Radar calibration of mesospheric and ionospheric echoes based on the incoherent scatter and magneto-ionic propagation theories (MST-ISR 2 campaign)

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November 29, 2010

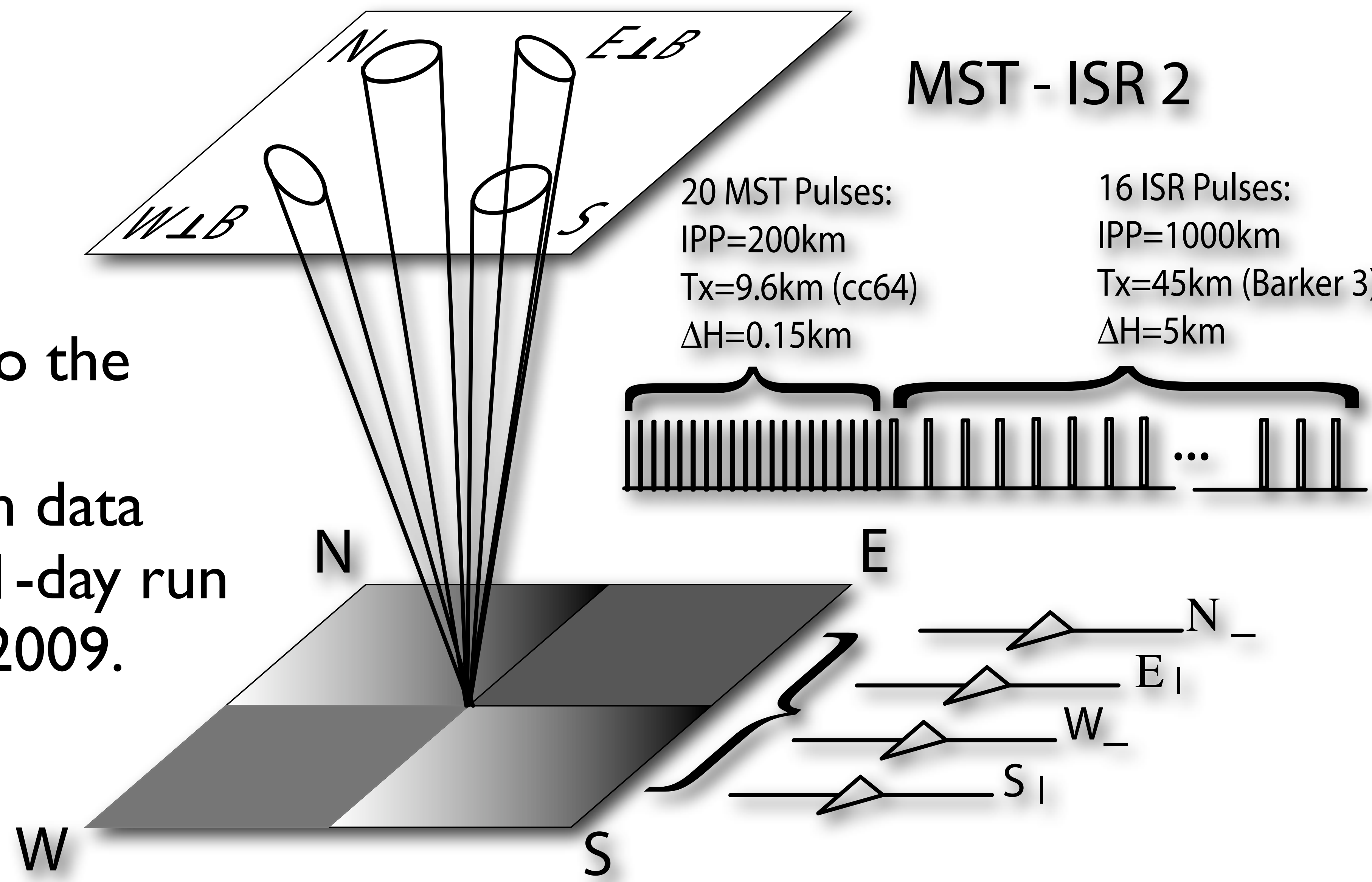
URSI PERÚ - II Encuentro Nacional de Radio Científicos e Investigadores Afines 2010

Pontificia Universidad Católica del Perú

Since Dec 2004, we have been sampling the F-region incoherent scatter returns in Jicamarca MST experiments in order to calibrate the data for absolute radar cross-section (RCS) measurements.

OUTLINE:

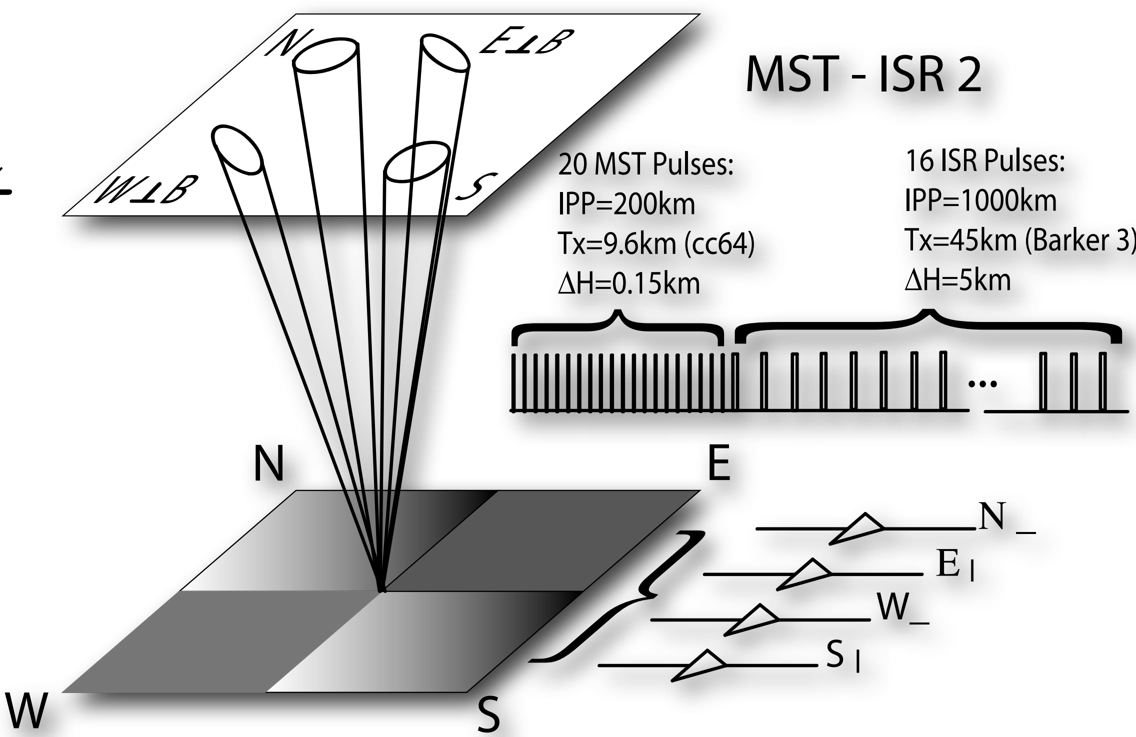
1) Describe how we do the calibration, and
2) Show examples with data collected during the 11-day run that took place in Jan 2009.



Absolute RCS measurements are possible by comparing the MST-scattered power with F-region ISR power because ISR power is proportional to the electron density that can be independently measured (or guessed).

$$\langle |V_r(t)|^2 \rangle = \frac{\kappa}{r^2} \int d\Omega \, G_{tx} G_{rx} \, \tilde{\sigma}$$

$$\tilde{\sigma} = 4\pi r_e^2 N_e f\left(\frac{T_e}{T_i}\right)$$

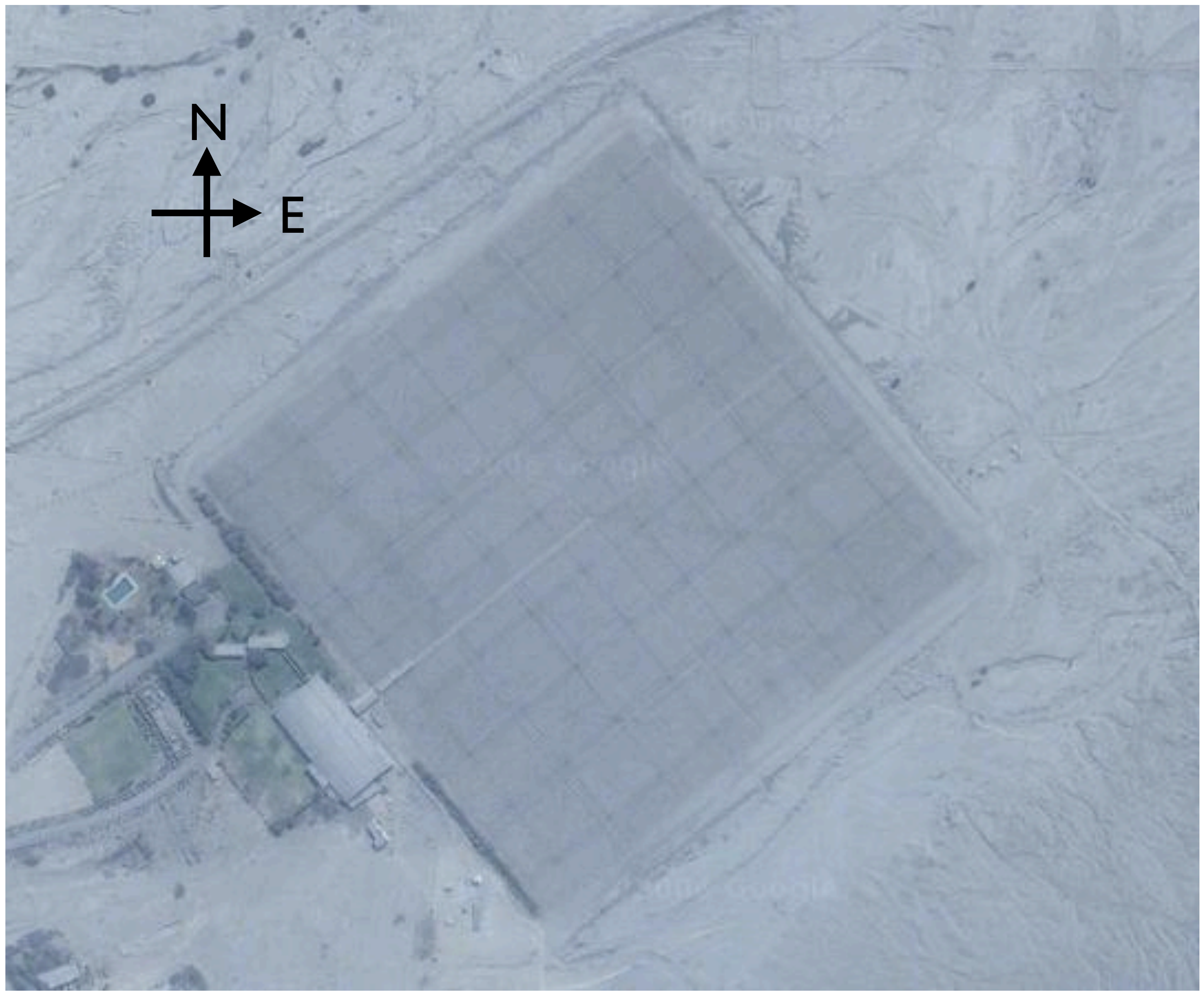


But there are complications:

1) The proportionality factor depends on Te/Ti

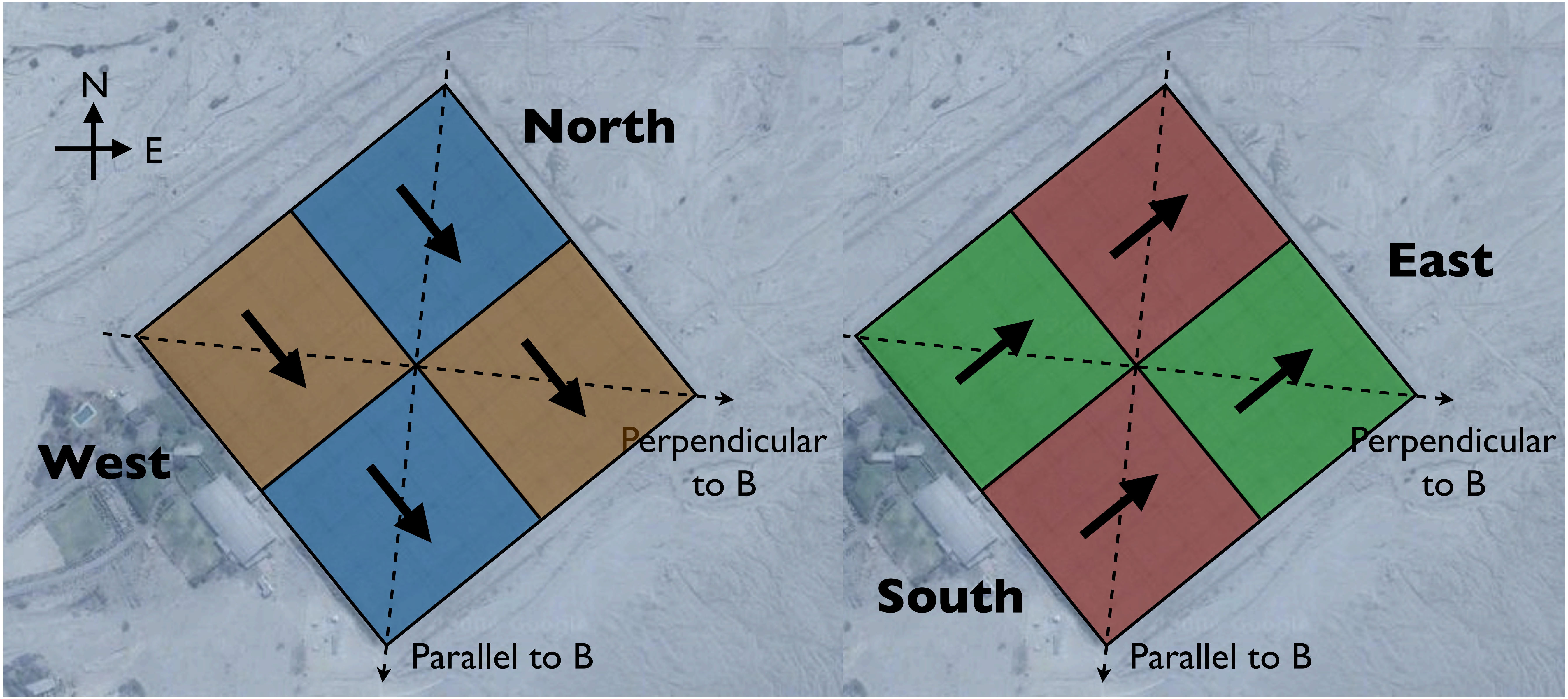
2) Unless a magneto-ionic "normal mode" is used for tx and rx, there are **magneto-ionic power distortions** --- wiggles --- to account for.

Jicamarca antenna array has 2 polarizations, each polarization is divided in quarters:



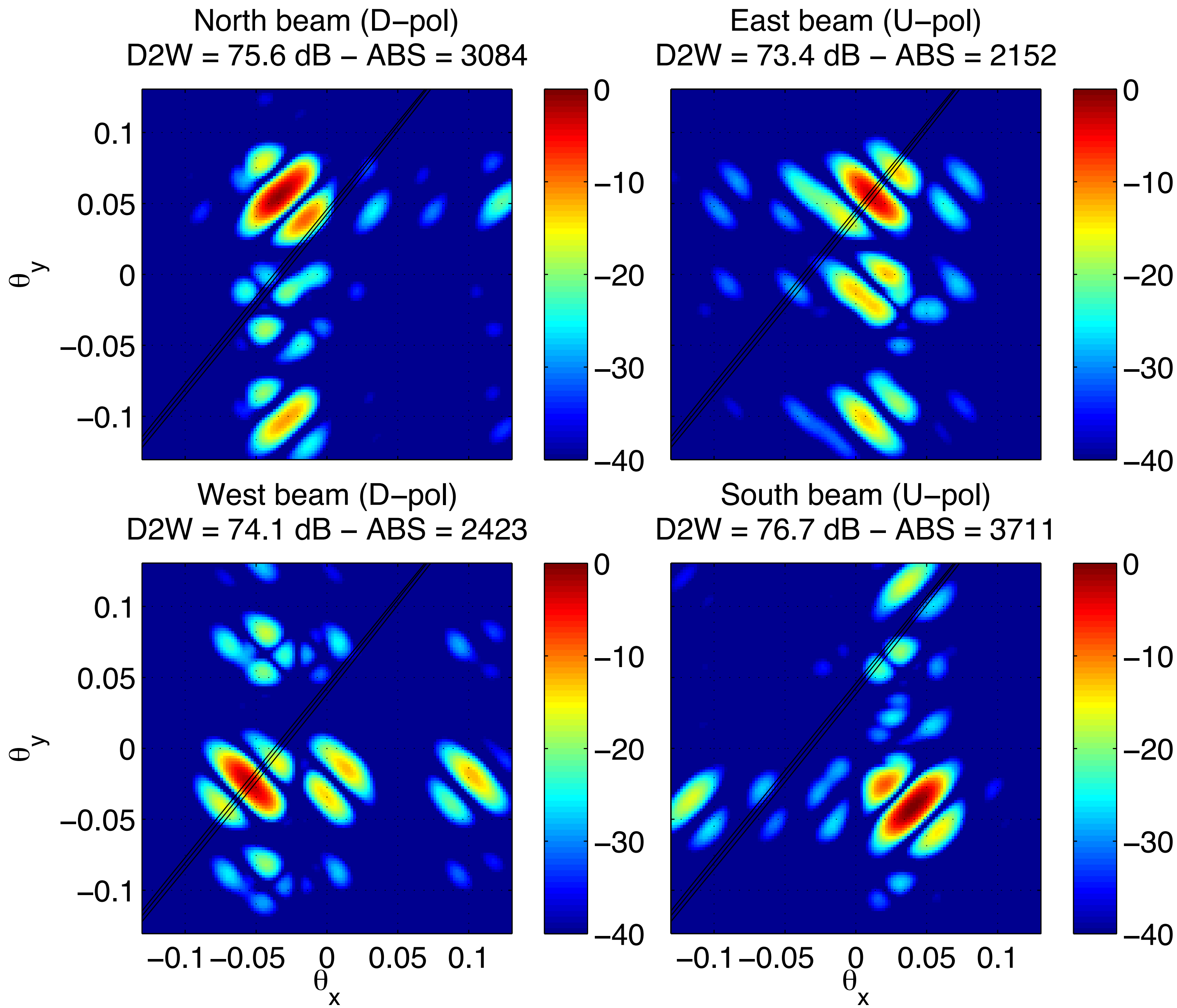
Jicamarca antenna array has 2 polarizations, each polarization is divided in quarters:

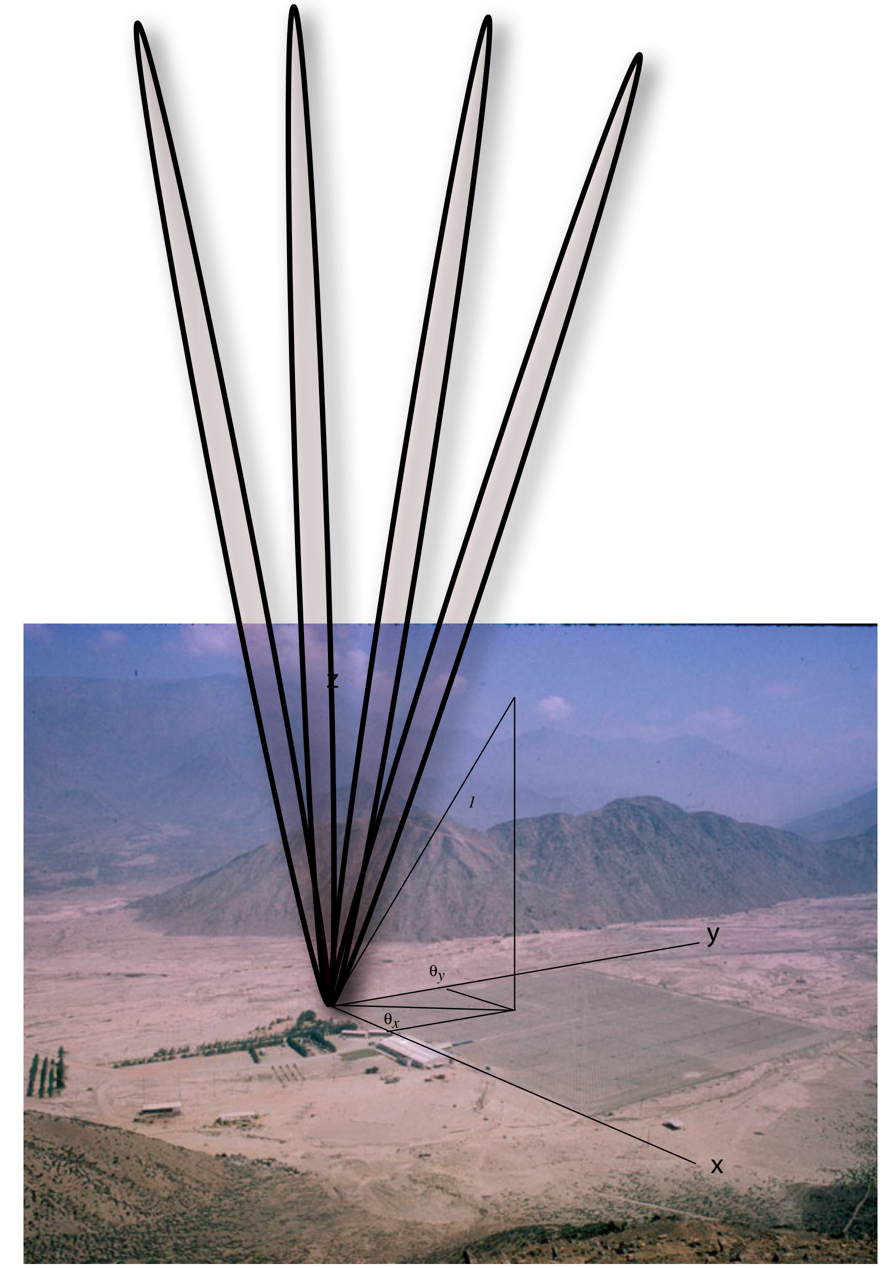
x-pol (D-pol) excites and detects the North and West beams



y-pol (U-pol) is used for East and South beams

4 beams are synthesized using both polarizations

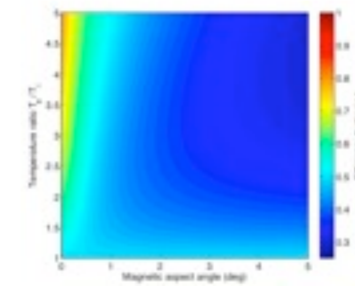




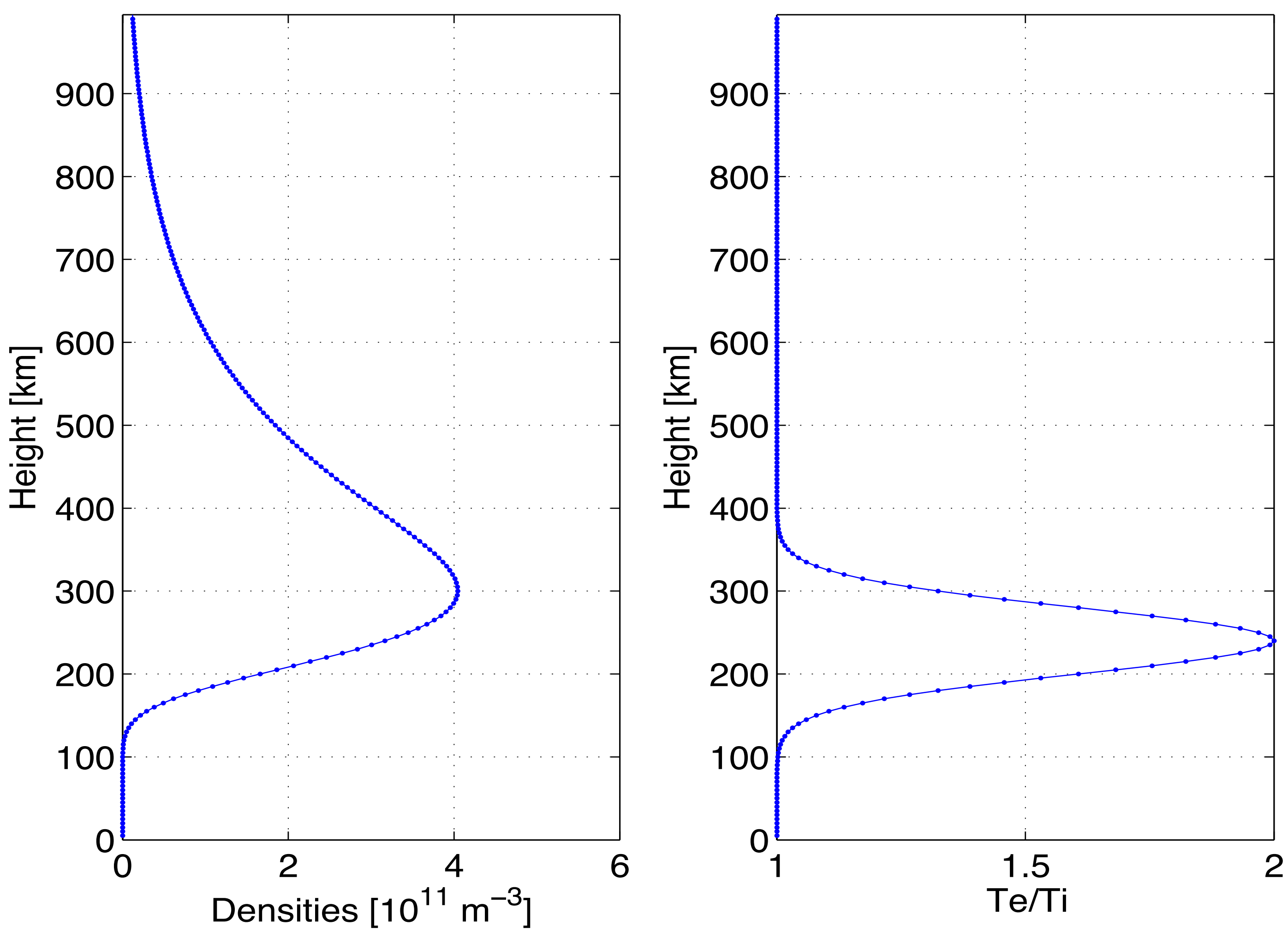
Magneto-ionic distortions cross-couple the beams because different beams have different aspect angles to **B**

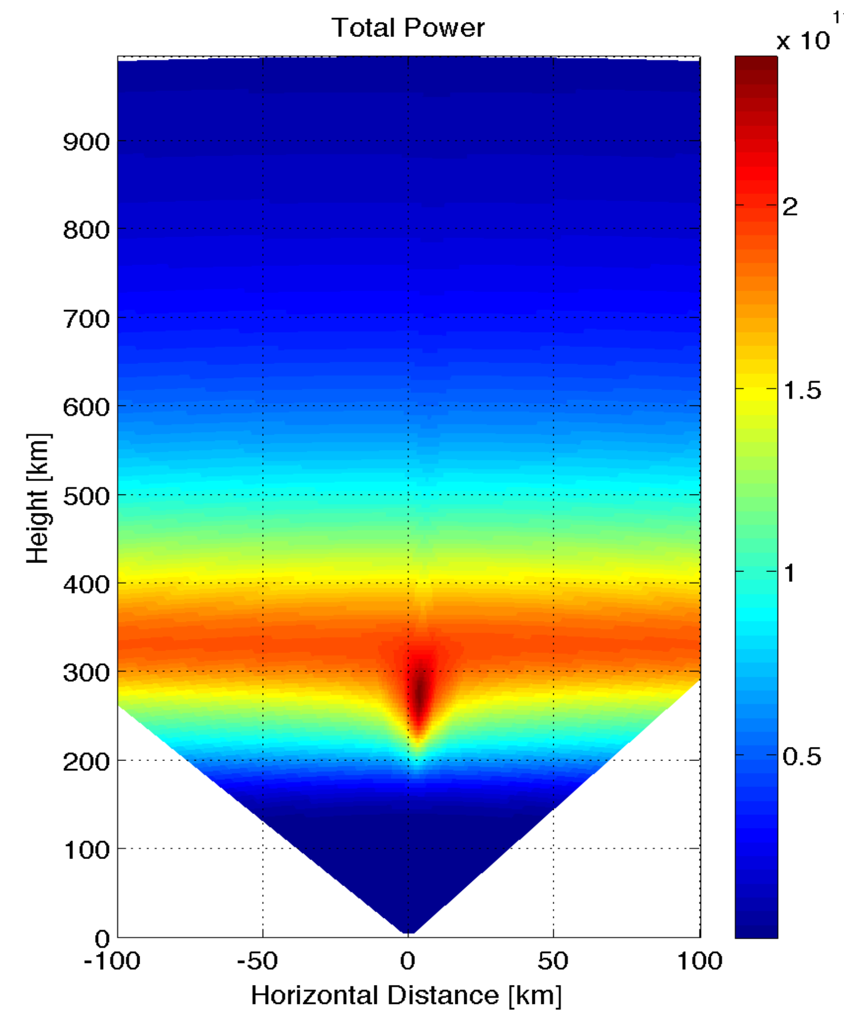
Basic idea used in the experiment: In an ionosphere with **Ne and Te/Ti profiles** shown on the left, a north-south beam scan would produce a **total backscatter power map** shown on the right, with the sharp enhancement ("dagger") in the direction where the radar beam is perpendicular to B:

$$P_s \propto \frac{N_e}{1 + T_e/T_i}$$ away from perp to B, otherwise $P_s \propto N_e \eta,\ \ \eta =$



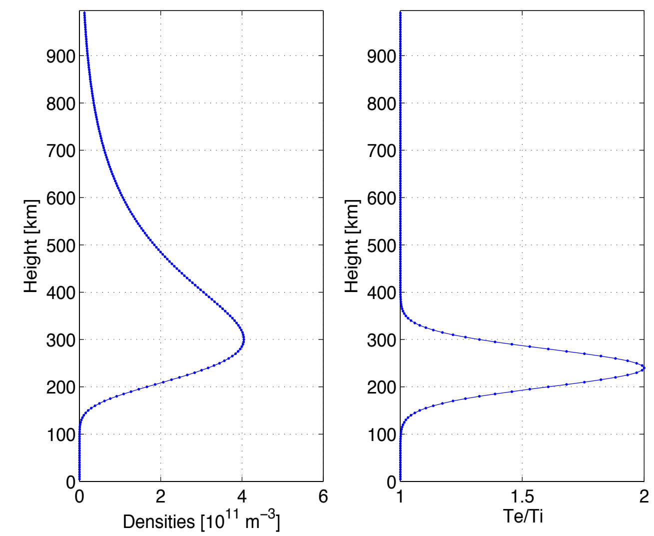
A scan like this cannot be done at JRO having fixed beams, but the effect has been observed and fully modeled at ALTAIR to estimate Ne and Te/Ti parameters from power scan data.

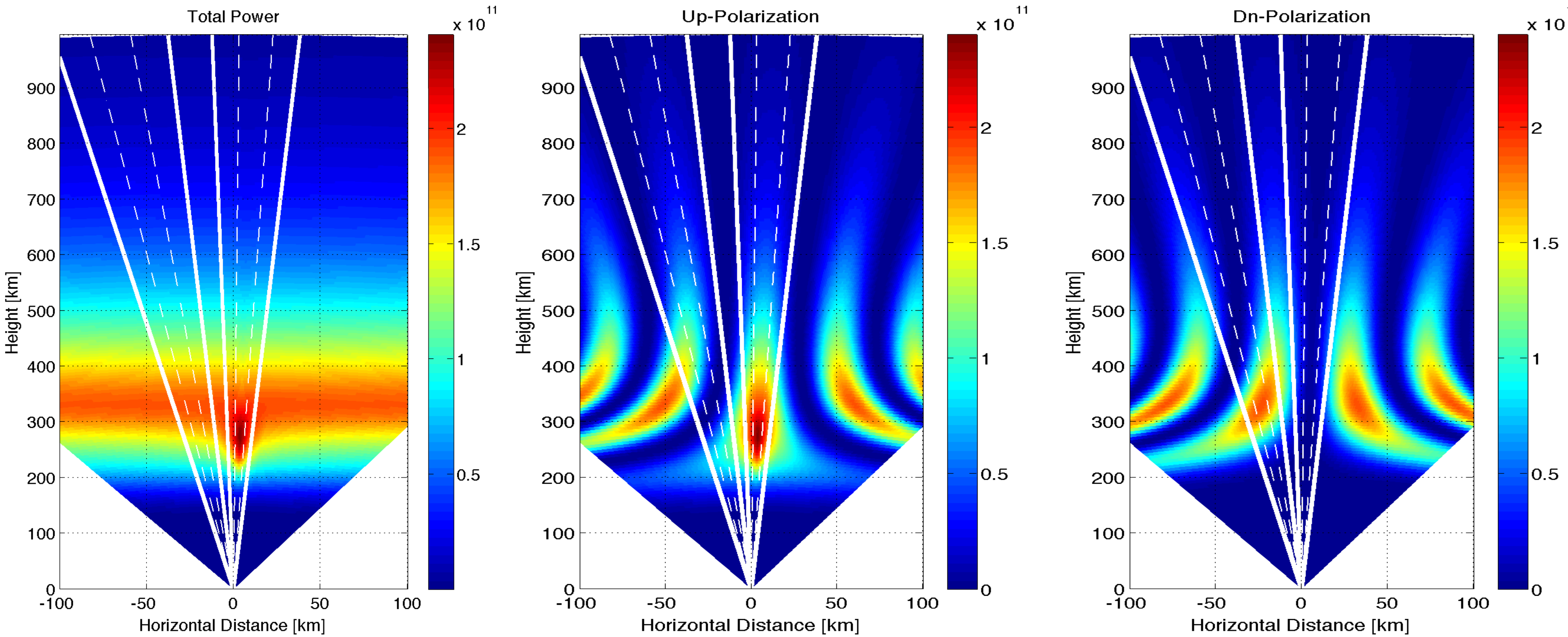




Simulated total power and JRO beams used in the experiment:

At JRO, operating at 50 MHz, MI-effects are important, and thus both "co-pol" and "x-pol" components of the scattered power need to be modeled and processed to make Ne and Te/Ti estimation.

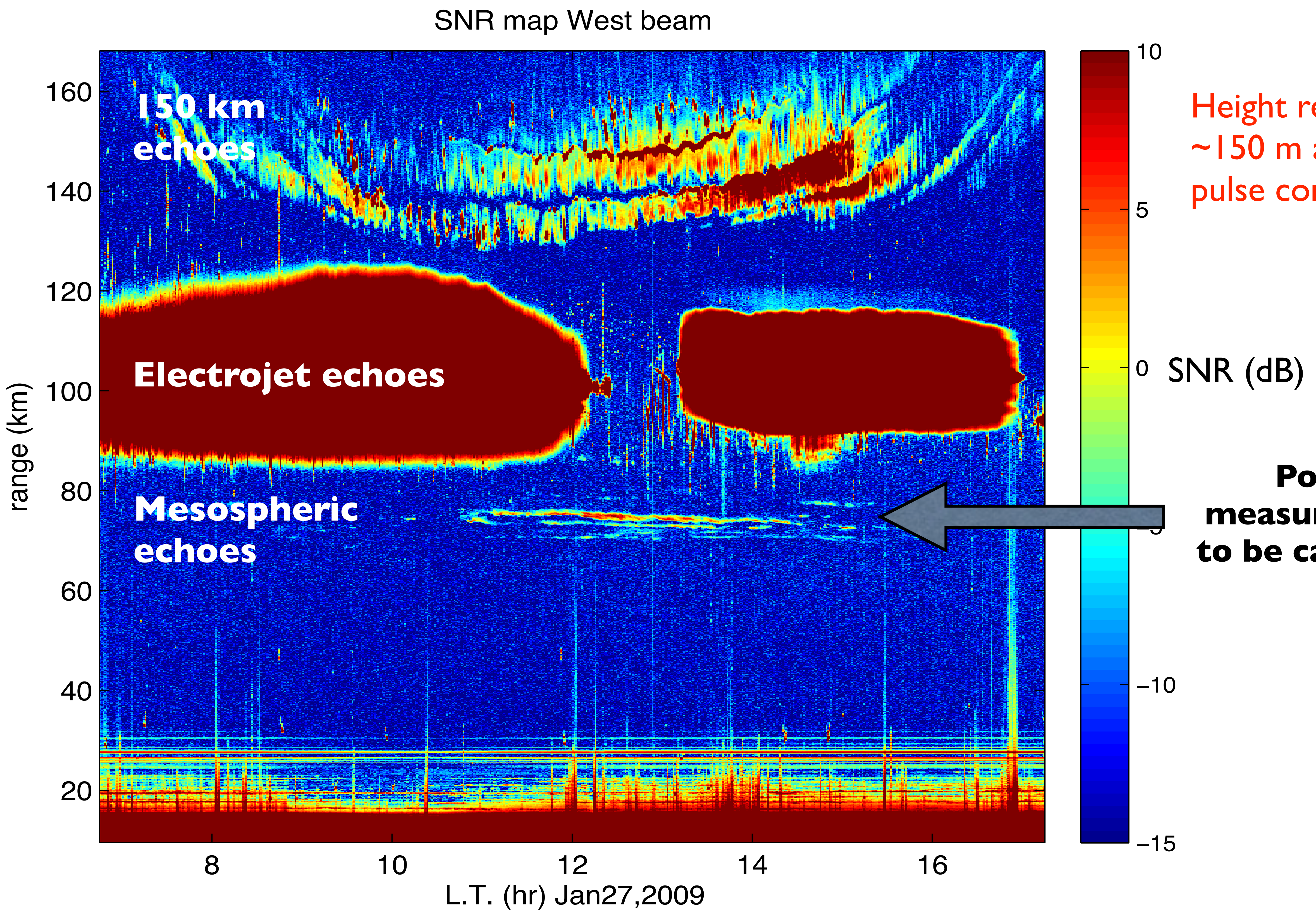




Co-pol

X-pol

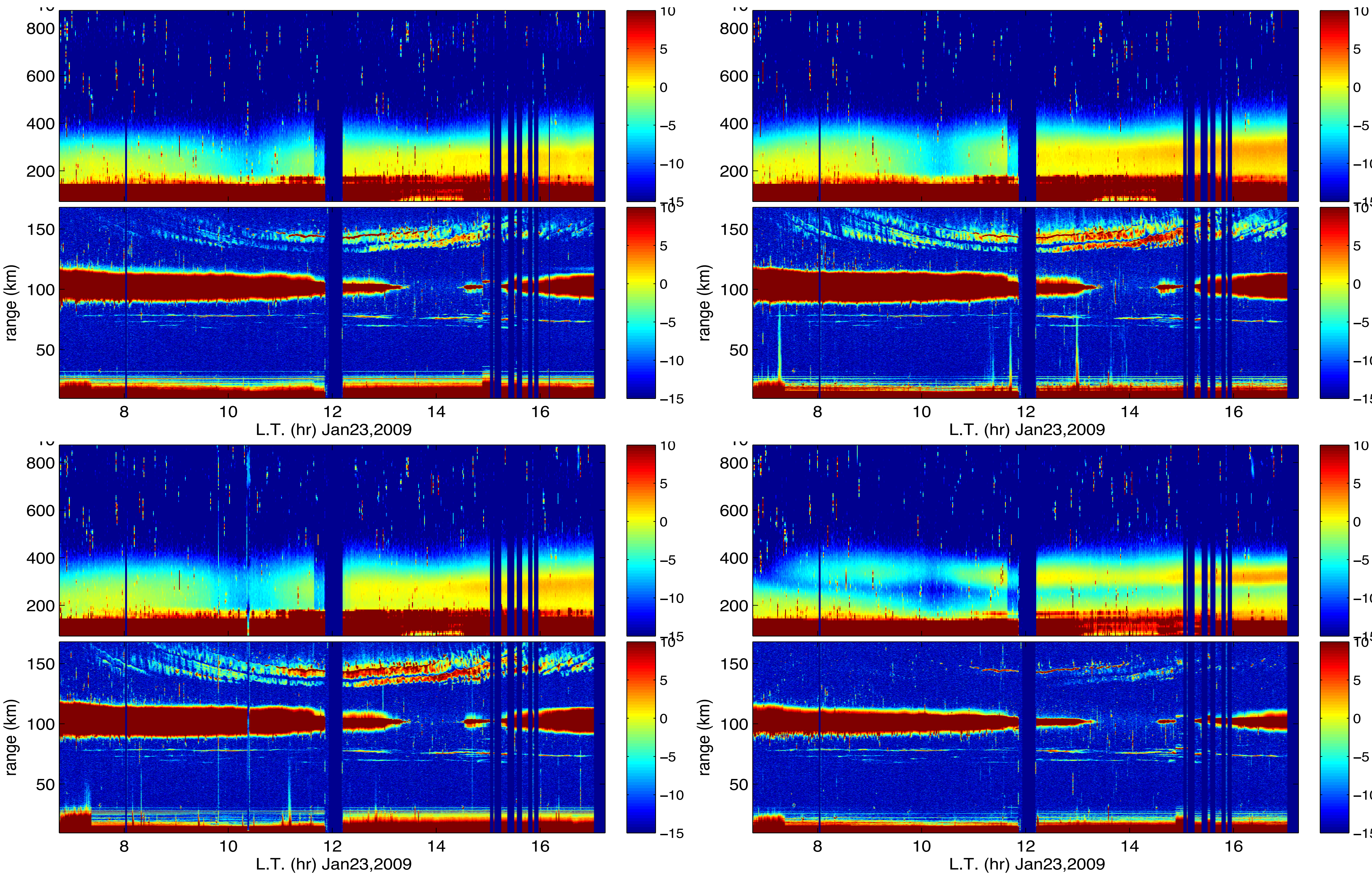
An example of high-resolution MST-mode data:

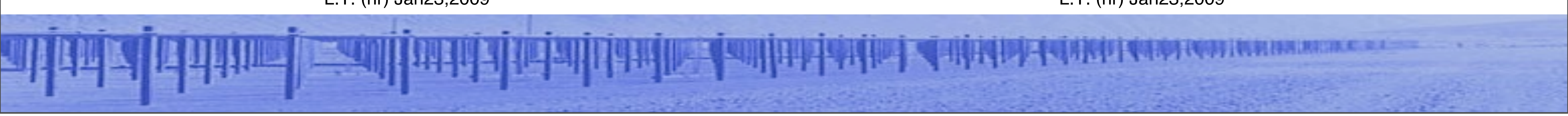


Height resolution ~150 m after pulse compression

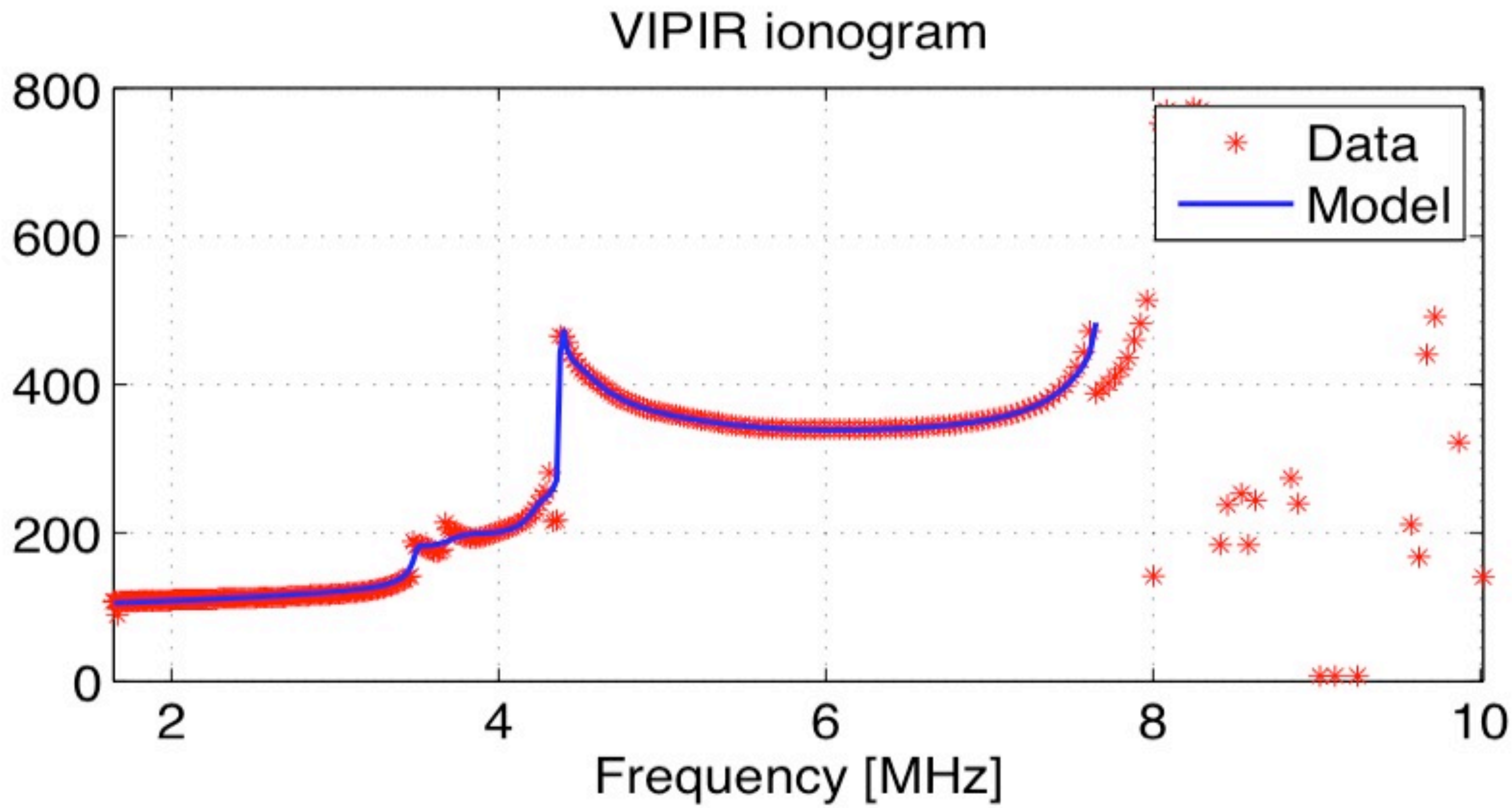
Power measurements to be calibrated

Jan 2009 --- less South Beam wiggles (solar-min conditions)



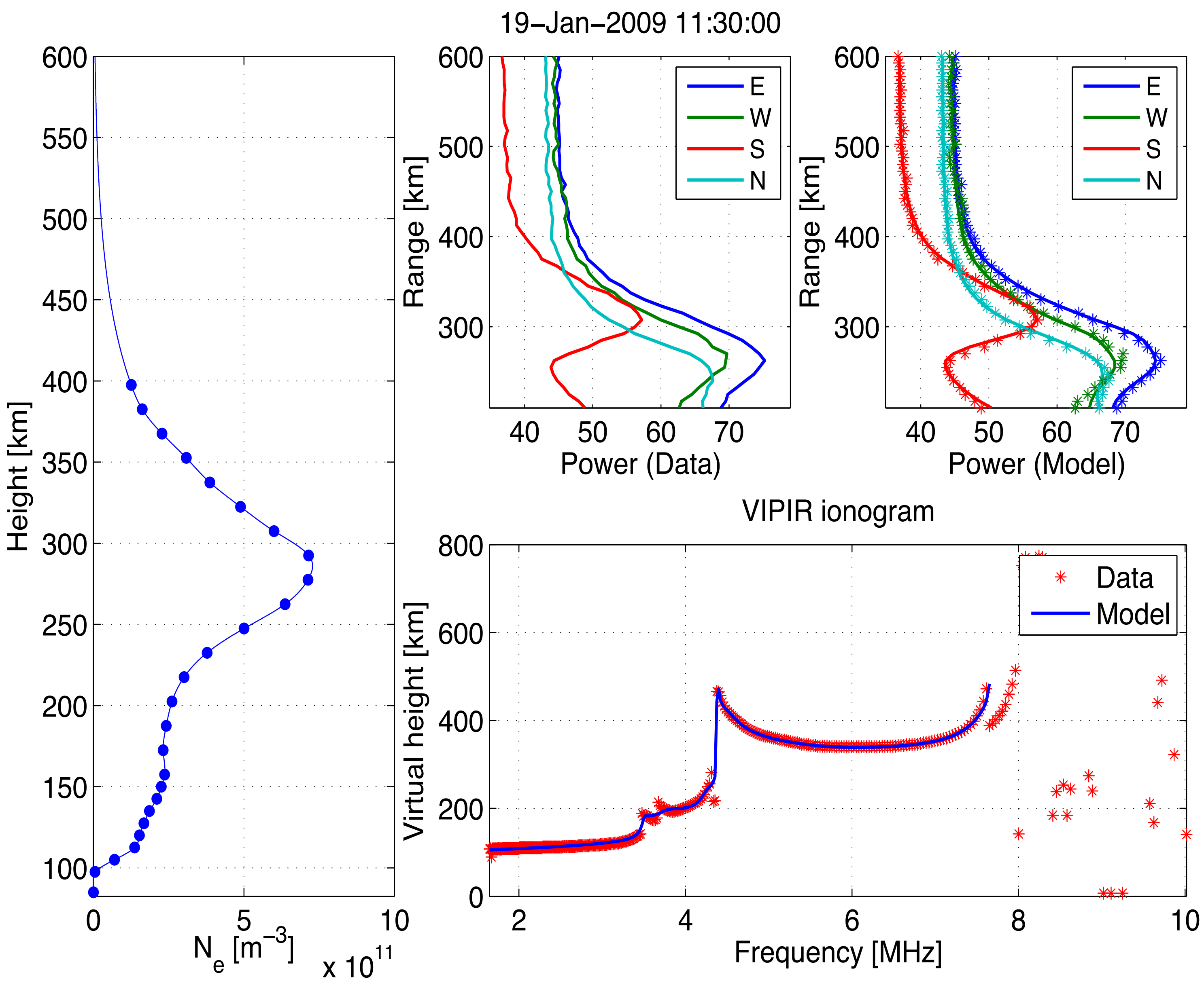


VIPIR ionograms every two minutes...



so far, only O-mode data is modeled.

Fit the observed ISR power profiles to density dependent model equations like



$$\langle |V_r(t)|^2 \rangle = \frac{\kappa}{r^2} \int d\Omega \, G_{tx} G_{rx} \, \tilde{\sigma}$$

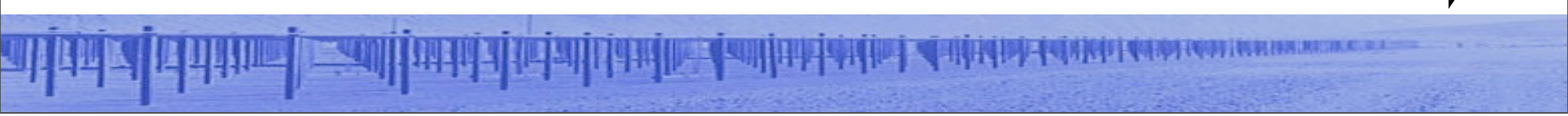
$$\tilde{\sigma} = 4\pi r_e^2 N_e f\left(\frac{T_e}{T_i}\right)$$

and estimate the "calibration constants"

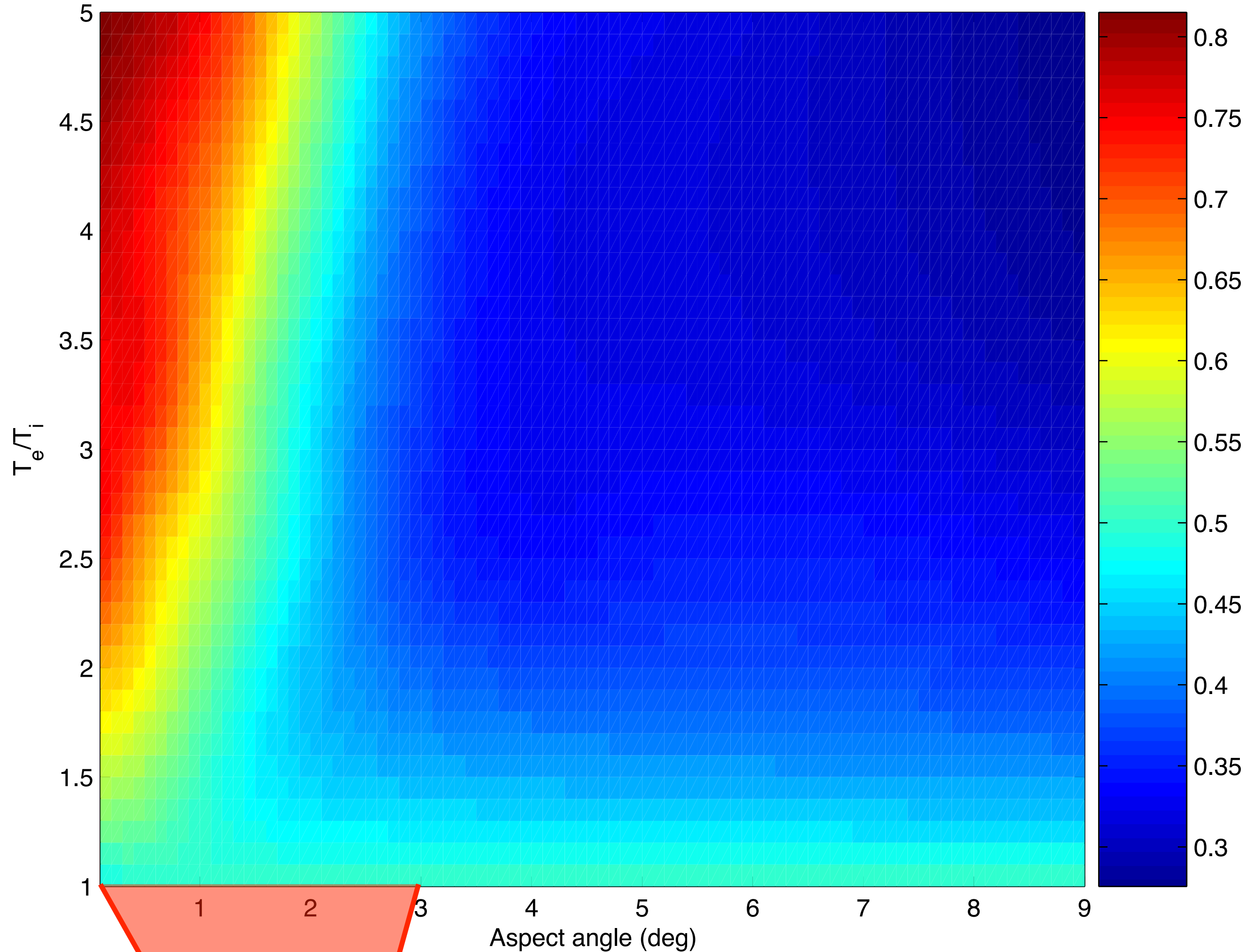
$$\kappa \propto \frac{E_t \delta r}{L}$$

one for each beam.

Forward model details...

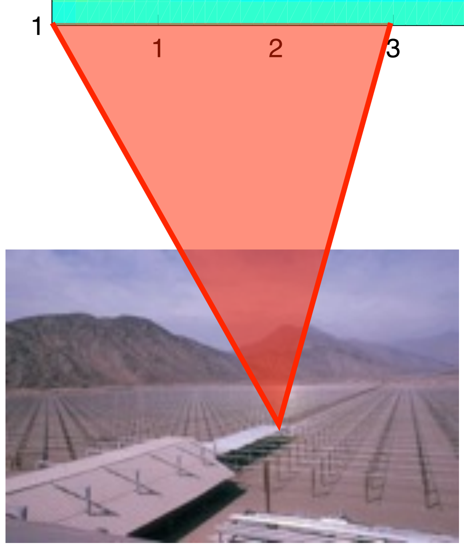


Dependence of cross-section on Te/Ti and magnetic aspect angle



Using the collisional IS spectra we compute IS-RCS as function of magnetic aspect angle and Te/Ti.

$$\tilde{\sigma} = 4\pi r_e^2 N_e f\left(\frac{T_e}{T_i}\right)$$



Jicamarca antenna beams illuminate a range of magnetic aspect angles

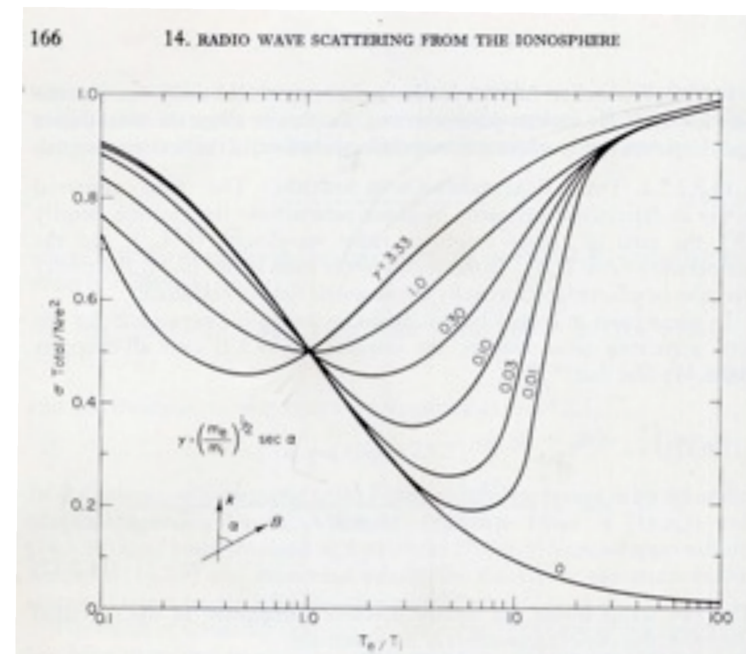
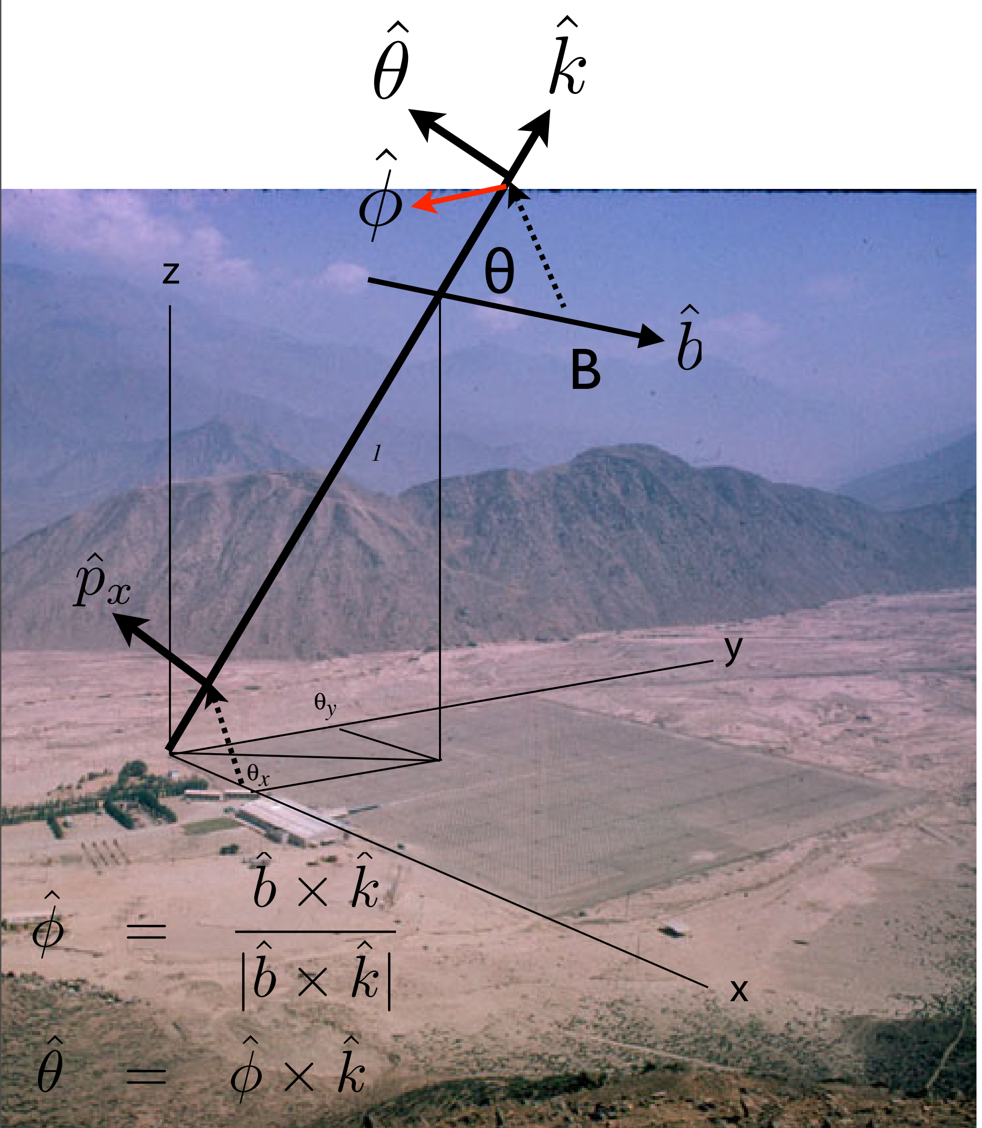


FIG. 7. The dependence of the scattering cross section for incoherent scatter on the electron-to-ion temperature ratio and $\gamma = (m_e/m_i)^{1/2} \sec \alpha$, where α is the angle between **k** and the magnetic field **B**, and $(m_e/m_i)^{1/2} \approx 6 \times 10^{-3}$ in the *F* region. The Debye length is assumed to be negligibly small. The curve for $\gamma = 0$ is just $(1 + T_e/T_i)^{-1}$. [From D. T. Farley, *J. Geophys. Res.* **71**, 4091 (1966).]



A magneto-ionic propagation problem through a multi-slab ionosphere model:

Polarization unit vector: $\hat{p}_x = \dfrac{\hat{k}\times\hat{k}\times\hat{x}}{|\hat{k}\times\hat{k}\times\hat{x}|} \equiv E_{xo}\hat{x} + E_{yo}\hat{y} + E_{zo}\hat{z} \equiv E_{\theta o}\hat{\theta} + E_{\phi o}\hat{\phi}$

$$Y_L = Y\cos\theta, \quad Y_T = Y\sin\theta, \quad Y = \frac{\Omega}{\omega}, \quad X = \frac{\omega_p^2}{\omega^2}$$

$$F_O = F_1 - F_2, \quad F_X = F_1 + F_2, \quad F_1 = \frac{Y_T^2/2}{1-X}, \quad F_2^2 = F_1^2 + Y_L^2$$

$$n_{O,X}^2 = 1 - \frac{X}{1 - F_{O,X}}$$

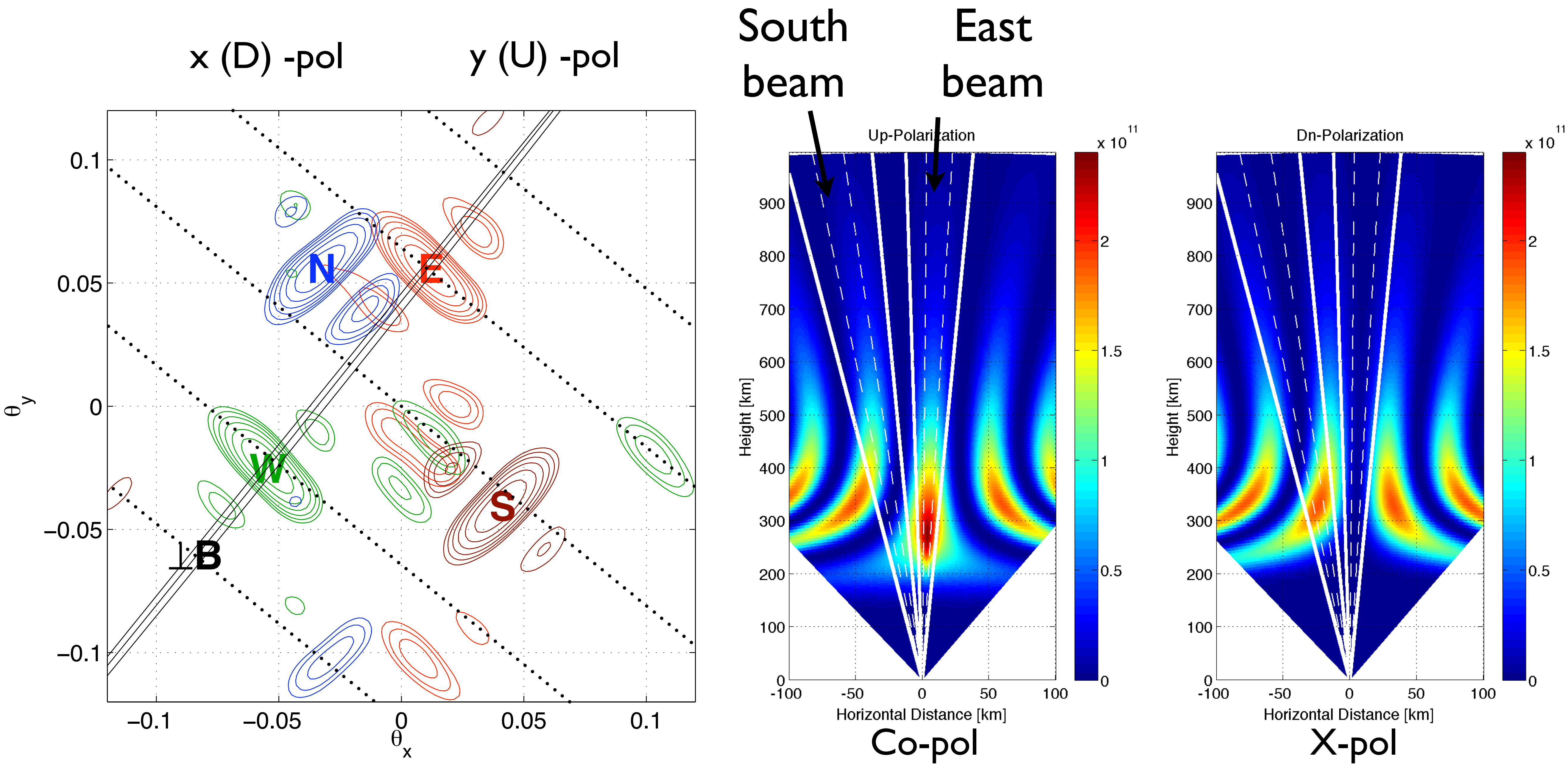
$$\Delta n = \frac{n_O - n_X}{2} \qquad \bar{n} = \frac{n_O + n_X}{2} \qquad a = \frac{F_O}{Y_L}$$

$$\mathbf{E}(\delta r) = \begin{bmatrix} E_\theta \\ E_\phi \end{bmatrix} = \underbrace{\frac{e^{-jk\bar{n}\delta r}}{1+a^2}\begin{bmatrix} a^2 e^{jk\Delta n\delta r} + e^{-jk\Delta n\delta r} & 2a\sin(k\Delta n\delta r) \\ -2a\sin(k\Delta n\delta r) & a^2 e^{-jk\Delta n\delta r} + e^{jk\Delta n\delta r}\end{bmatrix}}_{\bar{M}} \begin{bmatrix} E_{\theta_o} \\ E_{\phi_o}\end{bmatrix}$$

Iterate after modifying $\Delta n, \bar{n}, a, \hat{\theta}, \hat{\phi}$ due to slow varing density and $\vec{B}$

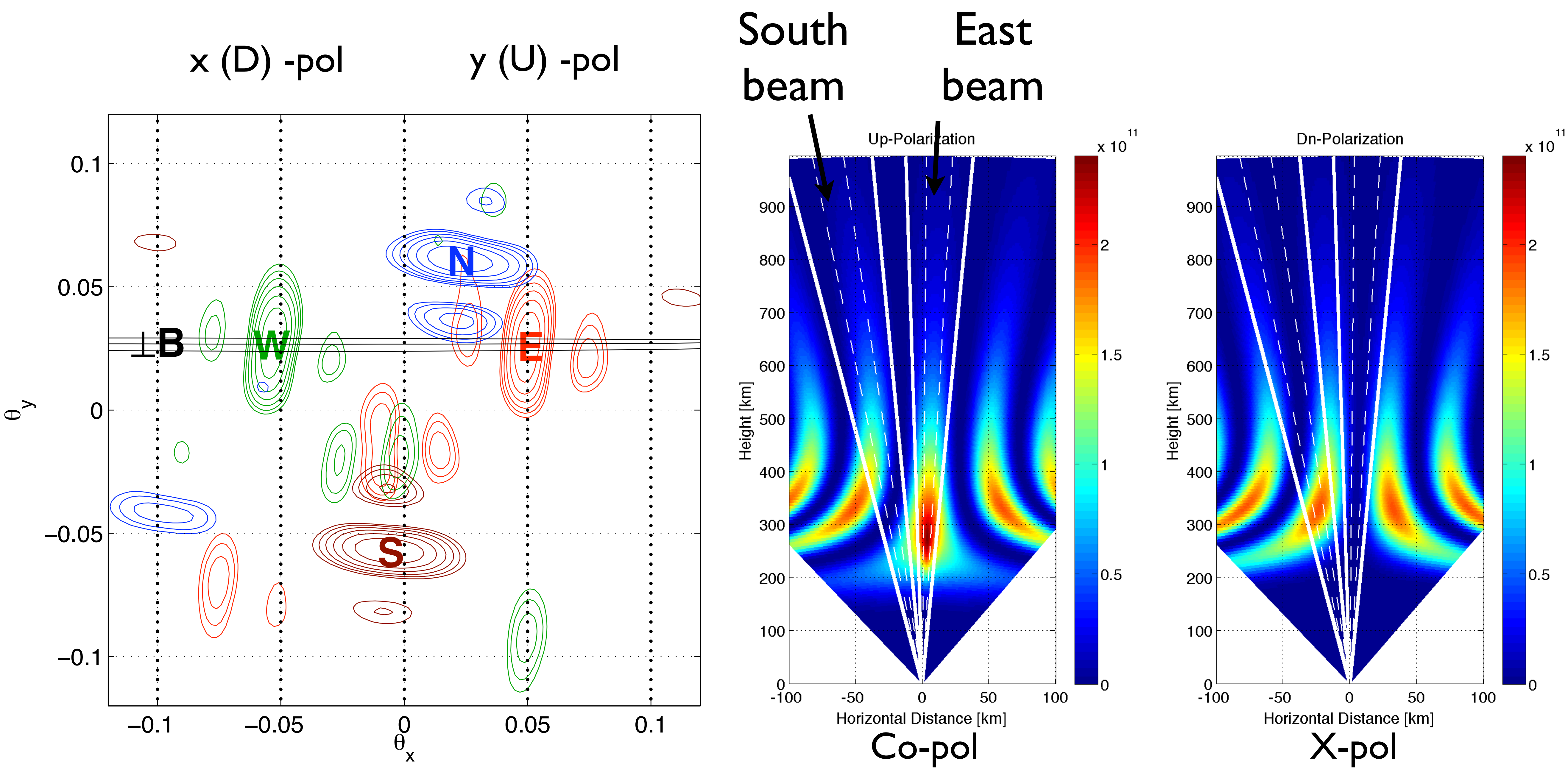
$$v_x \propto \hat{p}_x \cdot (E_\theta\hat{\theta} + E_\phi\hat{\phi}) \qquad\qquad v_y \propto \hat{p}_y \cdot (E_\theta\hat{\theta} + E_\phi\hat{\phi})$$

2-D integration of power samples in direction cosine coordinates

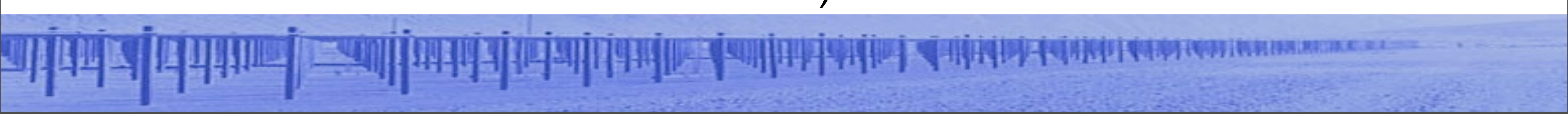


2-D integration implemented using a finite element method (rectangular elements).

2-D integration of power samples in direction cosine coordinates



2-D integration implemented using a finite element method (rectangular elements).

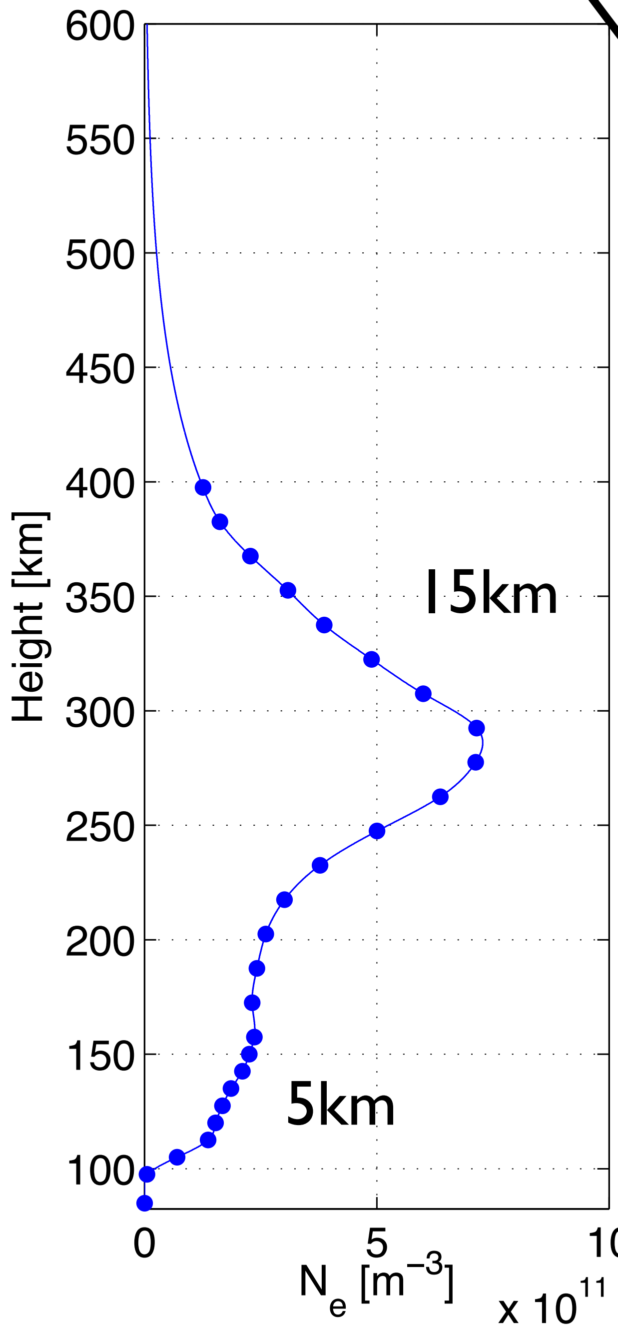


$$\langle |V_r(t)|^2 \rangle = \frac{\kappa}{r^2} \int d\Omega \, G_{tx} G_{rx} \, \tilde{\sigma}$$

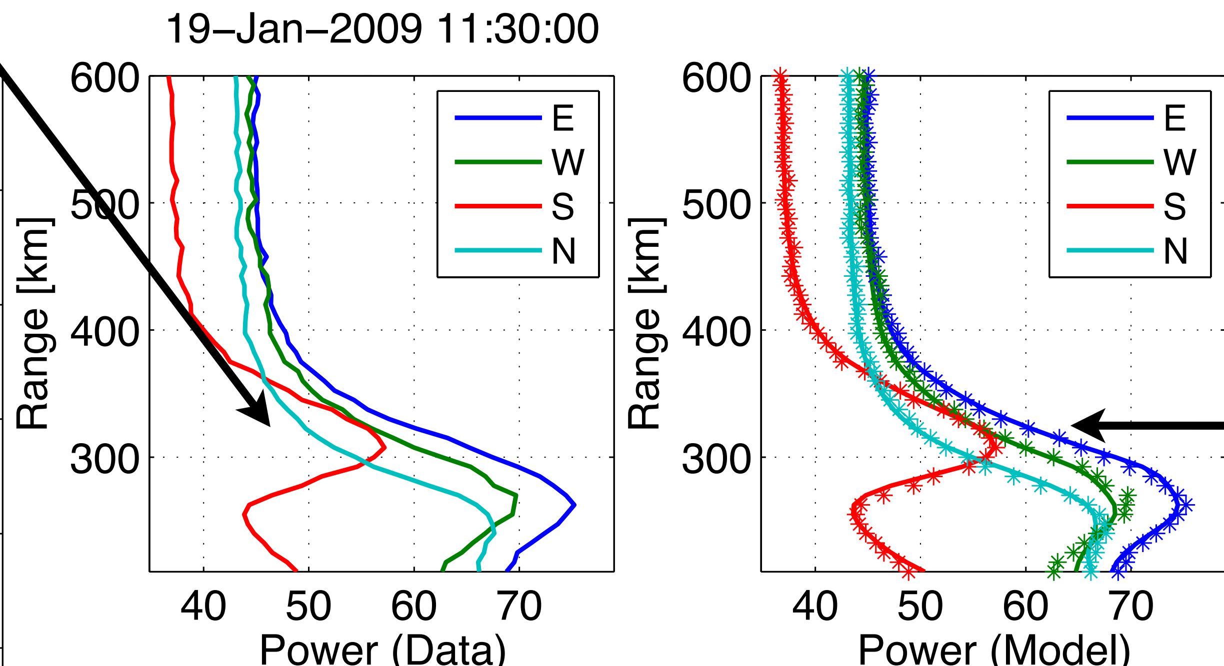
Fit the ISR power profile data from all four beams to power profile model and estimate density and Te/Ti profiles and calibration constants

$$\kappa \propto \frac{E_t \delta r}{L}$$

ISR power data

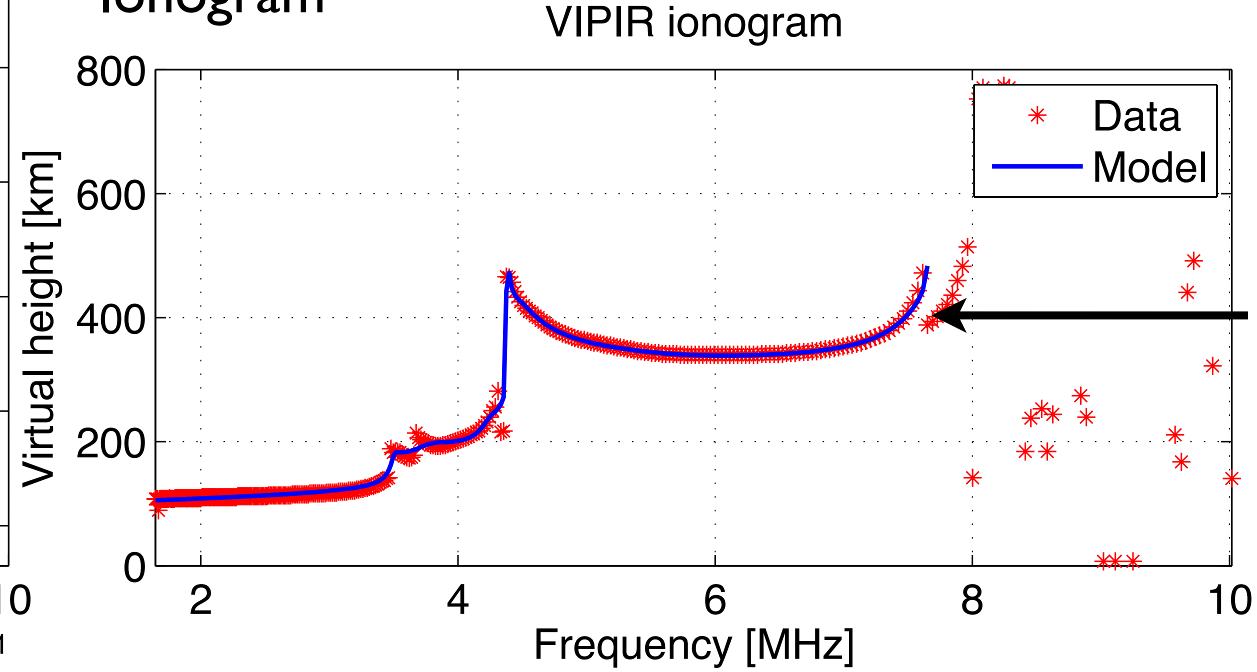


Density estimate (cubic splines)

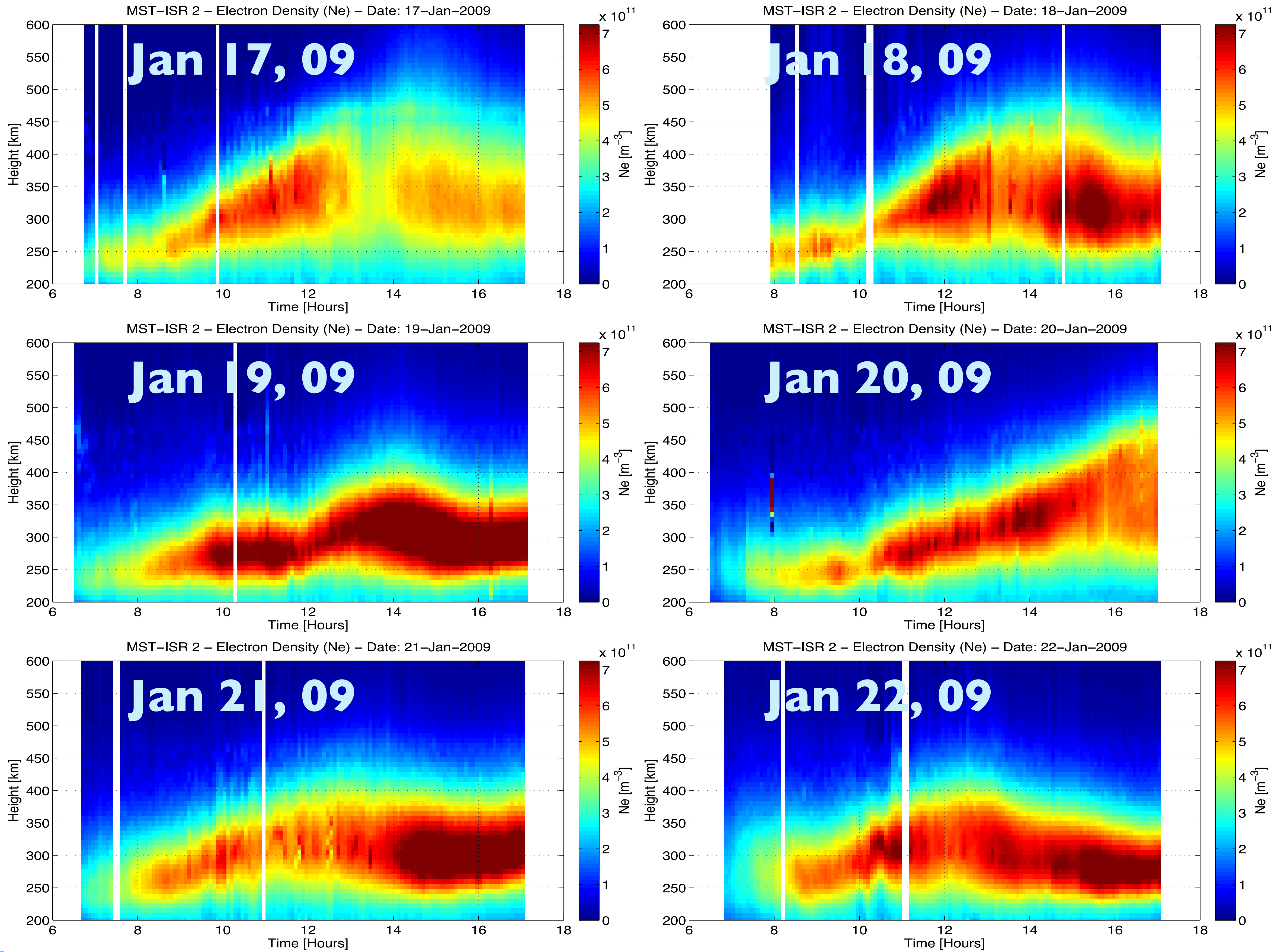


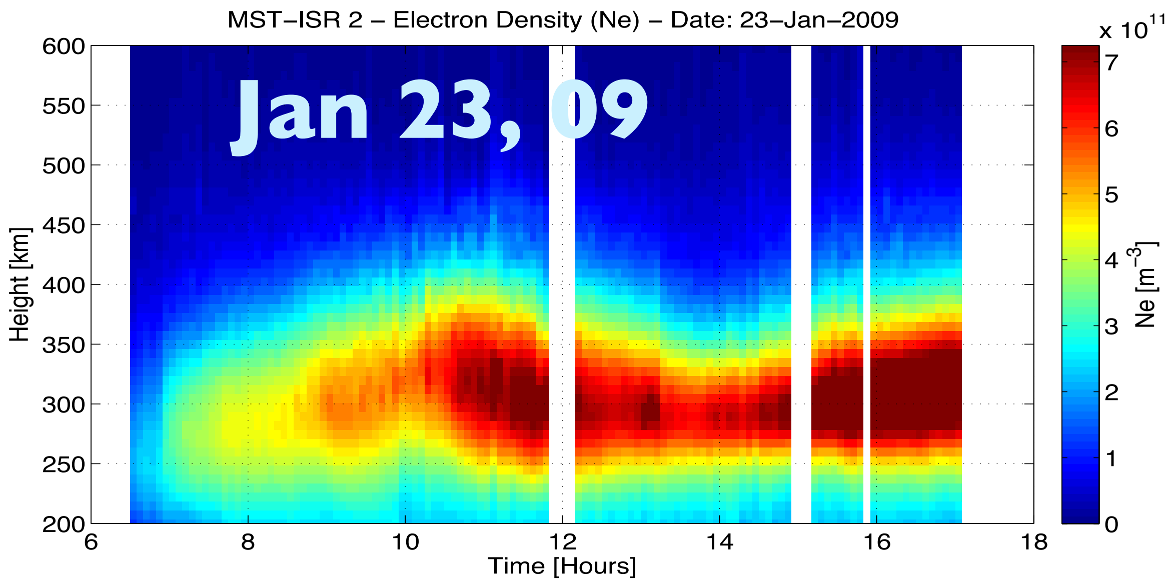
Model fits

Ionogram



Ionogram data is fitted to obtain E and F1 region density estimates. It improves accuracy of calibration parameters.


MST–ISR 2 – Electron Density (Ne) – Date: 17–Jan–2009
Jan 17, 09
MST–ISR 2 – Electron Density (Ne) – Date: 18–Jan–2009
Jan 18, 09
MST–ISR 2 – Electron Density (Ne) – Date: 19–Jan–2009
Jan 19, 09
MST–ISR 2 – Electron Density (Ne) – Date: 20–Jan–2009
Jan 20, 09
MST–ISR 2 – Electron Density (Ne) – Date: 21–Jan–2009
Jan 21, 09
MST–ISR 2 – Electron Density (Ne) – Date: 22–Jan–2009
Jan 22, 09
Height [km]
600
550
500
450
400
350
300
250
200
Time [Hours]
6
8
10
12
14
16
18
x 10^11
Ne [m^-3]
0
1
2
3
4
5
6
7


MST–ISR 2 – Electron Density (Ne) – Date: 23–Jan–2009
Jan 23, 09
Height [km]
Time [Hours]
Ne [m^-3]
x 10^11
600
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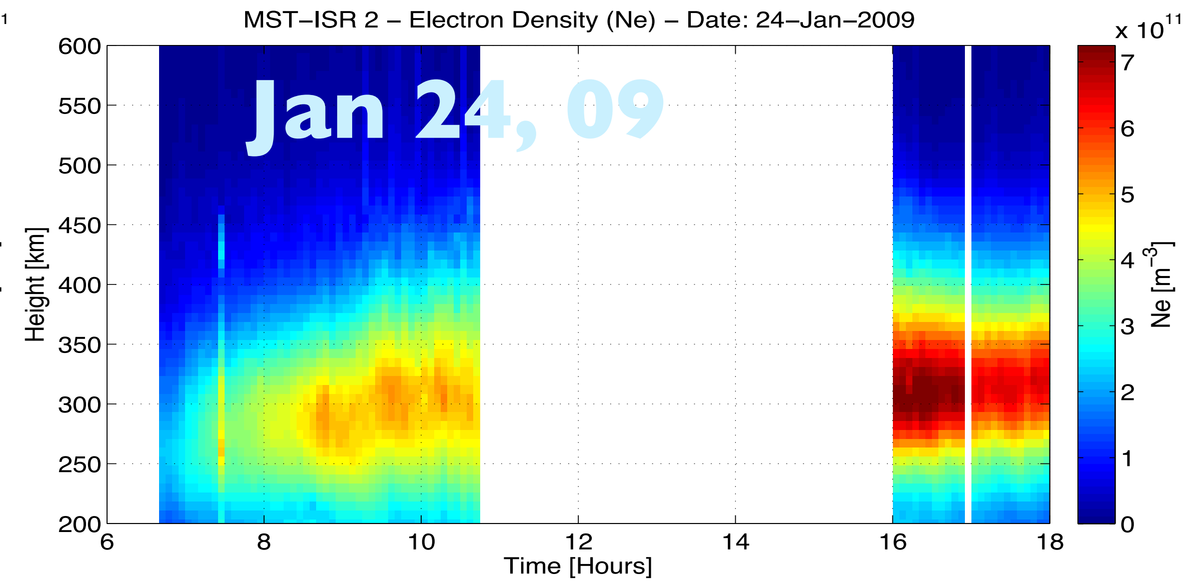
0


MST–ISR 2 – Electron Density (Ne) – Date: 24–Jan–2009
Jan 24, 09
Height [km]
Time [Hours]
Ne [m^-3]
x 10^11
600
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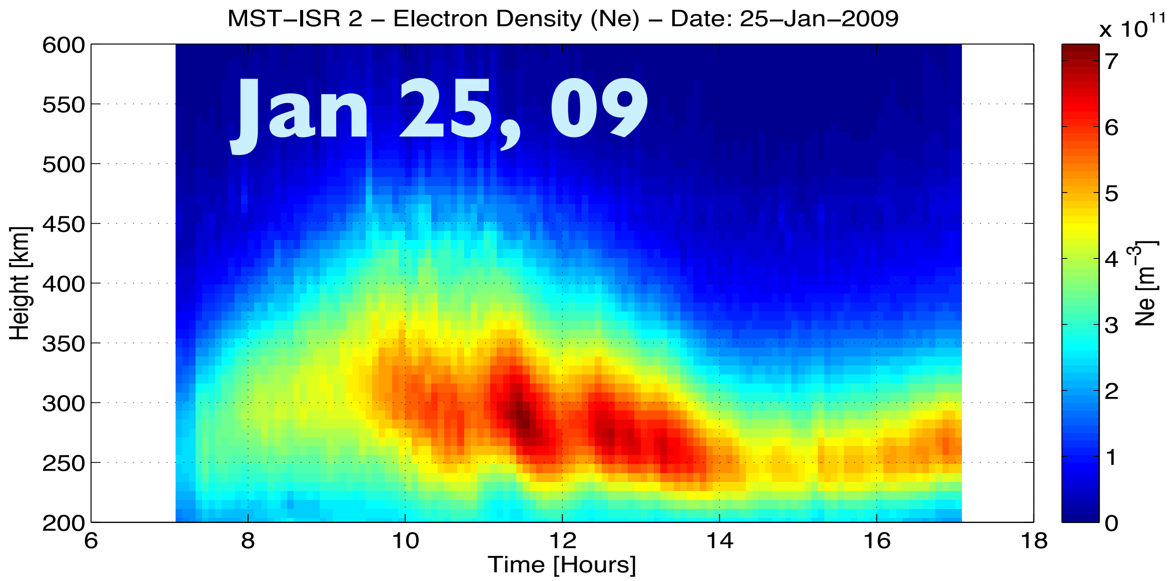
MST–ISR 2 – Electron Density (Ne) – Date: 25–Jan–2009
Jan 25, 09
Height [km]
Time [Hours]
Ne [m^-3]
x 10^11
600
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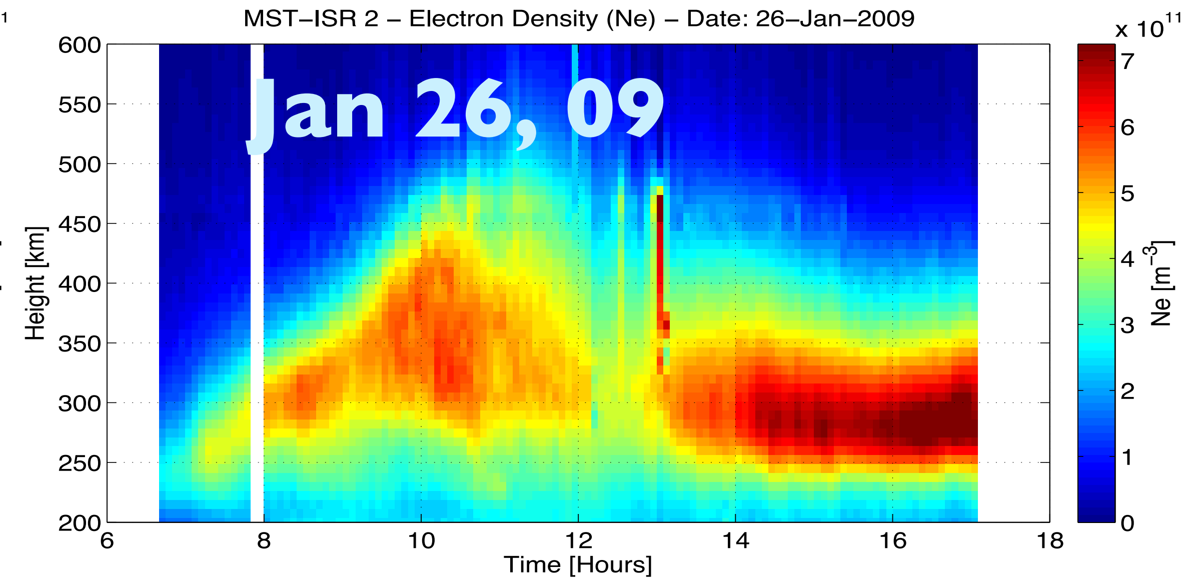
MST–ISR 2 – Electron Density (Ne) – Date: 26–Jan–2009
Jan 26, 09
Height [km]
Time [Hours]
Ne [m^-3]
x 10^11
600
550
500
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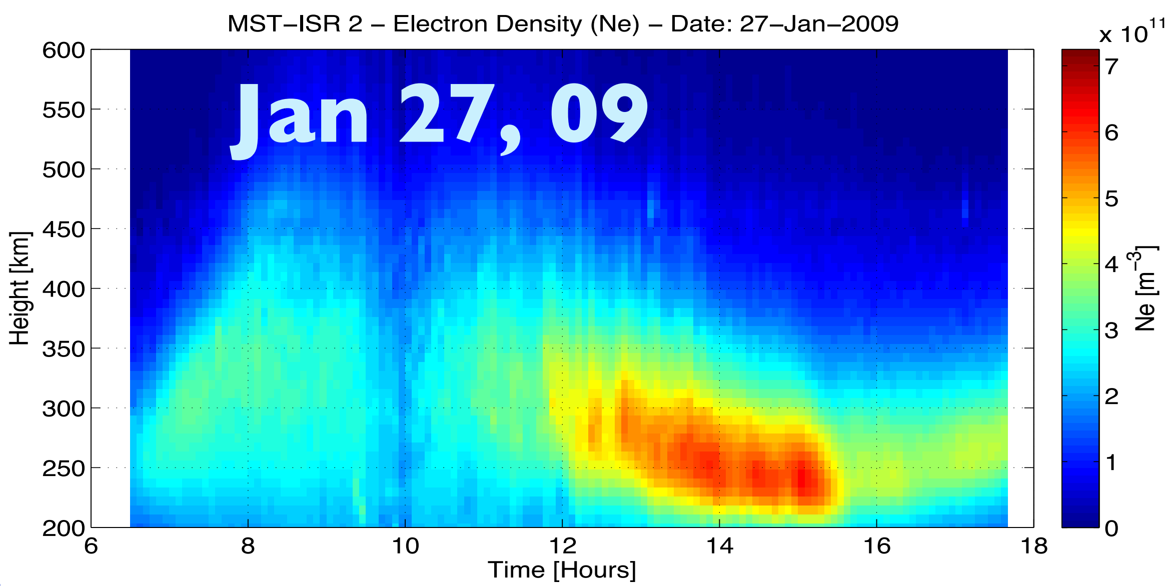
MST–ISR 2 – Electron Density (Ne) – Date: 27–Jan–2009
Jan 27, 09
Height [km]
Time [Hours]
Ne [m^-3]
x 10^11
600
550
500
450
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6
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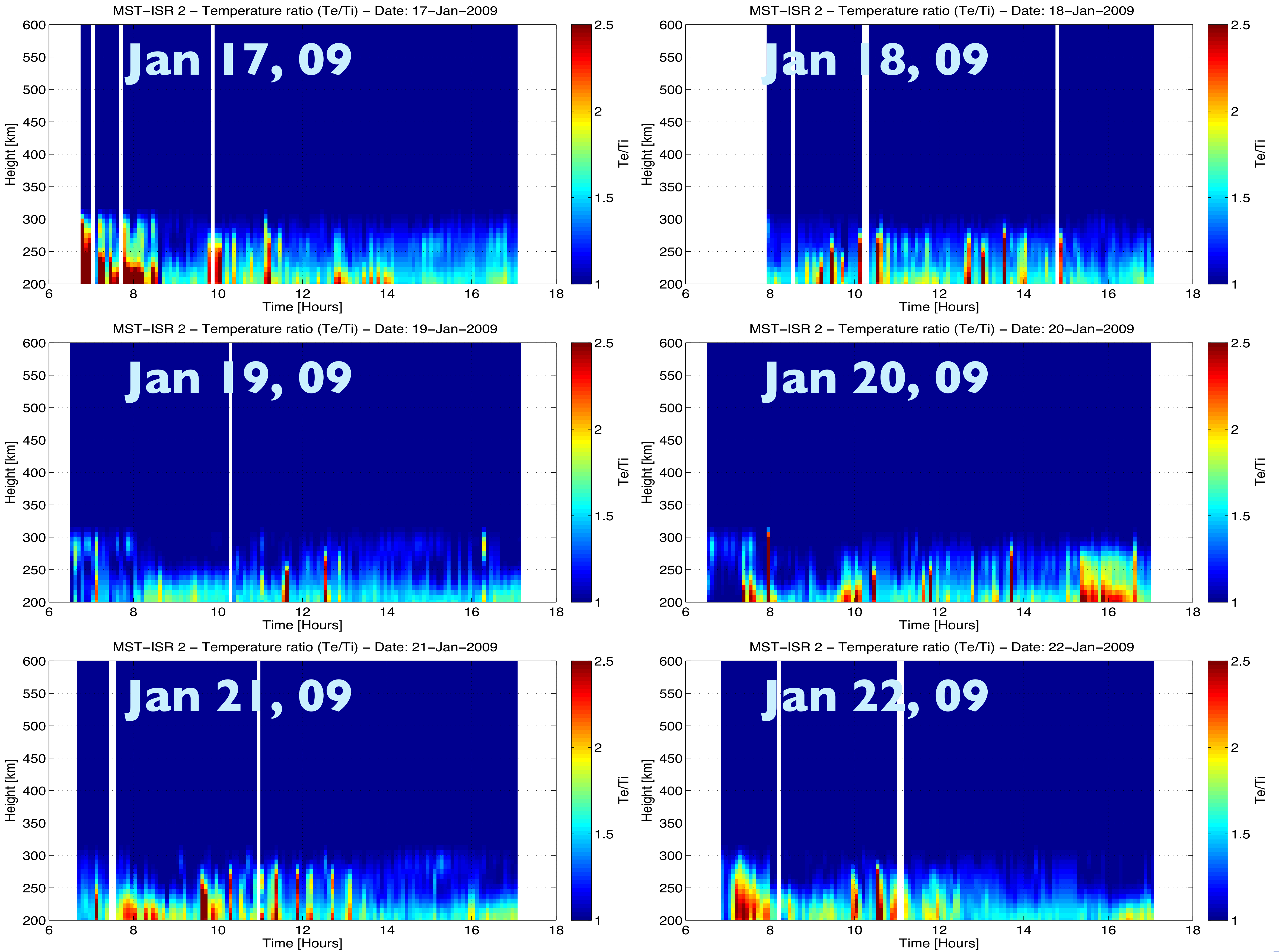
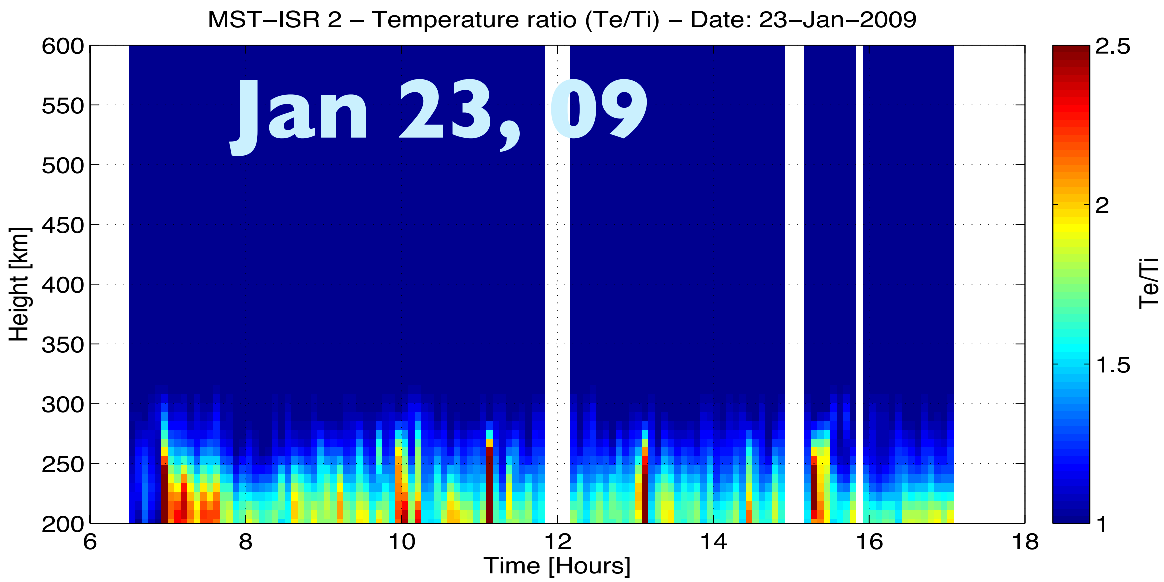
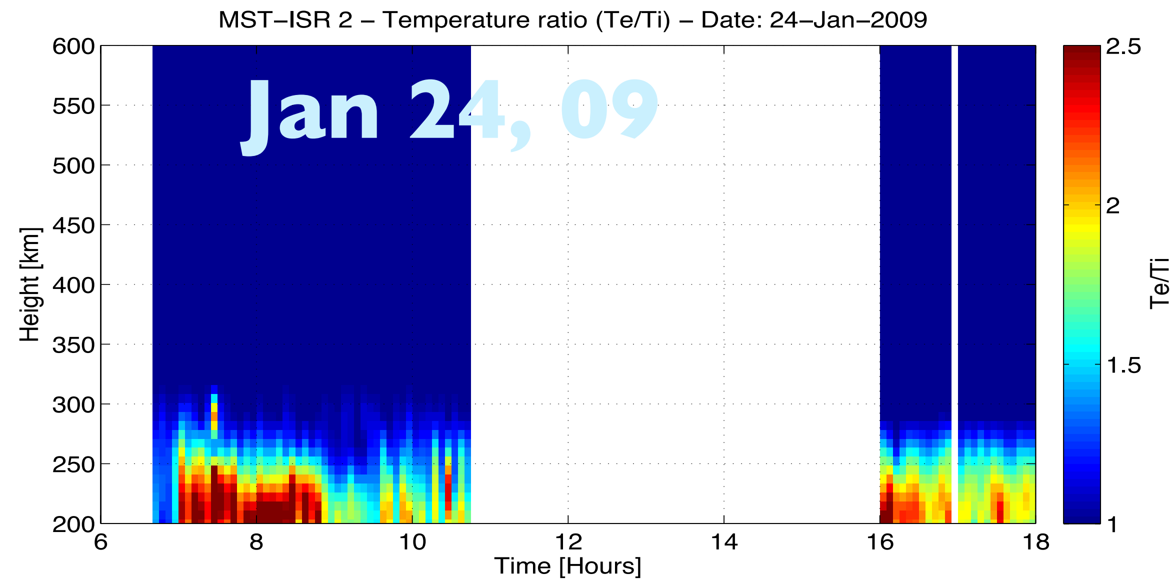
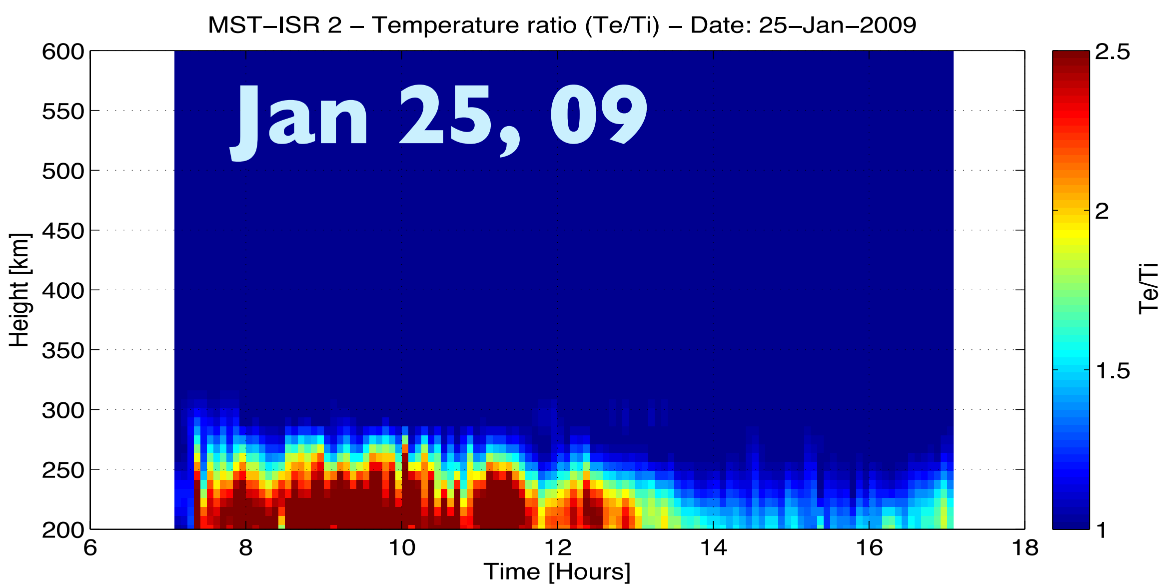
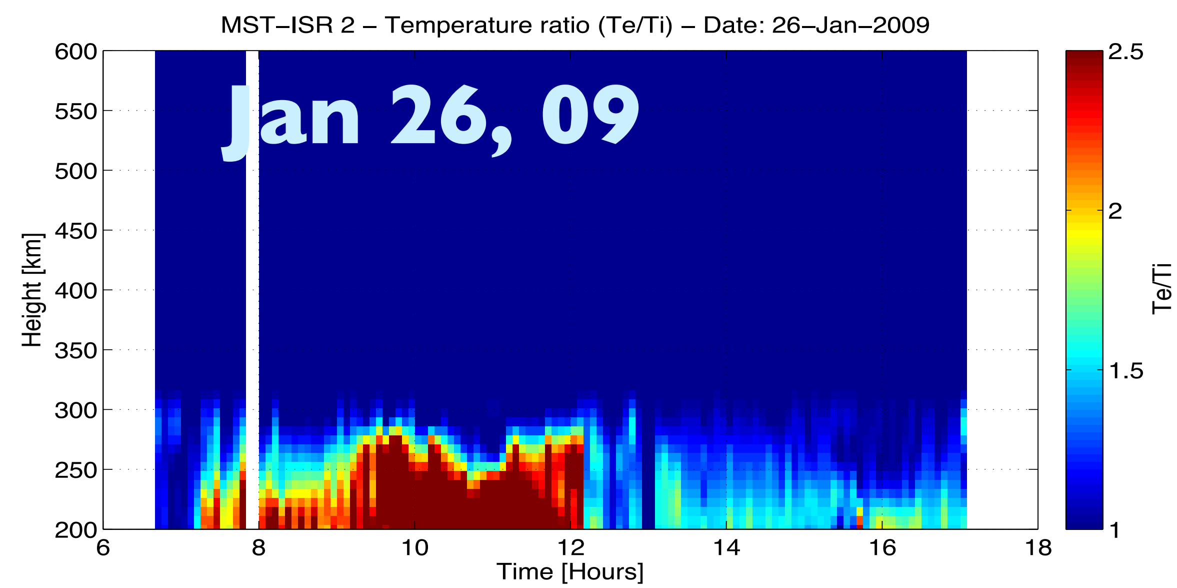


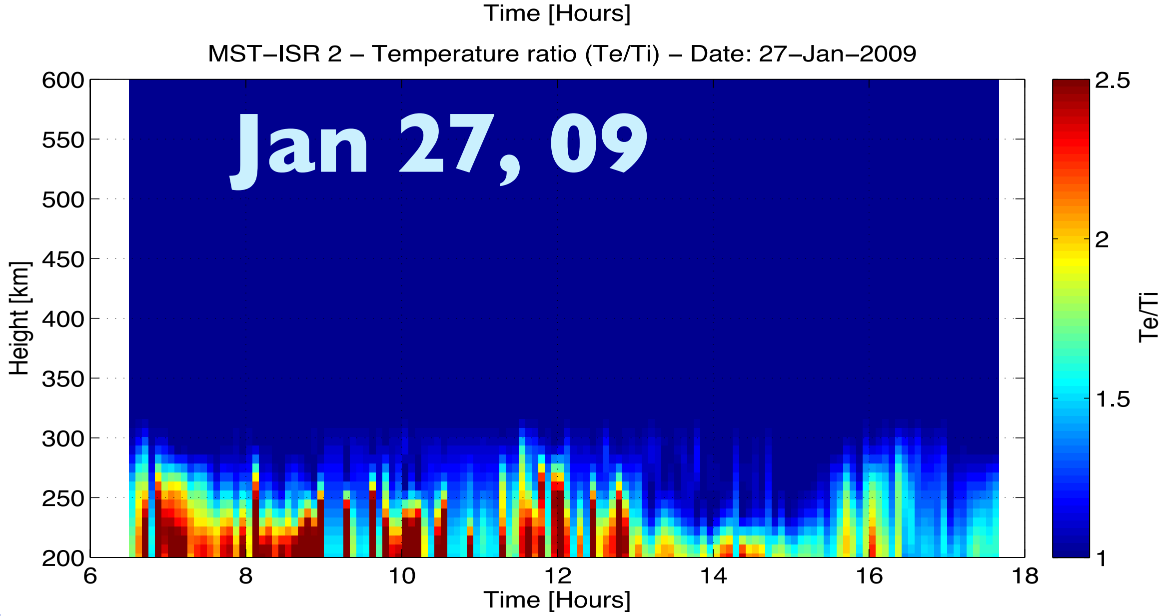
Monday, November 29, 2010


MST–ISR 2 – Temperature ratio (Te/Ti) – Date: 23–Jan–2009
Jan 23, 09
Height [km]
Time [Hours]
Te/Ti

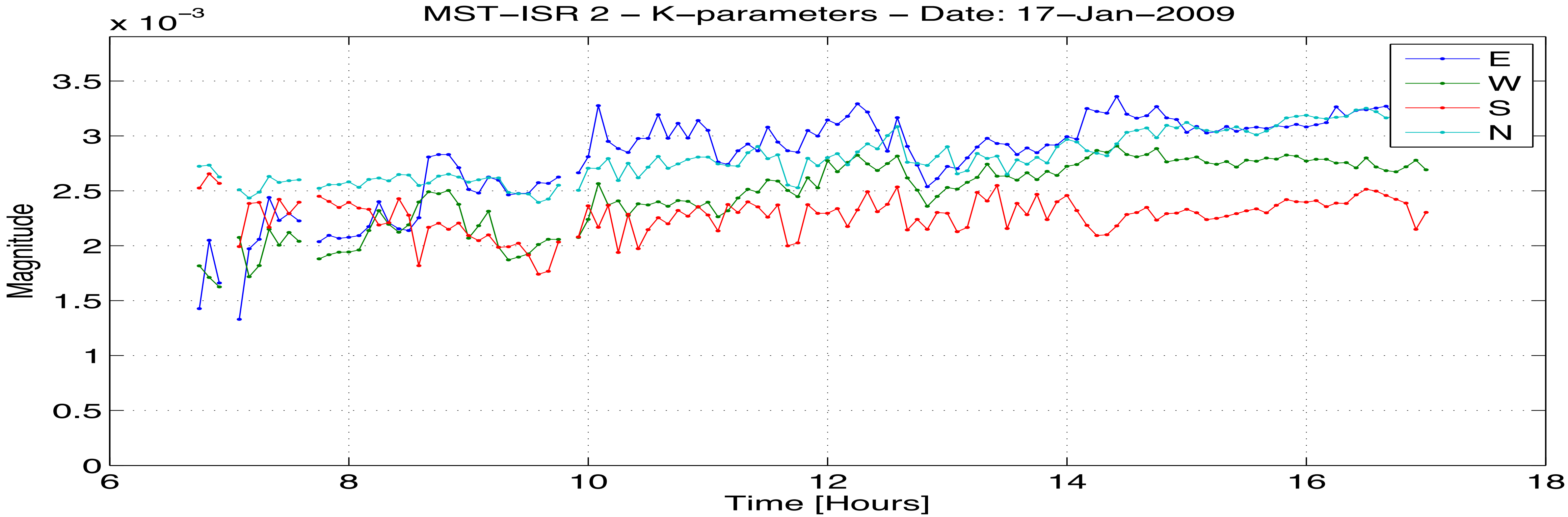

MST–ISR 2 – Temperature ratio (Te/Ti) – Date: 24–Jan–2009
Jan 24, 09
Height [km]
Time [Hours]
Te/Ti

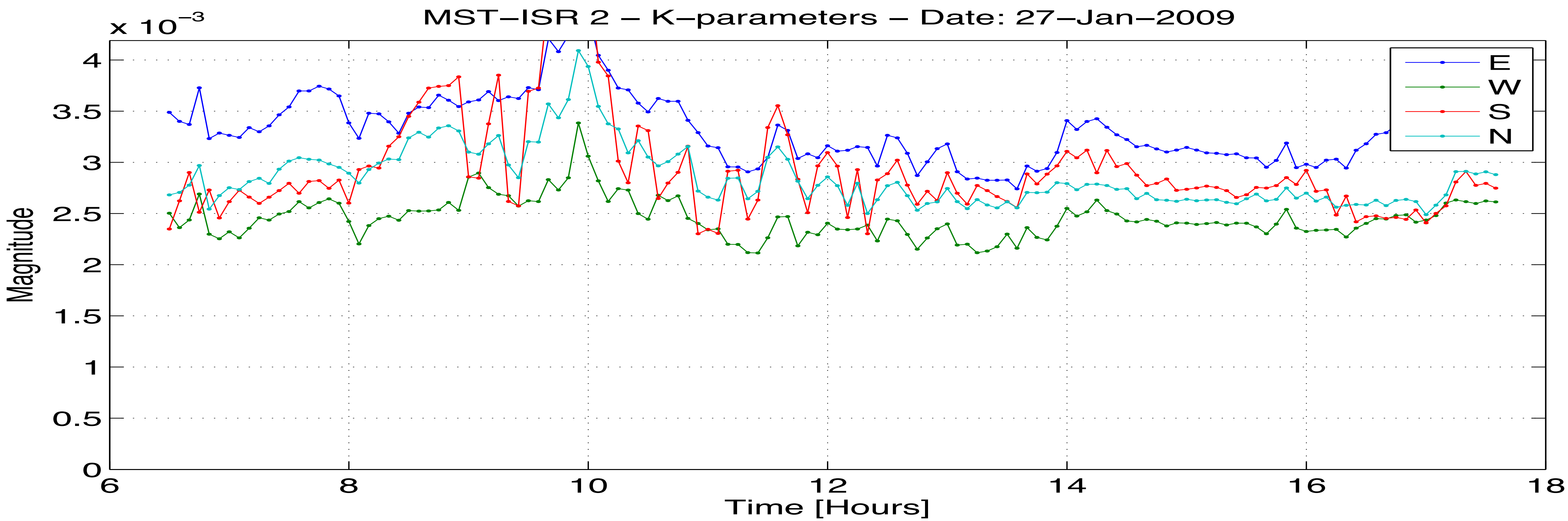

MST–ISR 2 – Temperature ratio (Te/Ti) – Date: 25–Jan–2009
Jan 25, 09
Height [km]
Time [Hours]
Te/Ti

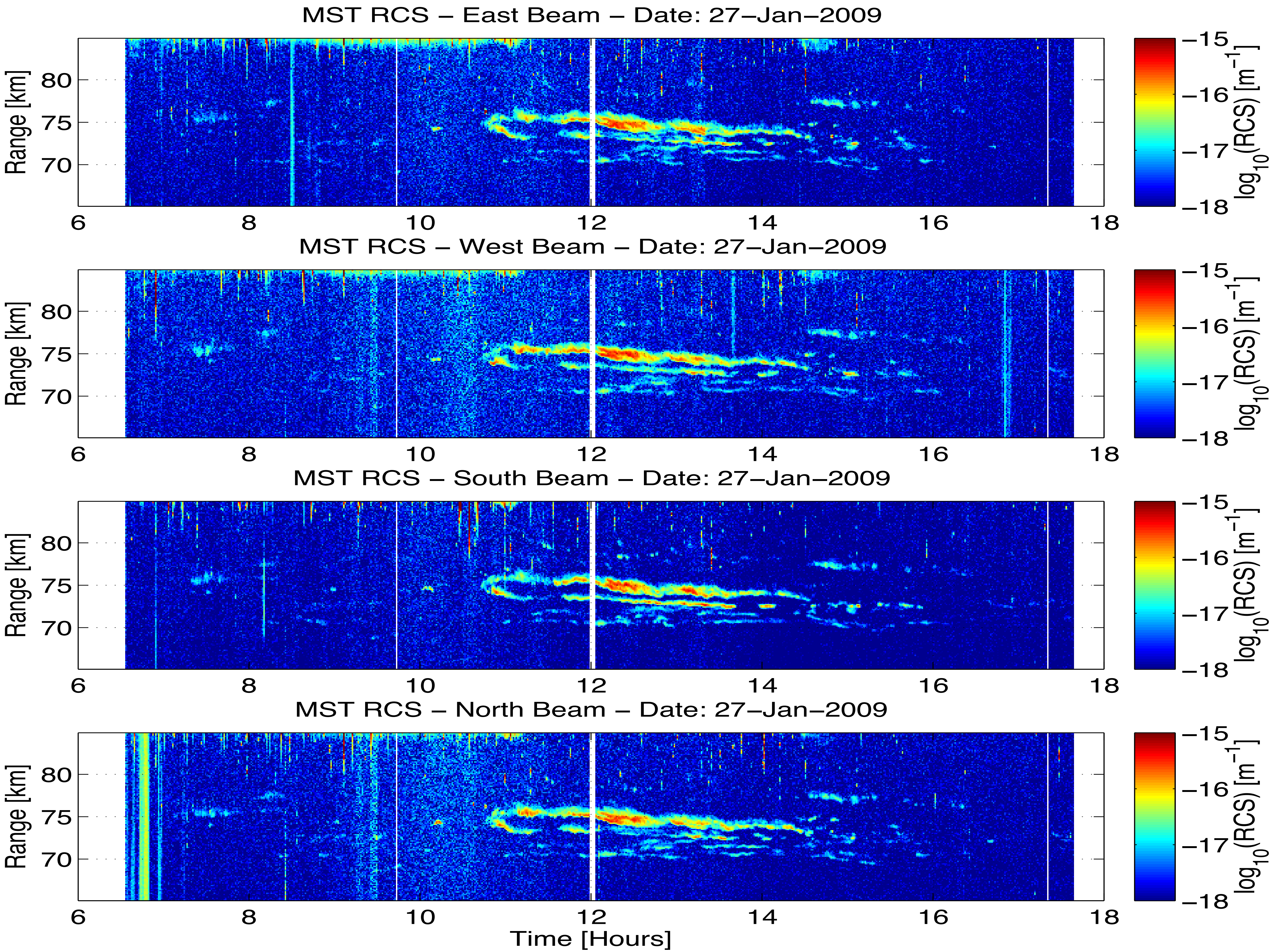

MST–ISR 2 – Temperature ratio (Te/Ti) – Date: 26–Jan–2009
Jan 26, 09
Height [km]
Time [Hours]
Te/Ti


MST–ISR 2 – Temperature ratio (Te/Ti) – Date: 27–Jan–2009
Jan 27, 09
Height [km]
Time [Hours]
Te/Ti

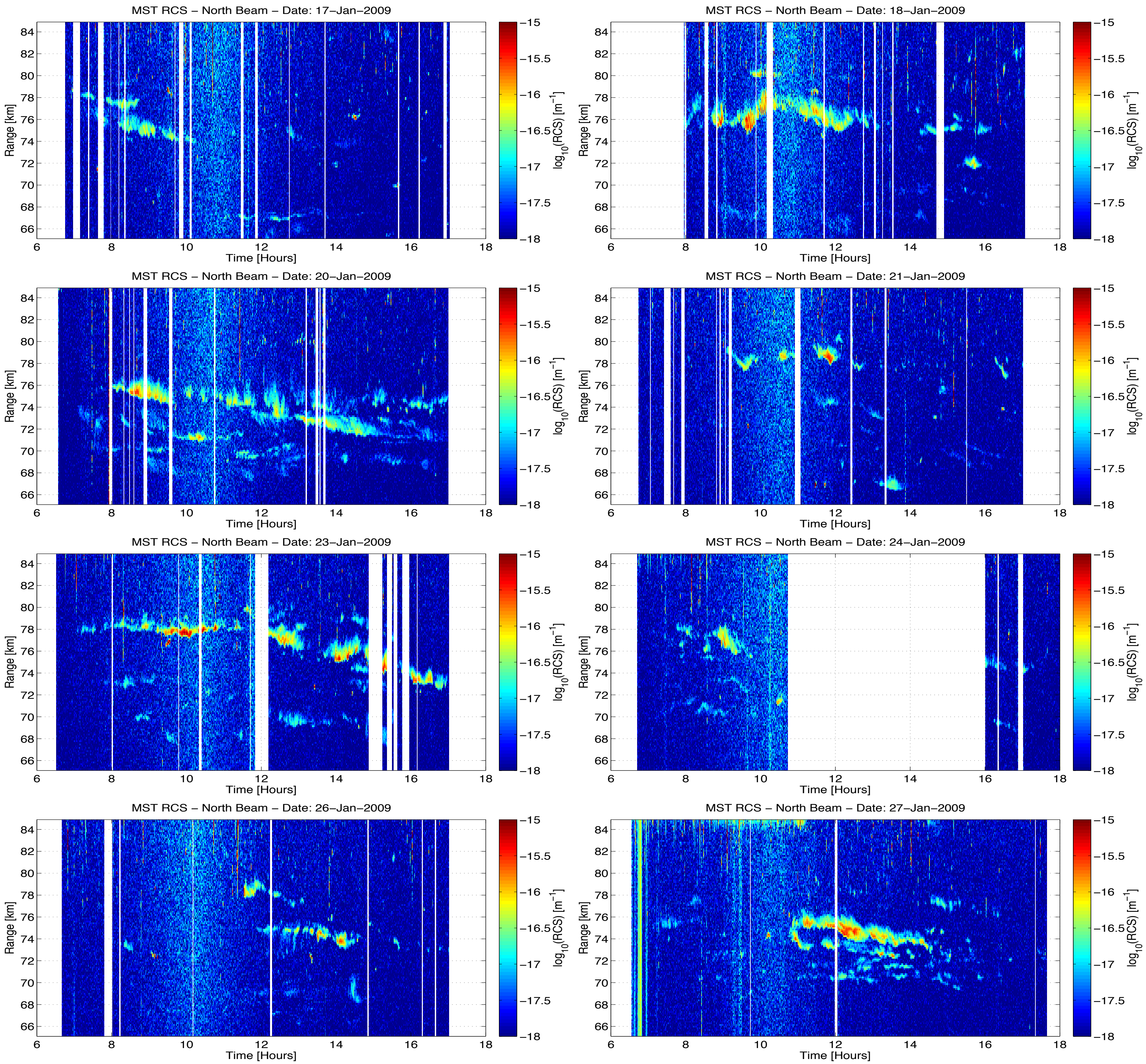
Calibration Parameters



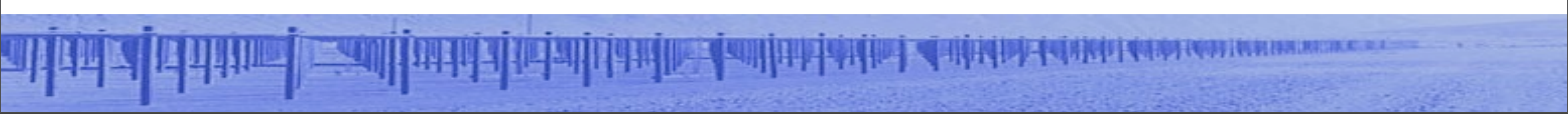



MST RCS – East Beam – Date: 27–Jan–2009
MST RCS – West Beam – Date: 27–Jan–2009
MST RCS – South Beam – Date: 27–Jan–2009
MST RCS – North Beam – Date: 27–Jan–2009
Range [km]
80
75
70
6
8
10
12
14
16
18
Time [Hours]
–15
–16
–17
–18
log10(RCS) [m^-1]

Jan 2009 - North Beam RCS estimates:

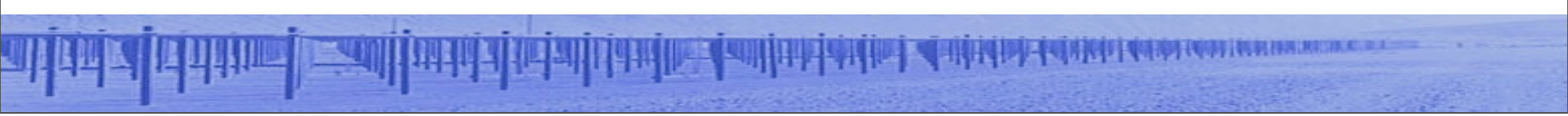


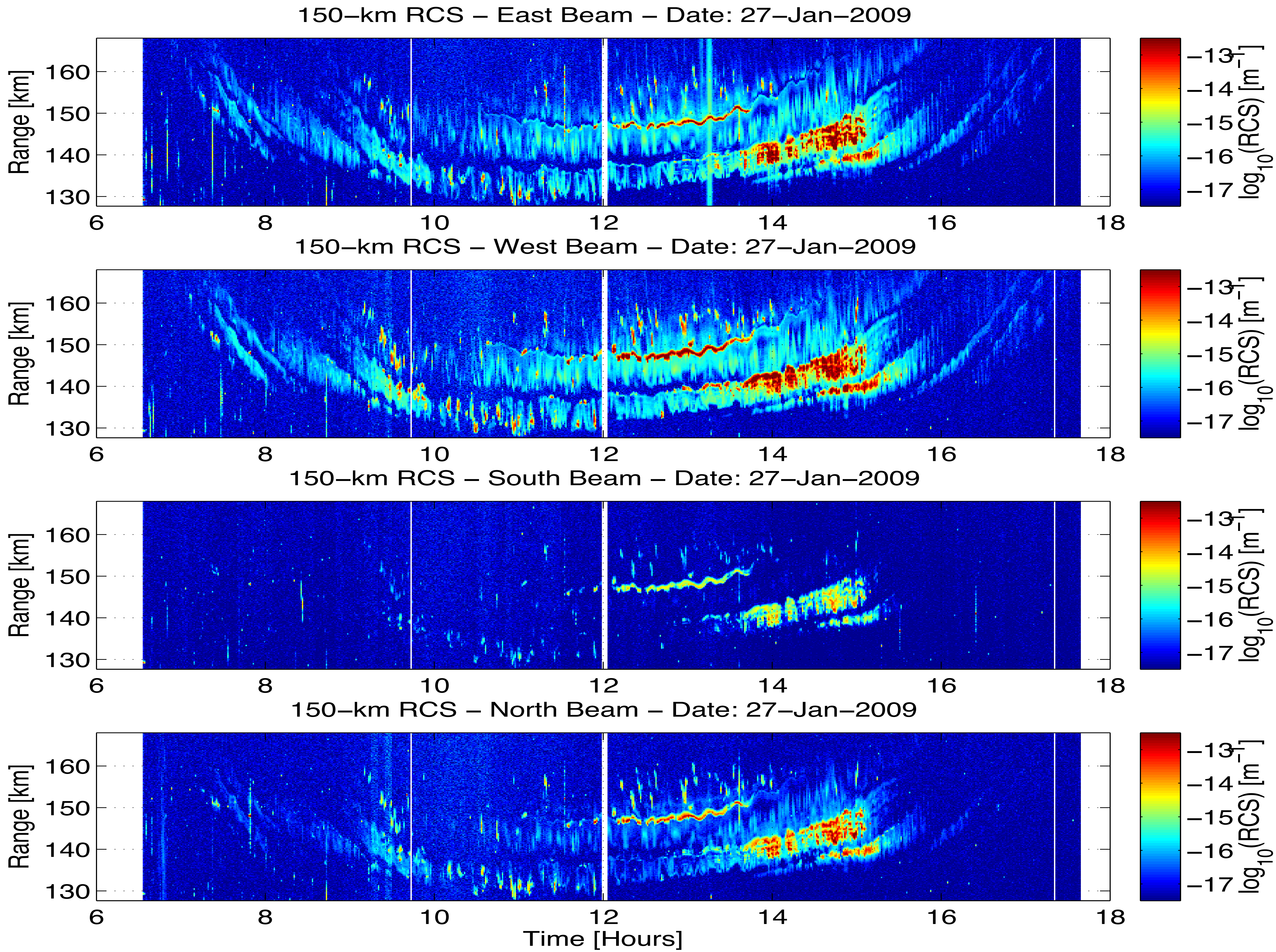
We find RCS up to 10^-15 1/m.



Conclusions

- MST-ISR mode data collected with linearly polarized oblique antennas can be inverted for F-region electron densities, Te/Ti ratios, and channel calibration constants.
- Ionosonde data provides density estimates in the E- and F1-regions and improves the accuracy of the estimates in the F2-region.
- Absolute cross-section measurements useful for beam-to beam and day to day comparisons.
- Multiple-layered vs sparsely layered "days" have been observed to have comparable RCS's.
- Largest RCS's observed in 70-75 km
- RCS's up to 4 orders of magnitude stronger than D-region ISR (typically unobservable at JRO without MST contamination).




150–km RCS – East Beam – Date: 27–Jan–2009
150–km RCS – West Beam – Date: 27–Jan–2009
150–km RCS – South Beam – Date: 27–Jan–2009
150–km RCS – North Beam – Date: 27–Jan–2009
Range [km]
160
150
140
130
6
8
10
12
14
16
18
Time [Hours]
−13
−14
−15
−16
−17
$\log_{10}$(RCS) [m^{-1}]