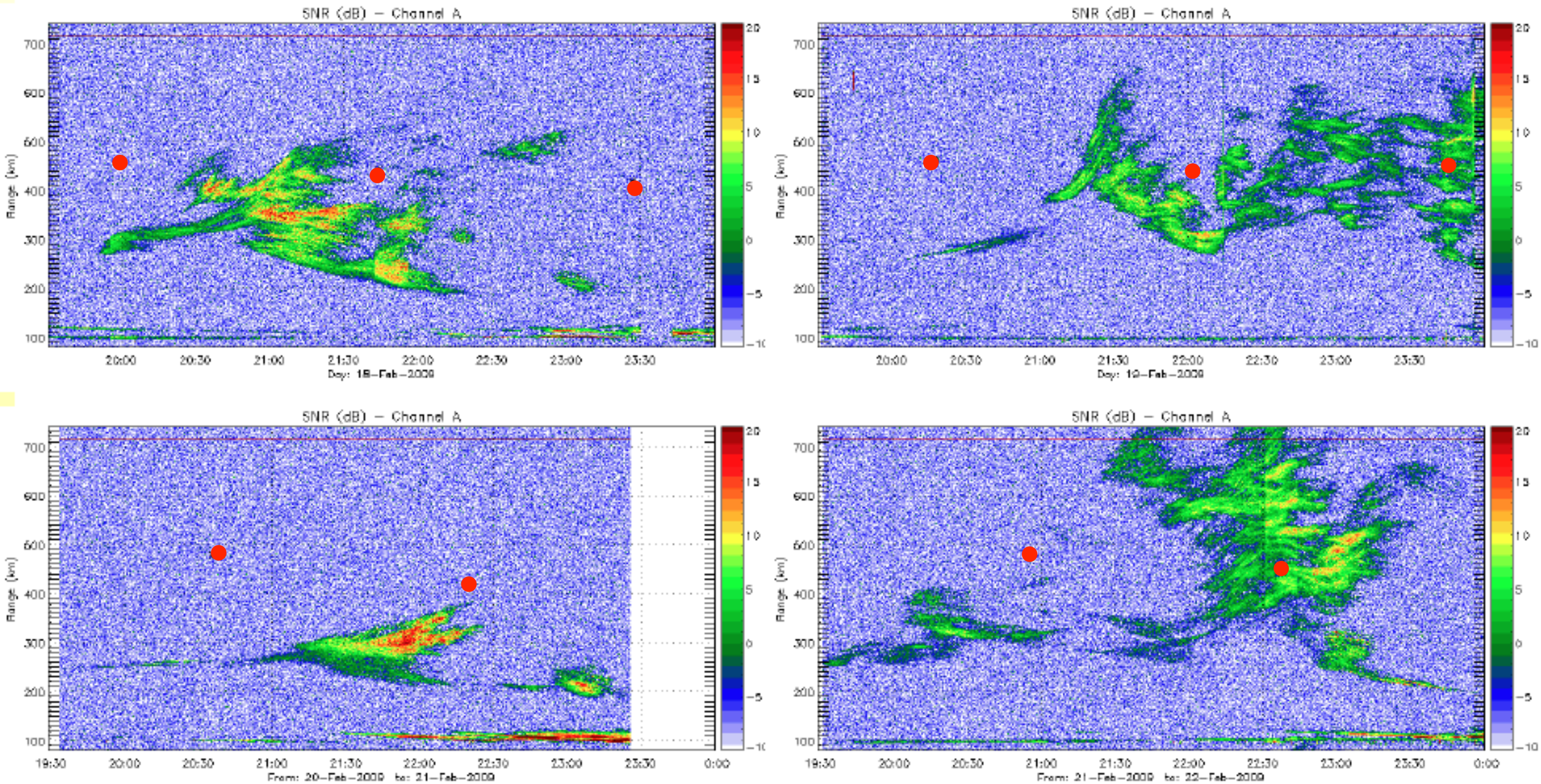

Irregularity comparison: In-situ vs. Radar

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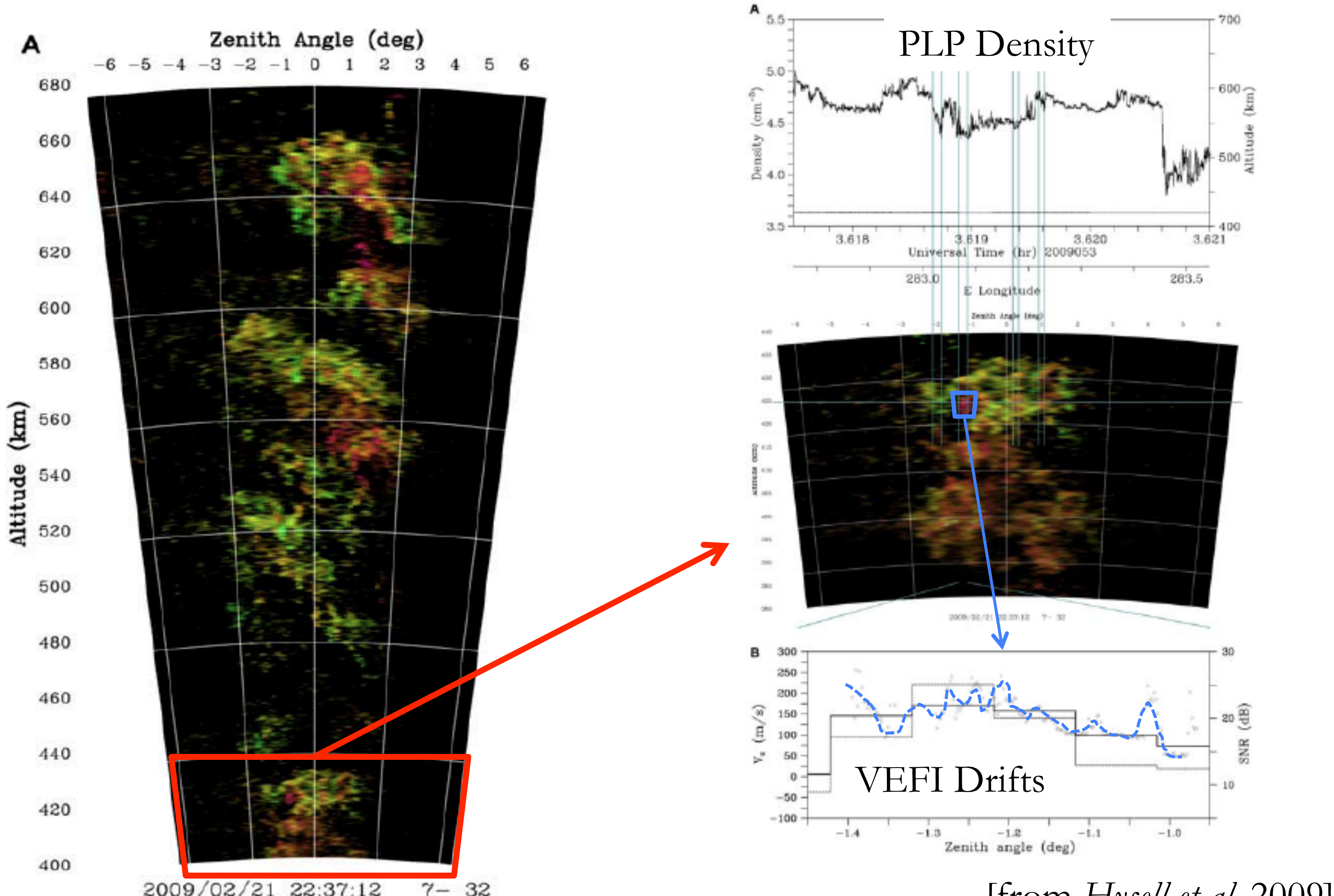

[from *Hysell et al.*,2009]

Kiitos