Ionospheric heating effects on transionospheric VLF to MF propagation

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DEMETER 2011 Workshop

DEMETER observations have raised questions on the propagation of plasma waves through the ionosphere

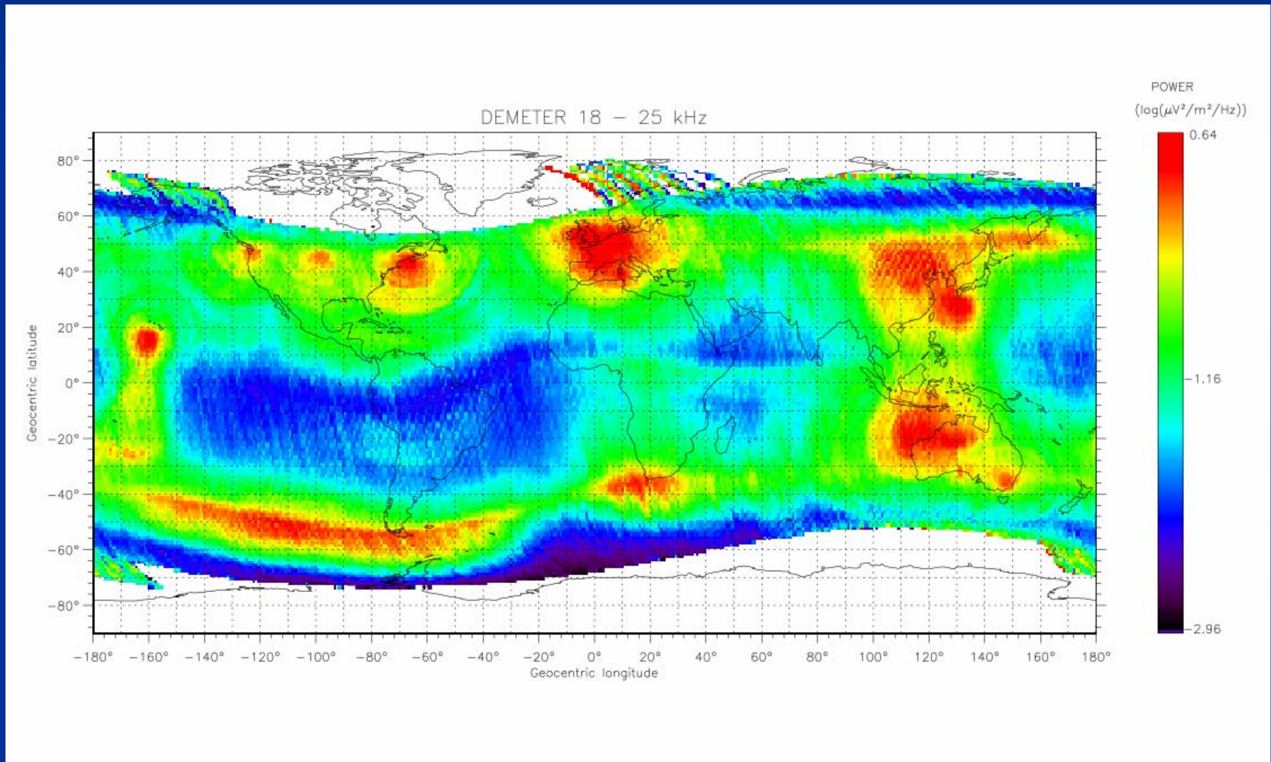
Preliminary answers have been given in Parrot et al. 2008 and 2009 papers

The aim of the present paper is to provide a general view on :

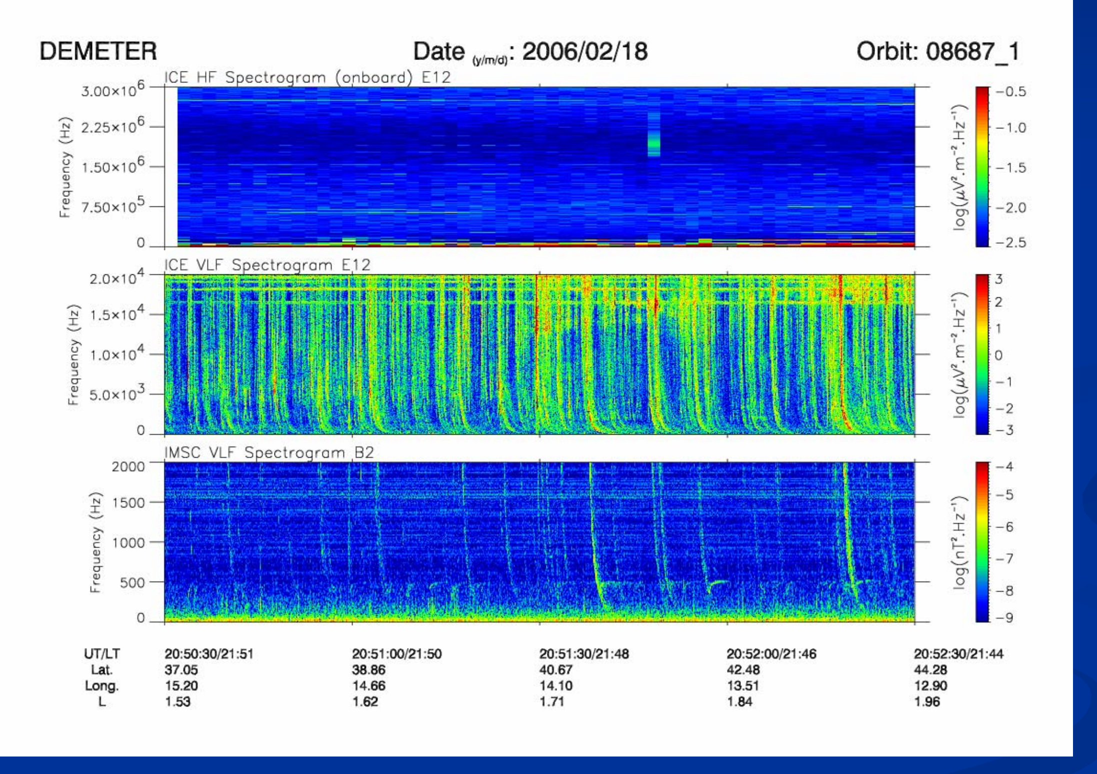
Propagation of cold plasma waves

1. Questions raised by DEMETER

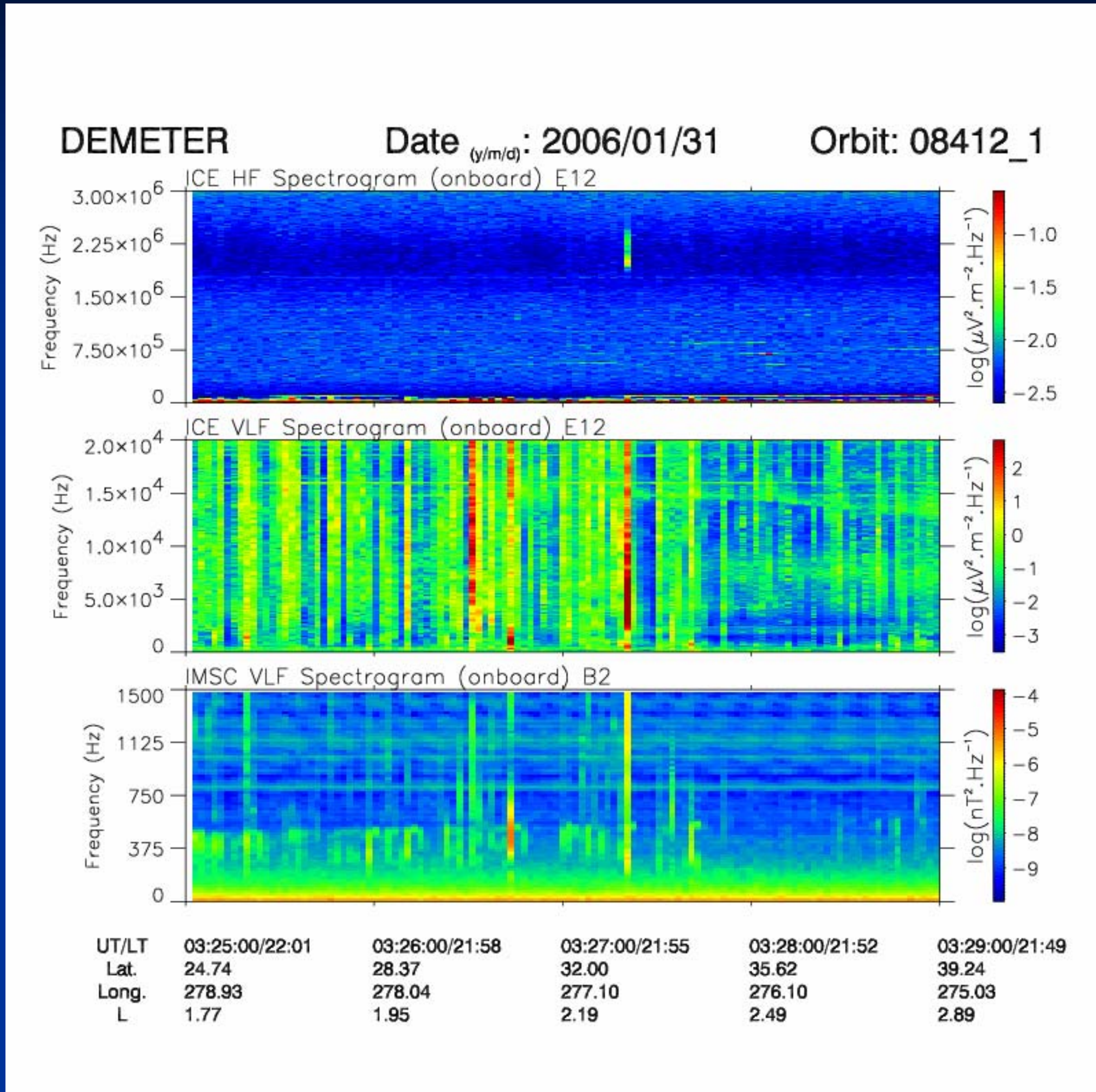
QUESTION 1 - Dispersion of nighttime VLF signals (18-25 kHz), recorded from 2006 to 2008, above powerful VLF transmitters (Parrot et al., JGR, Vol 114, 2009) ?



QUESTION 2 -Origin of bursts of MF bands (~ 2. – 2.5 MHz) in geographical regions far from VLF transmitters (Parrot et al. , JGR, Vol. 113, 2008) ?

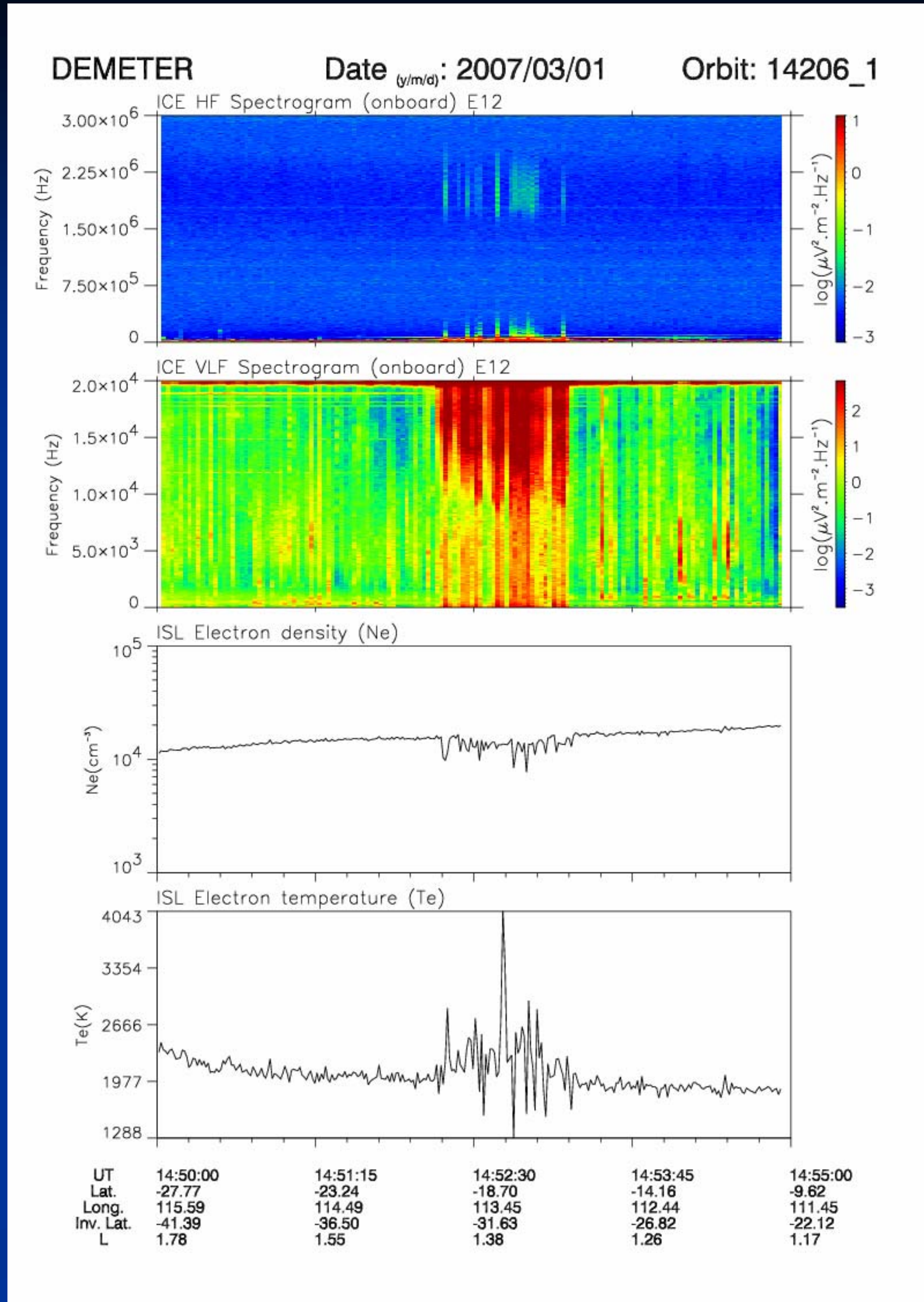


The peaks in intensity correspond to intense 0+ whistlers

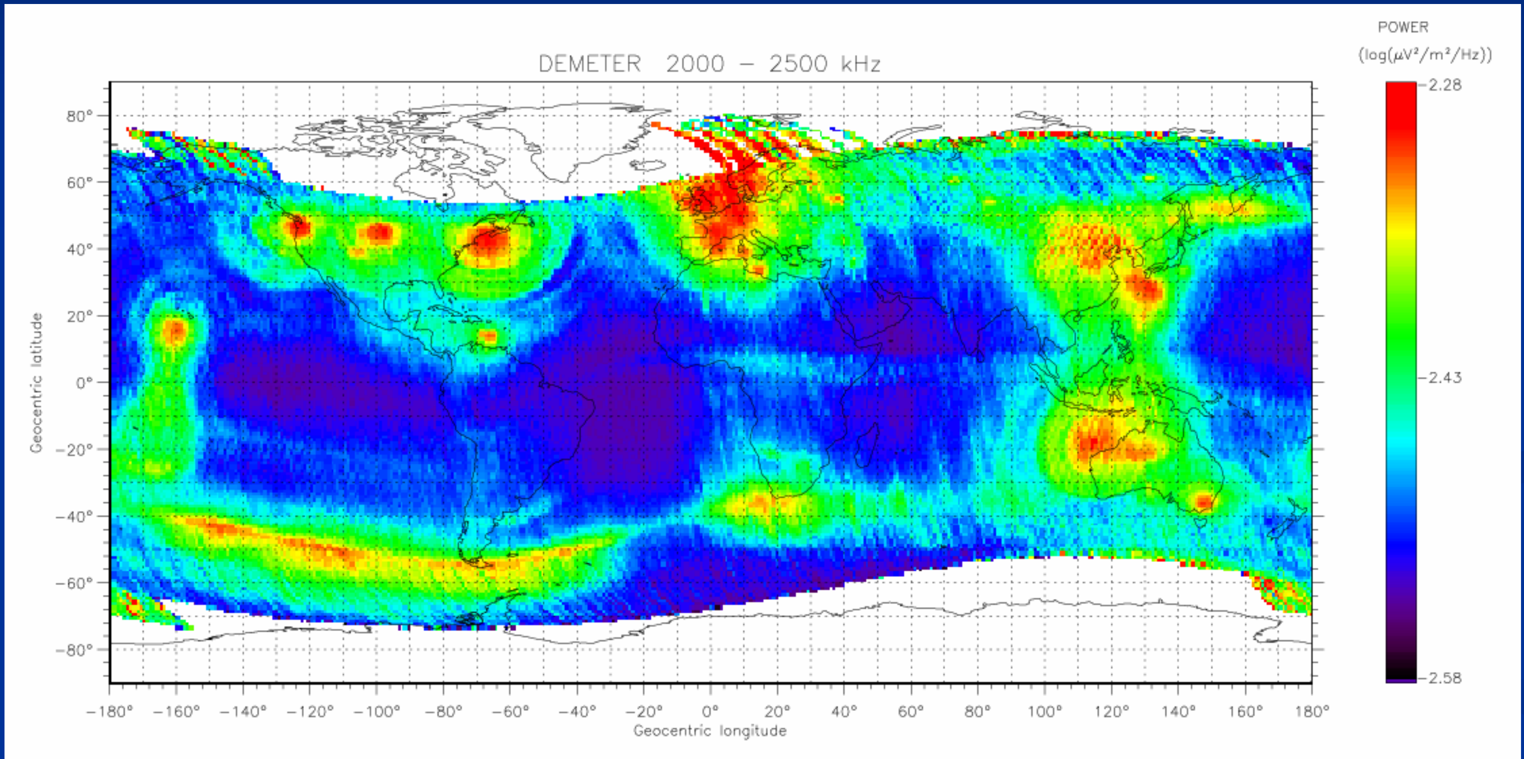

DEMETER
Date (y/m/d): 2006/01/31
Orbit: 08412_1
ICE HF Spectrogram (onboard) E12
Frequency (Hz)
log(µV².m⁻².Hz⁻¹)
ICE VLF Spectrogram (onboard) E12
Frequency (Hz)
log(µV².m⁻².Hz⁻¹)
IMSC VLF Spectrogram (onboard) B2
Frequency (Hz)
log(nT².Hz⁻¹)
UT/LT 03:25:00/22:01 03:26:00/21:58 03:27:00/21:55 03:28:00/21:52 03:29:00/21:49
Lat. 24.74 28.37 32.00 35.62 39.24
Long. 278.93 278.04 277.10 276.10 275.03
L 1.77 1.95 2.19 2.49 2.89

QUESTION 3 - Origin of MF bands (~ 2. – 2.5 MHz) above the NWC transmitter (Parrot et al. , JGR, Vol. 114, 2009) ?

Propagation through density irregularities?



QUESTION 4 - Origin of nighttime MF signals (2 – 2.5 MHz), recorded from 2006 to 2008, above powerful VLF transmitters (Parrot et al., JGR, Vol 114, 2009) ?



The peaks in intensity correspond to ~3dB enhancements of the lightnings above powerful VLF transmitters

Propagation through density irregularities?

Answers will be looked for from variations in the refractive index n^2 (Appleton – Lassen formula)

$$n^2 = 1 - \frac{A\,(X,U)}{B\,(X,Y,\theta,U) \pm \{ C\,(X,Y,\theta,U\}^{1/2}}$$

Ordinary wave
+ sign for $\pm\{\ \}1/2$

Extraordinary wave
- sign for $\pm\{\ \}1/2$

$X = fpe^2/f^2$

$Y = f_{ce}/f$

$\theta = (k, B_0)$

$U = 1 - iZ$ with $Z = \nu/\omega$ (ν , collision frequency)

Cold and collisionless plasma waves

$Y = f_{ce}/f > 1$

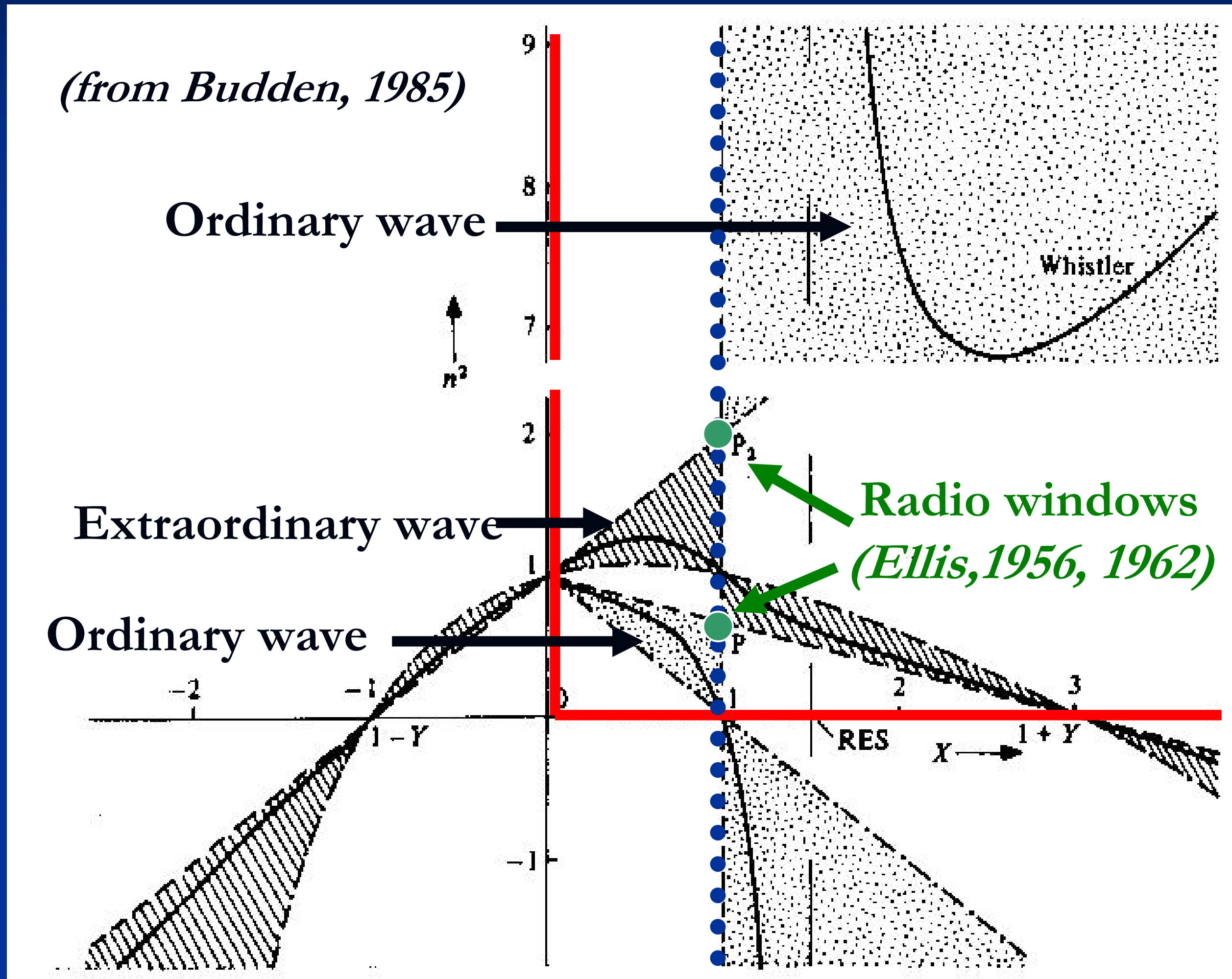
(ELF, VLF, LF, lower part of MF)

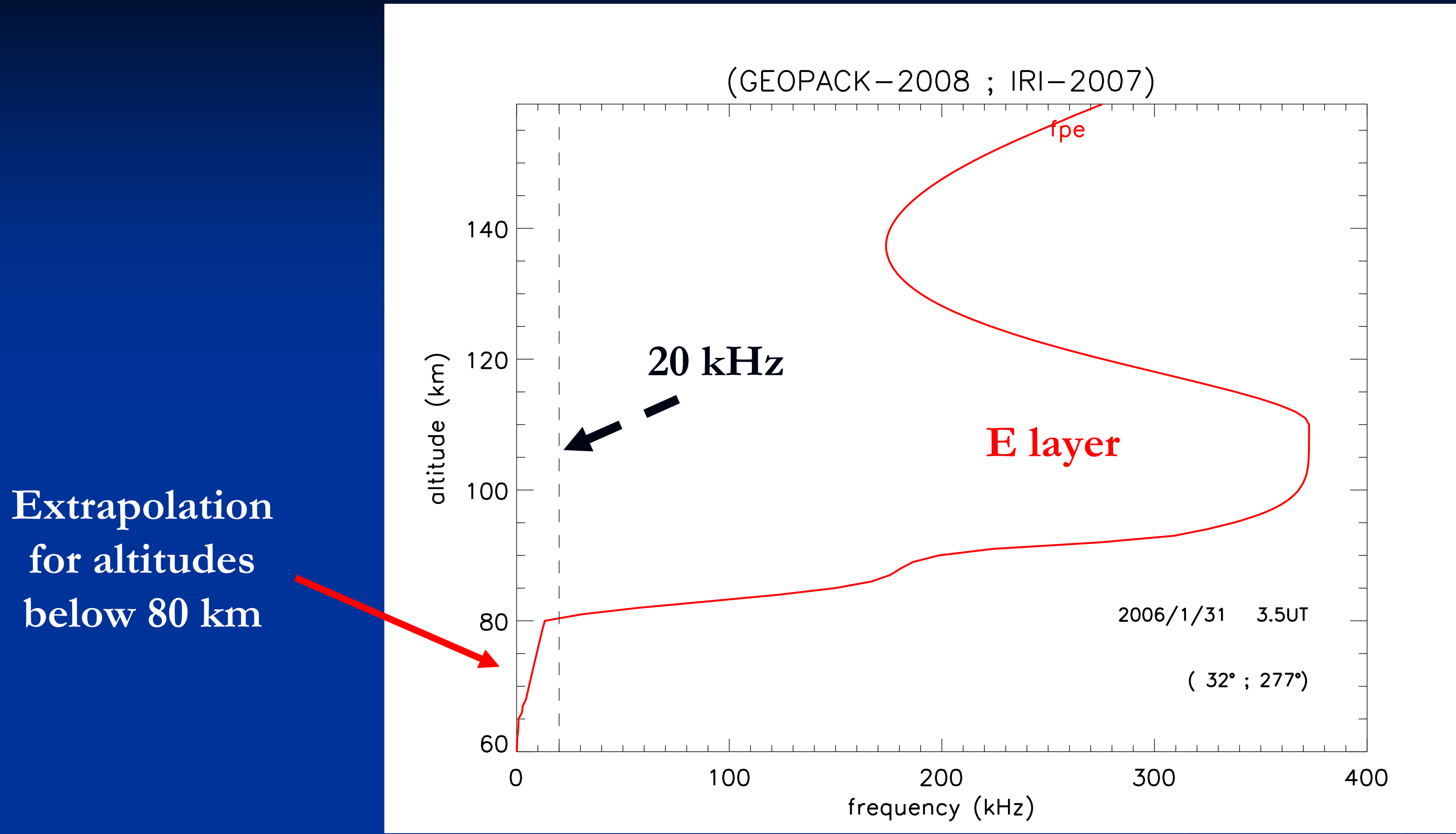
U=1

Two windows points:

-P, propagation stopped for X = 1+Y

-P_2, propagation to space




(GEOPACK−2008 ; IRI−2007)
fpe
20 kHz
E layer
Extrapolation for altitudes below 80 km
altitude (km)
140
120
100
80
60
0
100
200
300
400
frequency (kHz)
2006/1/31 3.5UT
(32° ; 277°)

f = 20 kHz

$\nu < 5.82\ 10^3$ s-1 at 85 km altitude

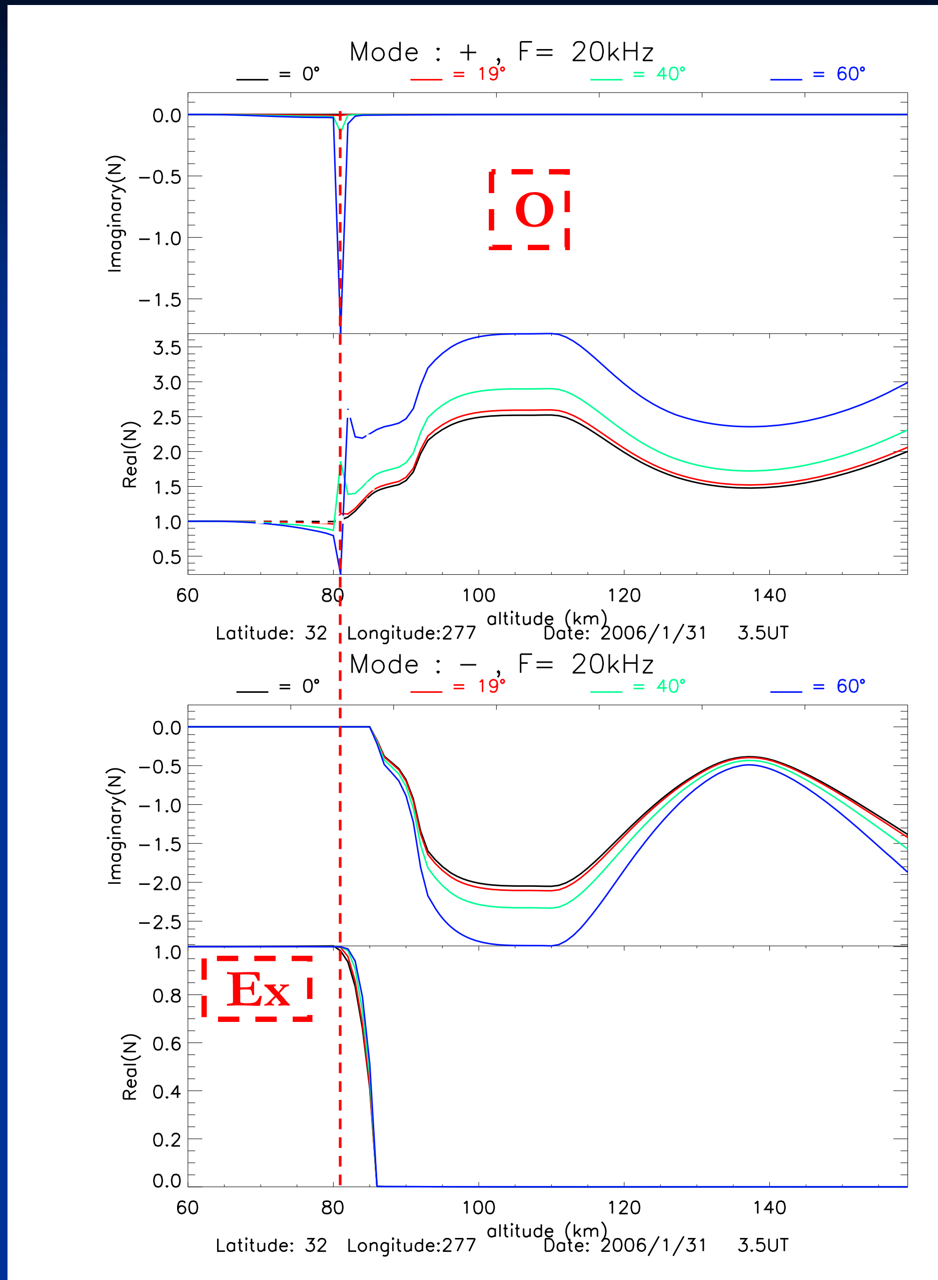
h < 80 km, Ex Mode

1st X = 1 crossing, Ex → O mode

$\theta = 0°$ crosses X =1
propagation up to 2d crossing (if any)

For all other θ values, discontinuity and absorption around X =1
(if generated at altitudes where X > 1, they may propagate)

O waves generated below X =1 are transmitted in Ex mode then are stopped at the altitude where X =1+Y

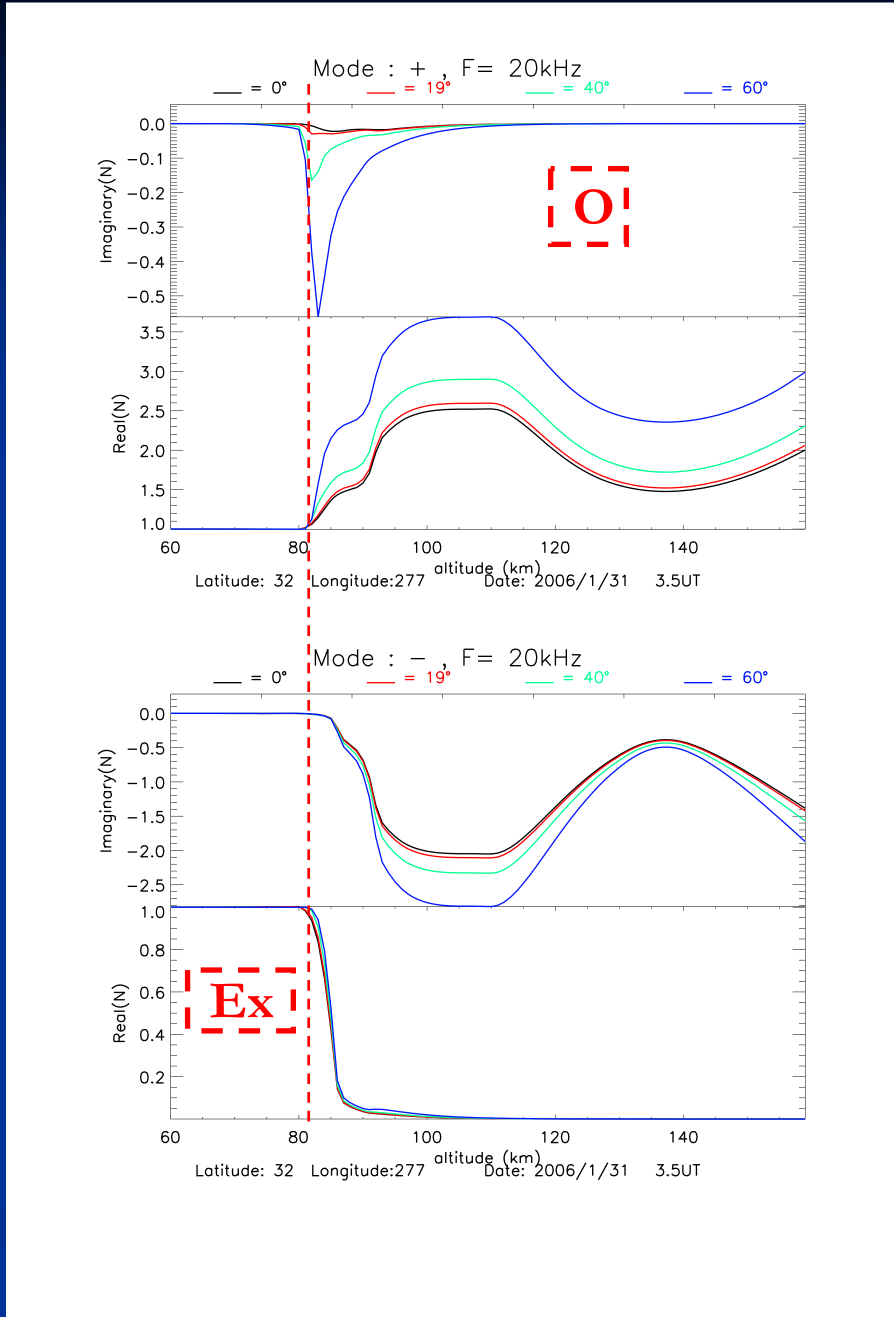


For ~ $\nu = 5.82\ 10^5\ s^{-1}$
at 85 km altitude

all the oblique waves
cross the X = 1 cut-off

Globally, the attenuation
factor has been reduced.

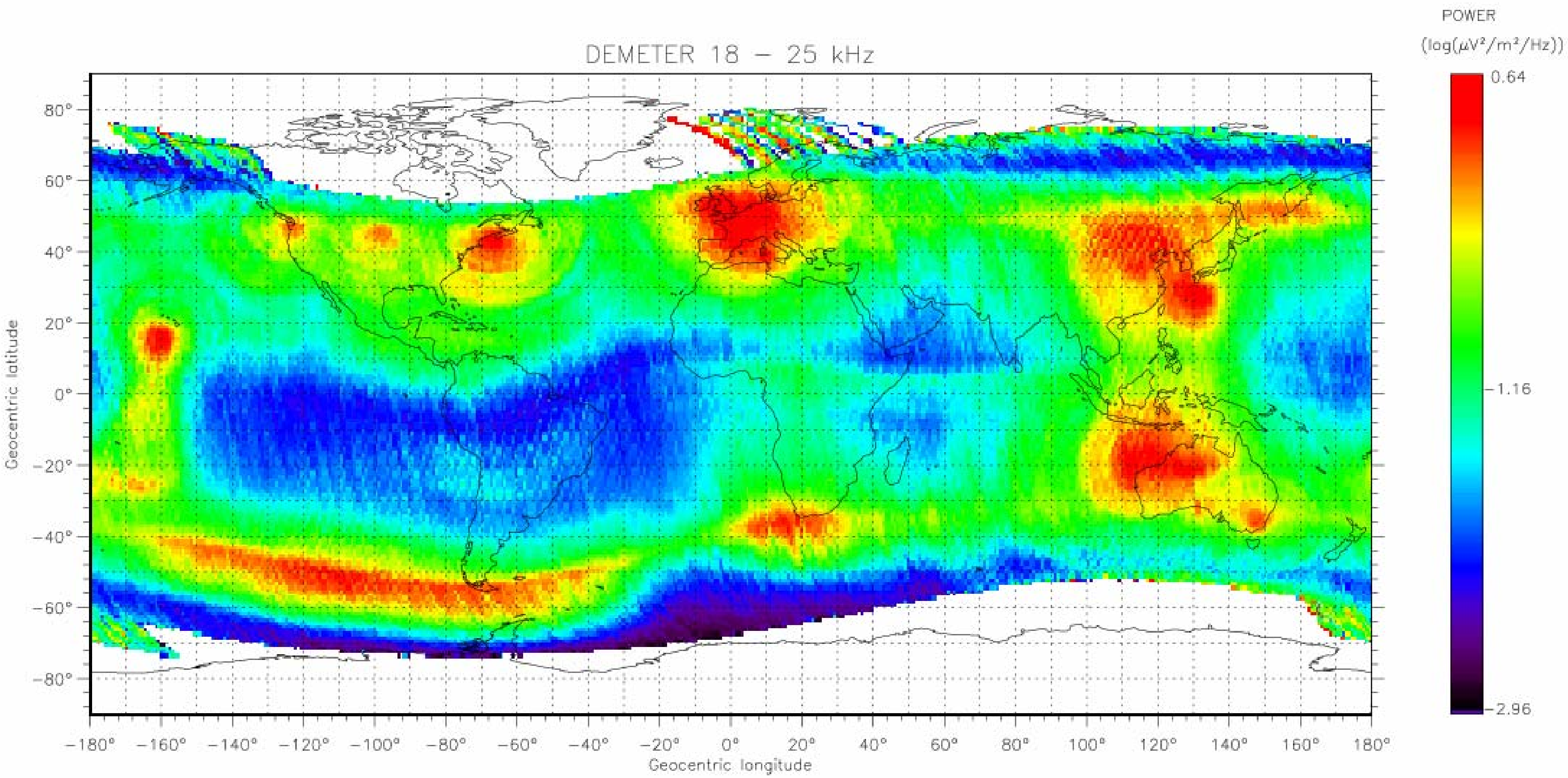
The VLF observations are
more geographically
dispersed above powerful
transmitters



- Heating produced by powerful VLF transmitters increase the electron collision frequency

- Increases in the electron collision frequency affect the transparency and the angular width of the radio windows

- This answers question 1 (see next slide)



DEMETER 18 – 25 kHz
POWER
(log(μV²/m²/Hz))
0.64
-1.16
-2.96
80°
60°
40°
20°
0°
-20°
-40°
-60°
-80°
Geocentric latitude
-180° -160° -140° -120° -100° -80° -60° -40° -20° 0° 20° 40° 60° 80° 100° 120° 140° 160° 180°
Geocentric longitude

Cold and collisionless plasma waves

Y=fce/f <1

(higher part of MF waves)

U=1

The only waves which reach the DEMETER altitude are those generated in the O mode at altitudes below X = 1, then propagated in the Extraordinary mode with

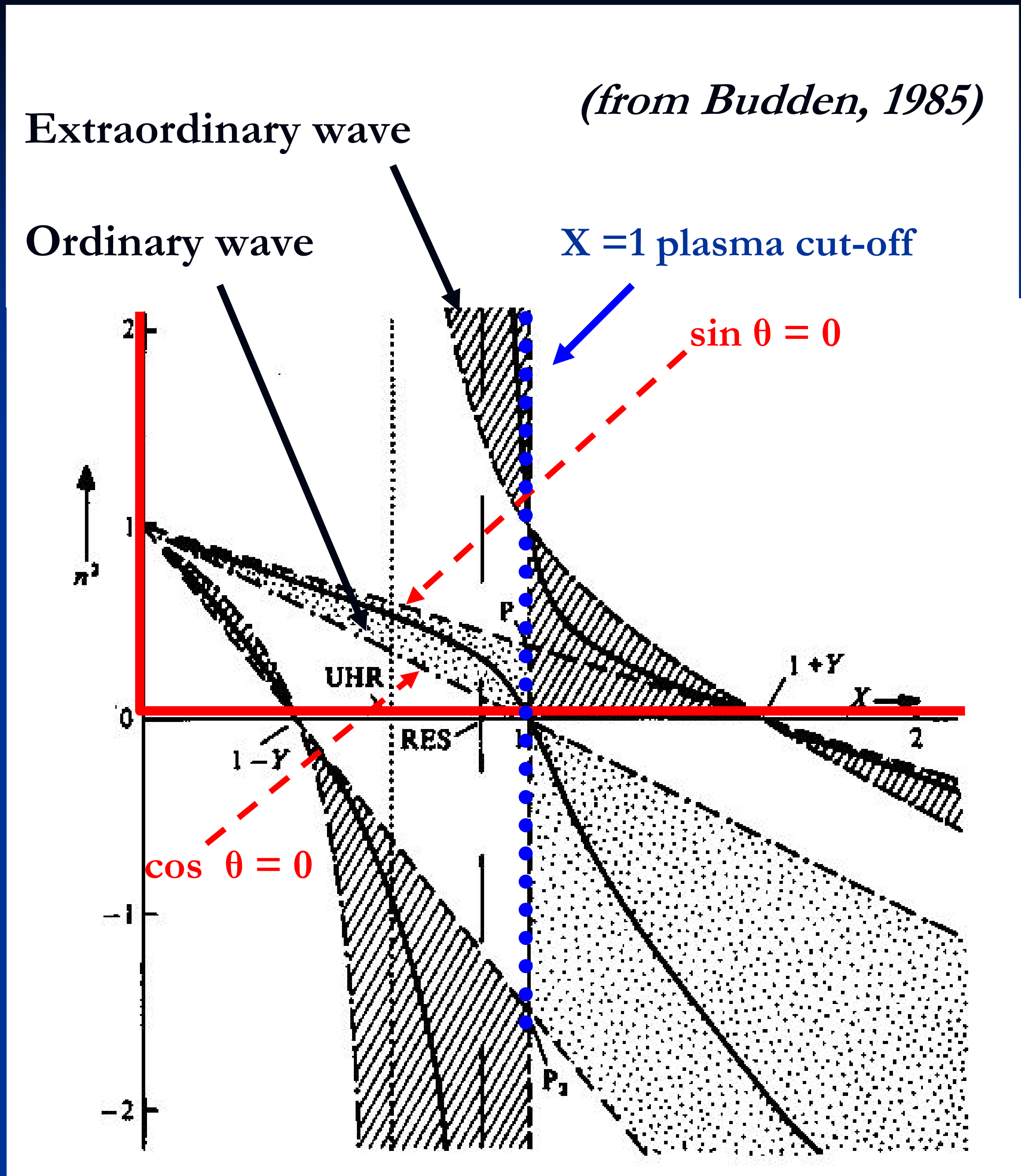
X < 1+Y

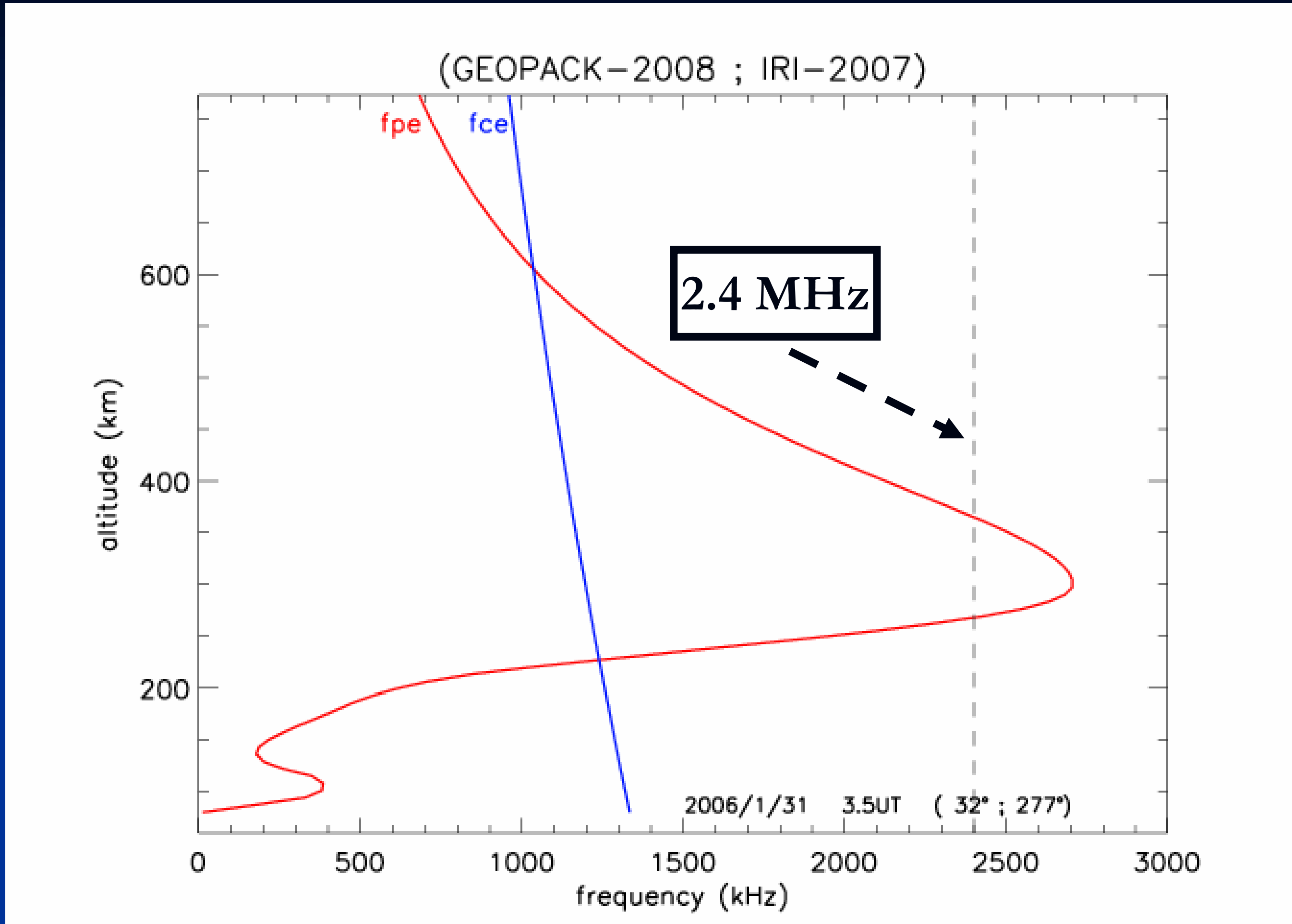
i.e.

fp2/f2 < 1 +fce/f

or

fp2 < f (f +fc





Condition for crossing the F layer : $f_p^{\,2} < f\,(f + f_{ce})$

- at the max of the F layer, f_{ce} ~ 1.2 MHz
- for f = 2.4 MHz, f_p must be <2.94 MHz

the 2.4 MHz wave crosses the ionosphere

f = 2400 kHz, Y < 1

h < 250 km, O Mode

all waves may propagate

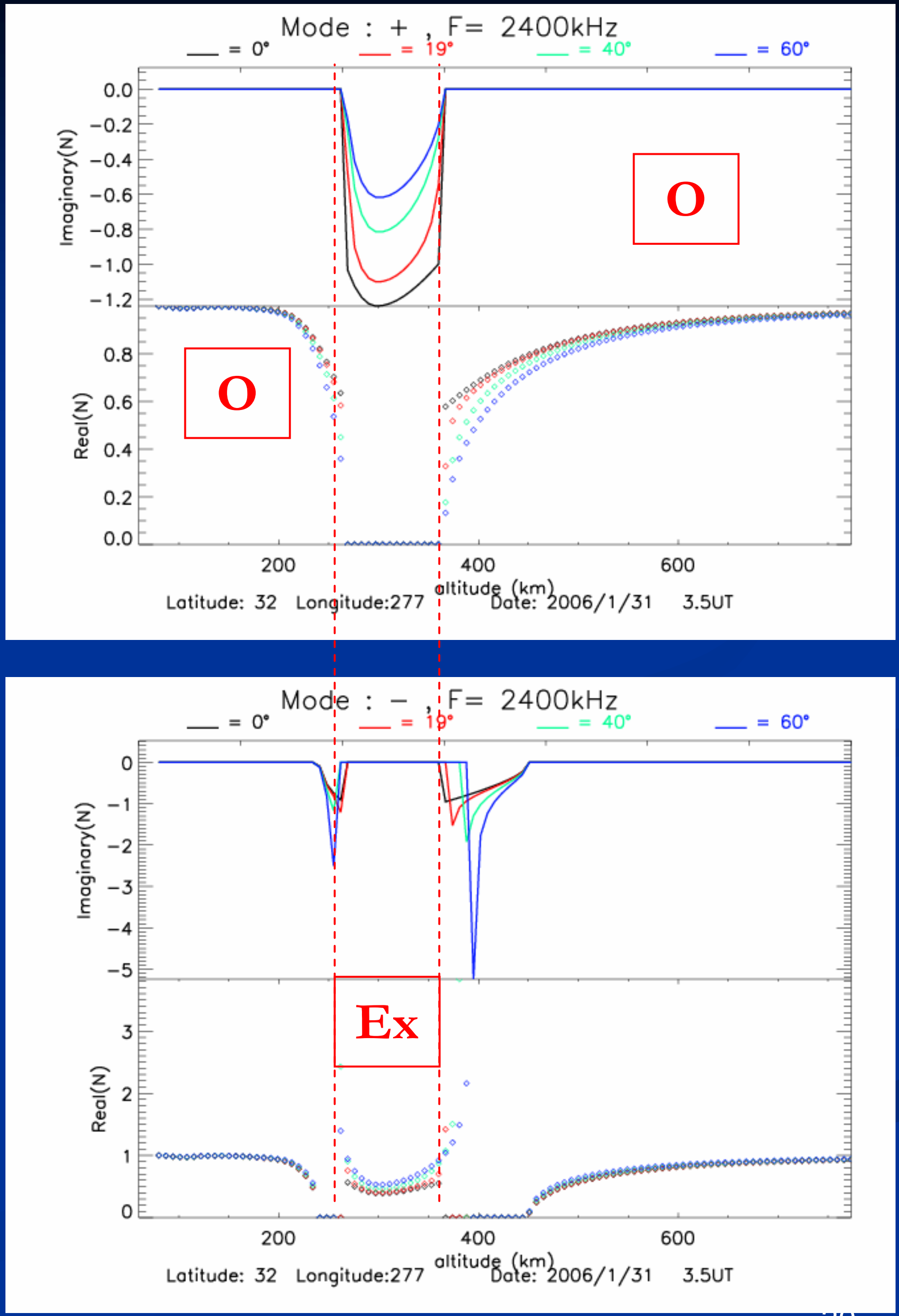
1st X = 1 crossing

θ = 0° crosses X =1
propagation up to 2d crossing
θ = 19° crosses X =1
stops before 2d crossing
θ = 40° does not cross X =1
(if generated there, may propagate between ~ 250 to 410 km)
θ = 60° does not propagate

2d crossing

θ = 0° crosses X =1
then propagates to space

Above 2d crossing, if generated there, other θ values may propagate.

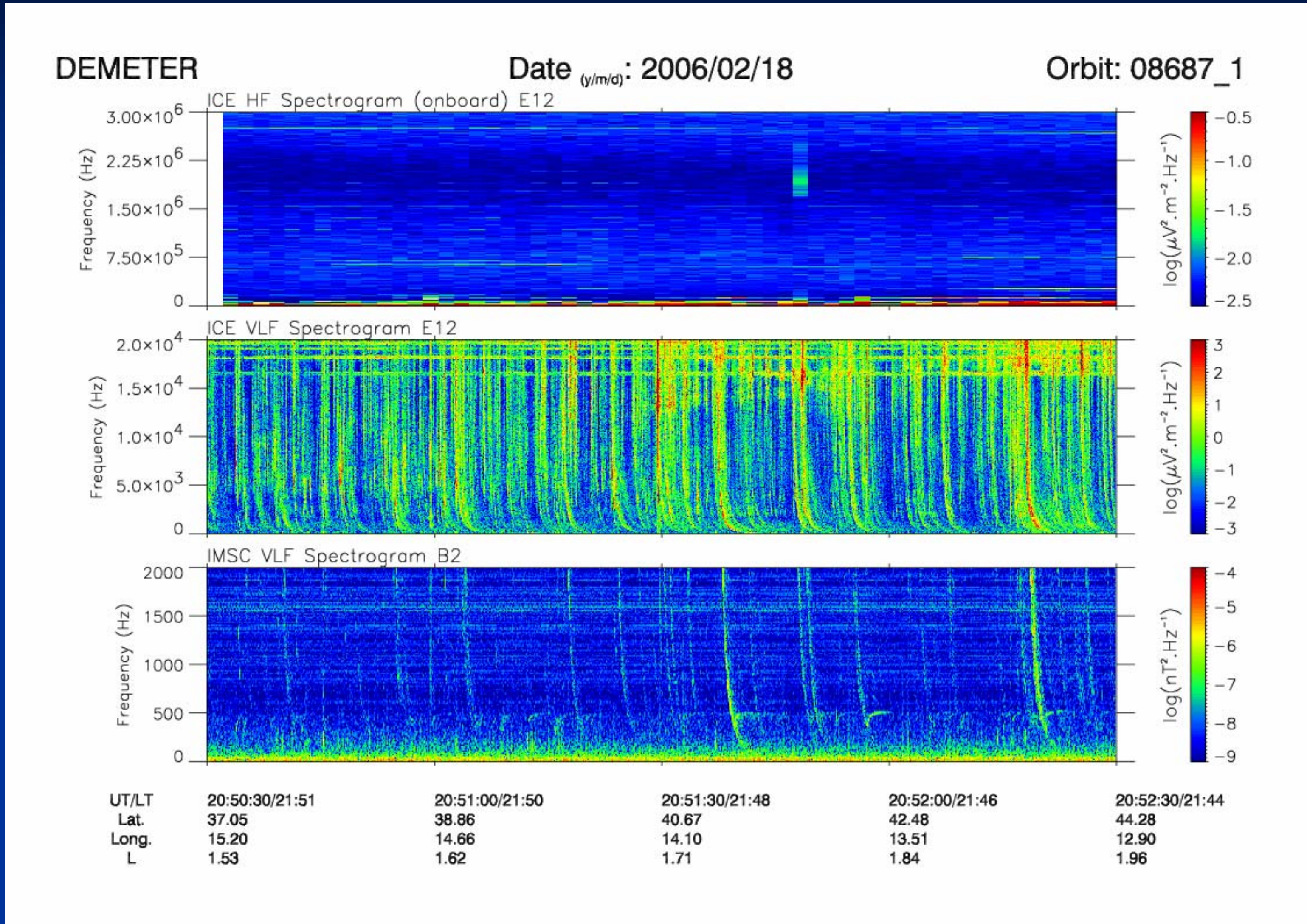


■ Far from powerful VLF transmitters, the MF waves that are observed on DEMETER respect the condition $X < 1+Y$ all over their propagation path (the F layer maximum plasma frequency is generally rather low).

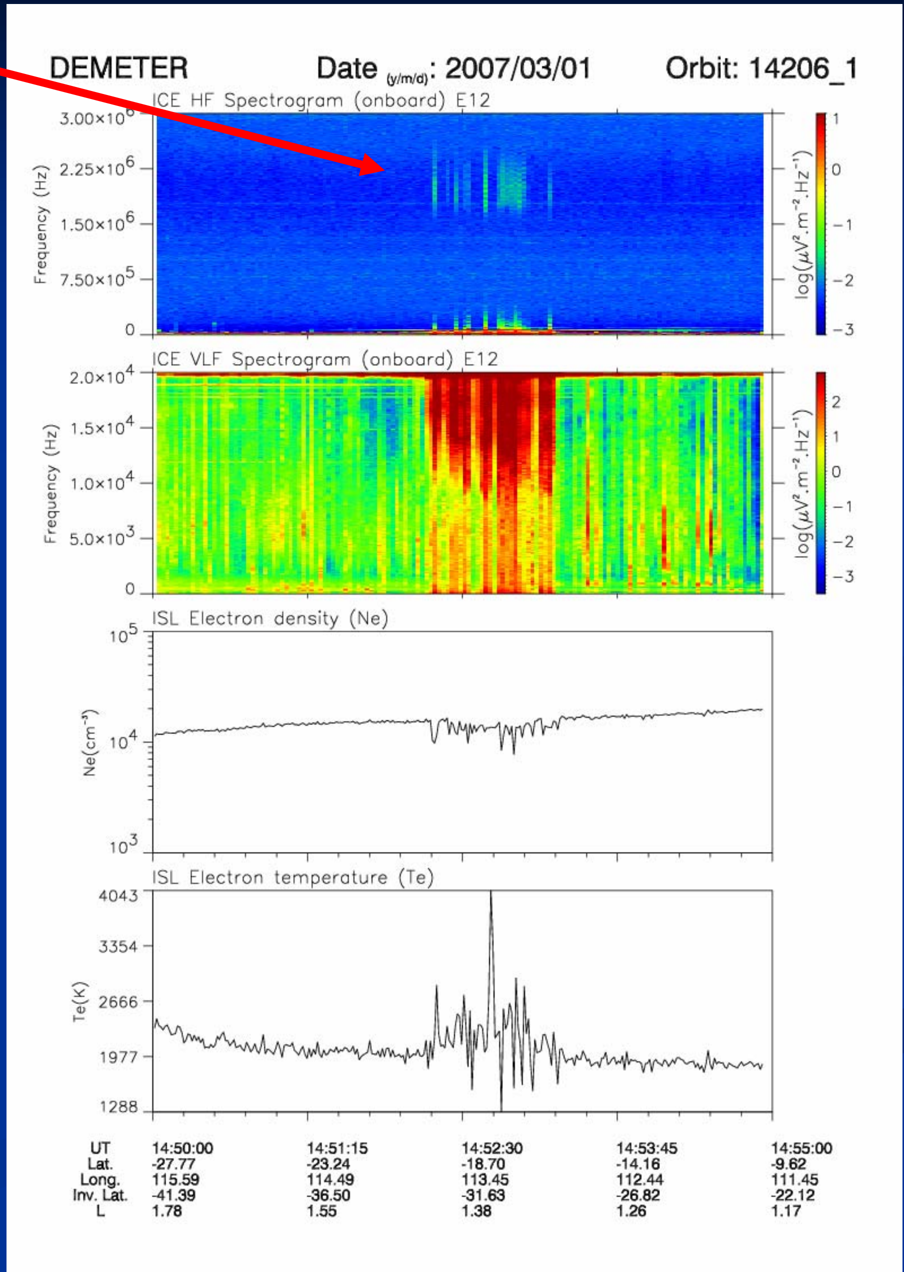
■ The upper cut-off of the MF band seems to be due to :

- the slope of the power spectrum of the observed O^+ whistlers
- or/and the slope of the filters used for the HF electric field measurements

■ This answers question 2 (see next slide)

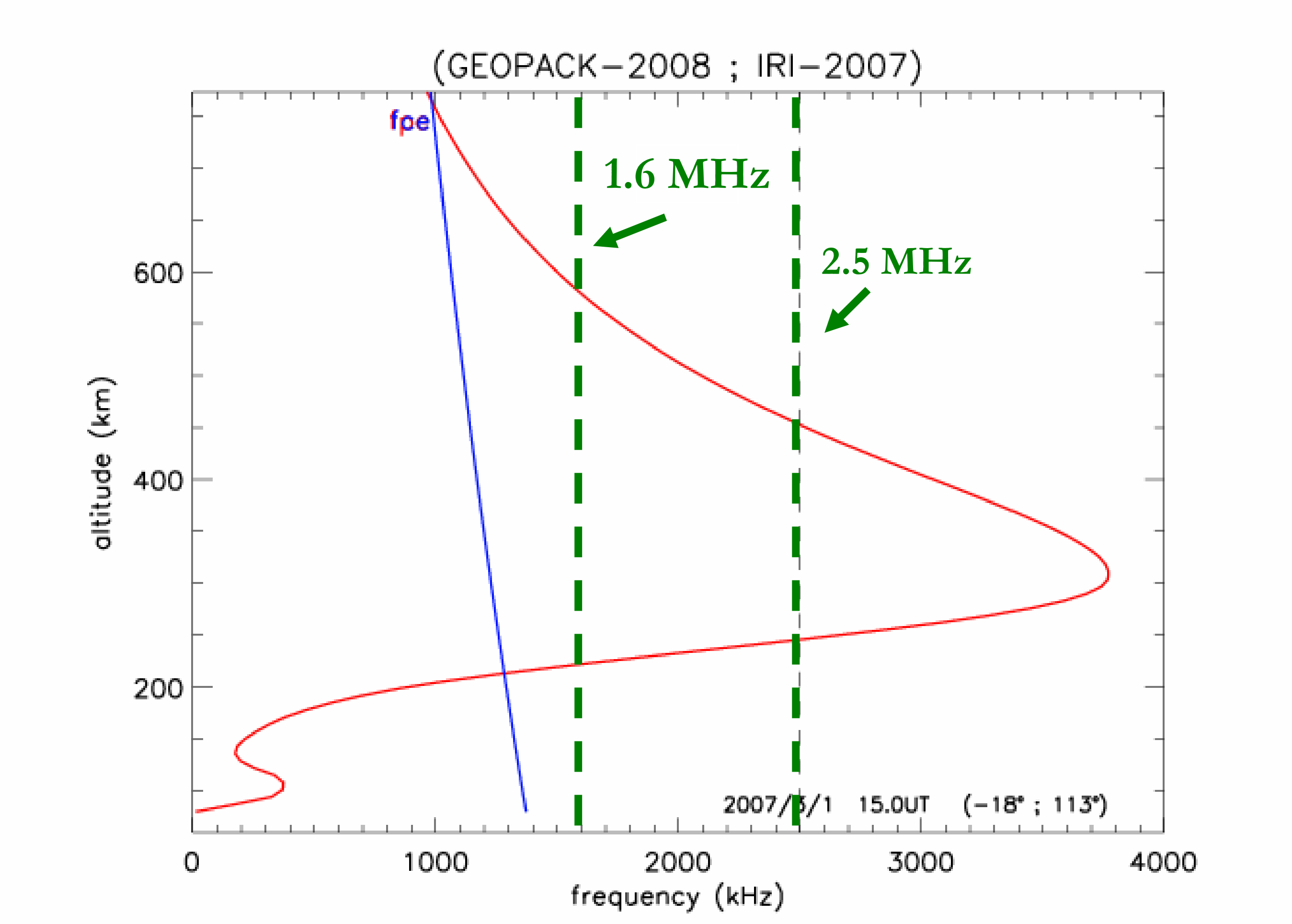

DEMETER
Date (y/m/d): 2006/02/18
Orbit: 08687_1
ICE HF Spectrogram (onboard) E12
Frequency (Hz)
3.00×10^6
2.25×10^6
1.50×10^6
7.50×10^5
0
log(μV².m⁻².Hz⁻¹)
-0.5
-1.0
-1.5
-2.0
-2.5
ICE VLF Spectrogram E12
2.0×10^4
1.5×10^4
1.0×10^4
5.0×10^3
3
2
1
0
-1
-2
-3
IMSC VLF Spectrogram B2
2000
1500
1000
500
log(nT².Hz⁻¹)
-4
-5
-6
-7
-8
-9
UT/LT 20:50:30/21:51 20:51:00/21:50 20:51:30/21:48 20:52:00/21:46 20:52:30/21:44
Lat. 37.05 38.86 40.67 42.48 44.28
Long. 15.20 14.66 14.10 13.51 12.90
L 1.53 1.62 1.71 1.84 1.96

1.6 – 2.5 MHZ frequency band



Other interpretations are needed when the F layer maximum f_p value is too large to respect $X < 1+Y$

i.e. if plasma waves propagation laws don't apply



Condition for crossing the F layer : $f_p^2 < f\,(f + f_{ce})$

- at the max of the F layer, fce ~ 1.2 MHz
- for f = 2.5 MHz, fp must be <3.04 MHz
- for f = 1.6 MHz, fp must be <2.09 MHz

No crossing of the MF band without density depletion

Possible interpretation:

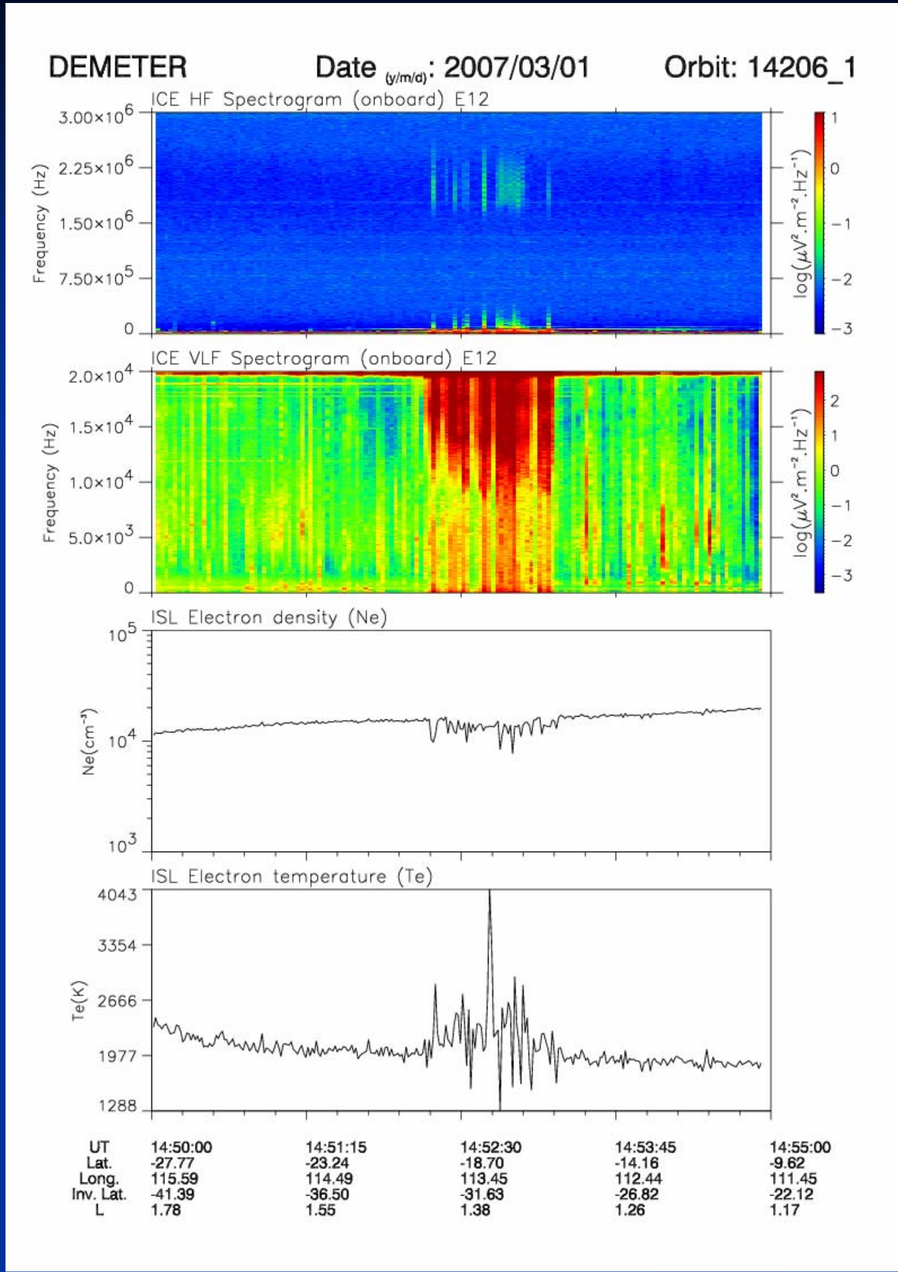
- The 1.6 – 2.5 MHz frequency band observed on DEMETER requires a density depletion with a maximum f_p value < 2 MHz

- density depletions may be associated with the Ne irregularities produced by the NWC VLF transmitter and observed on DEMETER (depletions of the order of ~ 50%, lateral extension of the order of a few kms)

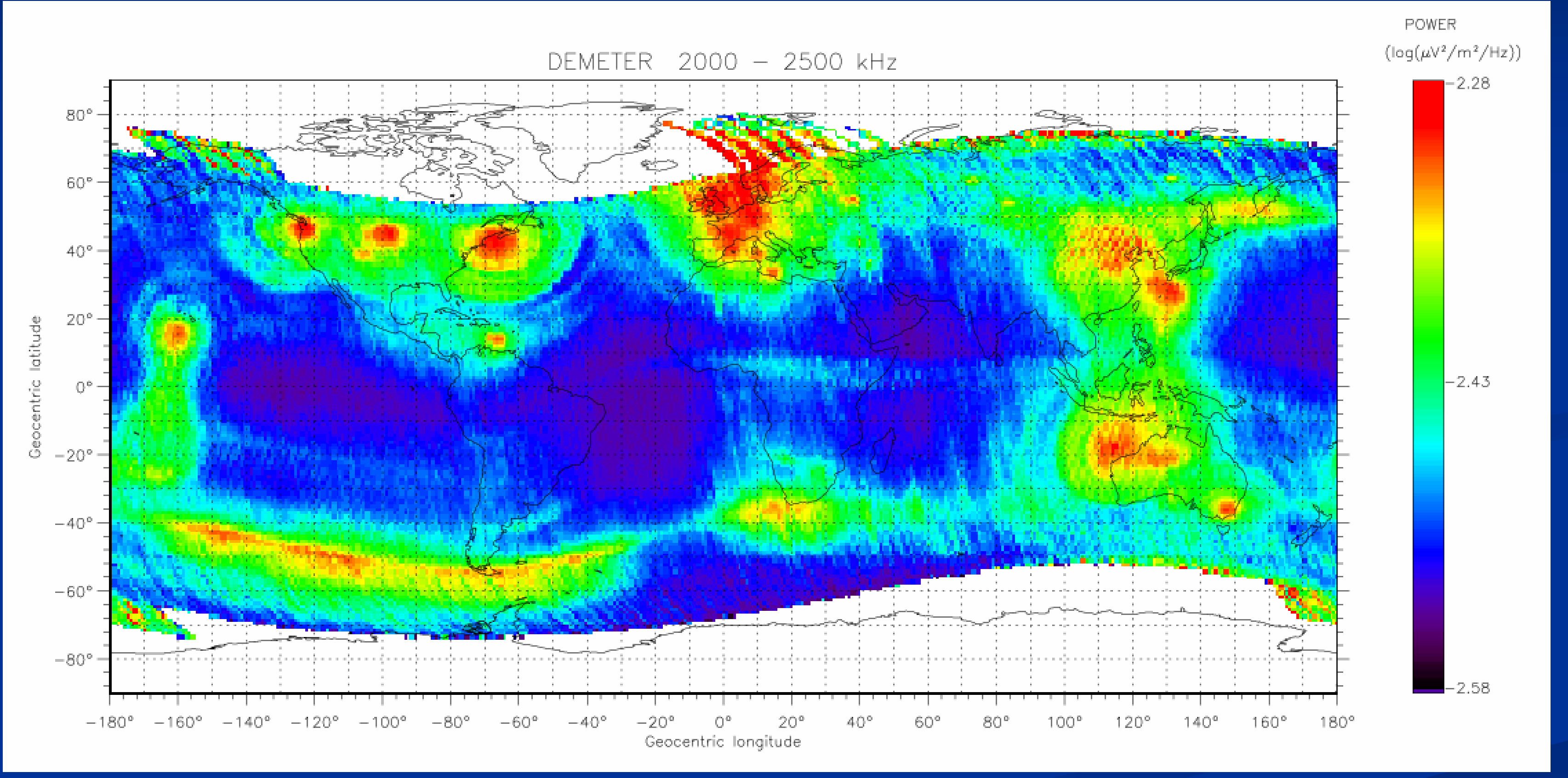
- those observations fit with the order of the density depletion required for the crossing of the F layer (depletions of the order of 70% around the maximum of the F layer) .

- Powerful VLF transmitters may generate density depletions allowing MF signals to cross the ionosphere.

- This answers questions 3 and 4 (see next two slides)



DEMETER
Date (y/m/d): 2007/03/01
Orbit: 14206_1
ICE HF Spectrogram (onboard) E12
ICE VLF Spectrogram (onboard) E12
ISL Electron density (Ne)
ISL Electron temperature (Te)
Frequency (Hz)
Ne(cm⁻³)
Te(K)
UT 14:50:00 14:51:15 14:52:30 14:53:45 14:55:00
Lat. -27.77 -23.24 -18.70 -14.16 -9.62
Long. 115.59 114.49 113.45 112.44 111.45
Inv. Lat. -41.39 -36.50 -31.63 -26.82 -22.12
L 1.78 1.55 1.38 1.26 1.17


DEMETER 2000 – 2500 kHz
POWER
(log(μV²/m²/Hz))
2.28
2.43
2.58
80°
60°
40°
20°
0°
−20°
−40°
−60°
−80°
Geocentric latitude
−180° −160° −140° −120° −100° −80° −60° −40° −20° 0° 20° 40° 60° 80° 100° 120° 140° 160° 180°
Geocentric longitude

CONCLUSION

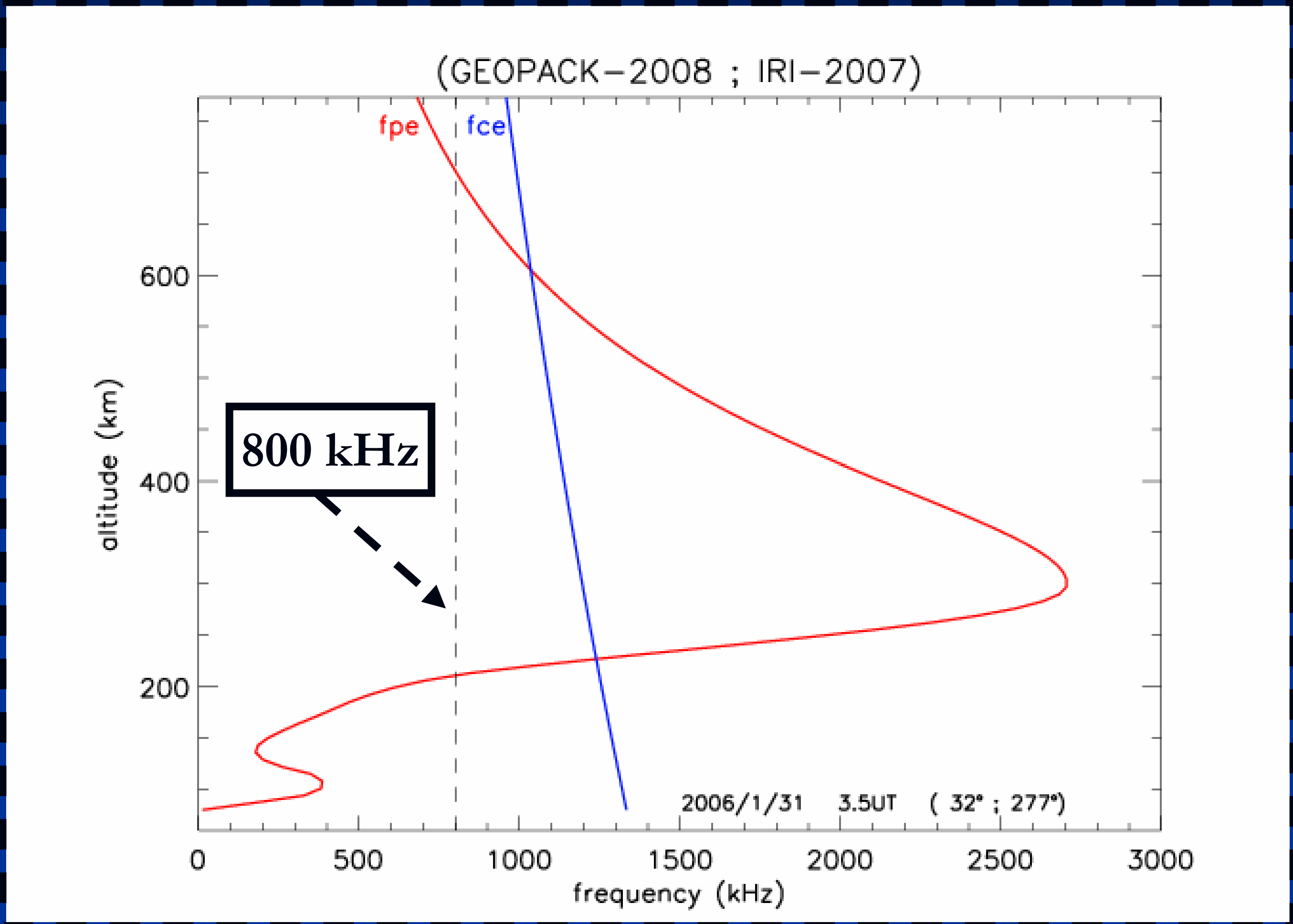
- Far from powerful VLF wave transmitters

The propagation laws of plasma waves (e.g. Budden, 1985) applies. They explain all original observations made by DEMETER

- Above powerful VLF transmitters

- increases in the electron collision frequency, increase the angular width of the waves which cross the X =1 plasma cut- off at the bottom of the ionosphere (which explains dispersion of VLF waves above powerful VLF transmitters)

- generation of Ne irregularities produce Ne depletions allowing MF waves to cross the ionosphere even for large $(f_p)_{max}$.


(GEOPACK-2008 ; IRI-2007)
fpe
fce
800 kHz
altitude (km)
600
400
200
0
500
1000
1500
2000
2500
3000
frequency (kHz)
2006/1/31 3.5UT (32° ; 277°)

f = 800 kHz, Y > 1

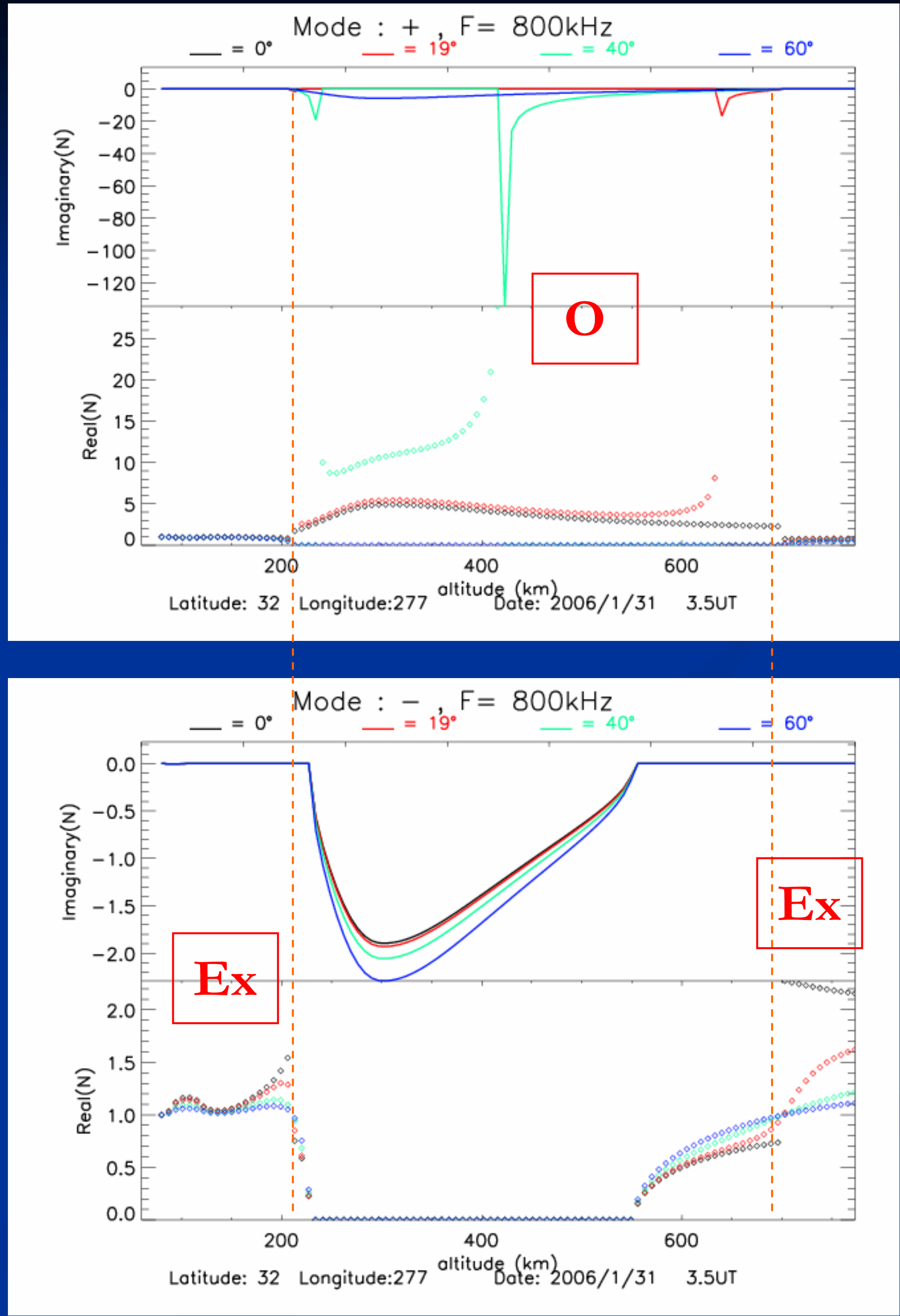
h < 200 km, Ex Mode
all waves may propagate

1^{st} X = 1 crossing, Ex → O mode

θ = 0° crosses X =1
propagates up to 2^d crossing
θ = 19° crosses X =1
stops before 2^d crossing
θ = 40° does not cross X =1
if generated there, may propagate between ~ 250 to 410 km
θ = 60° does not propagate

2^d X=1 crossing, O → E_X mode

θ = 0° propagates to space



According to their expected values at altitudes > 180 km electron collision frequencies don't affect X = 1 crossings.