Evaluation of latitude dependent time of trans-ionospheric ELF/VLF impulse propagation and LEO incident directions

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8th VERSIM Workshop Apatity
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motivation, target and tool:

- to provide (possibly) more accurate prop. time of **0^+ whistlers**, than used now in modelling
  - inversion of whistlers recorded on-board <– better plasmasphere density estimation due to better ionospheric correction
- to draw (refined) picture of impulse prop. topology across the ionosphere, consistent with the growing set of reference LEO satellite wave records
  - the use of 0^+ whistlers for ionosphere modeling, towards a unified plasma environment description

- UWB, real full-wave solutions of the Maxwell's eqs. [Ferencz et al. 2006], closed formulae for time domain field components
  - arbitrary excitation (Dirac or finite length waveform)
  - arbitary ion composition, loss by collision freq.
  - arbitrary inhomogenity (no WKB, longitudinal), or oblique (homogeneous)
  - common path for the whole impulse (*contradicting with RT/optic approach*)

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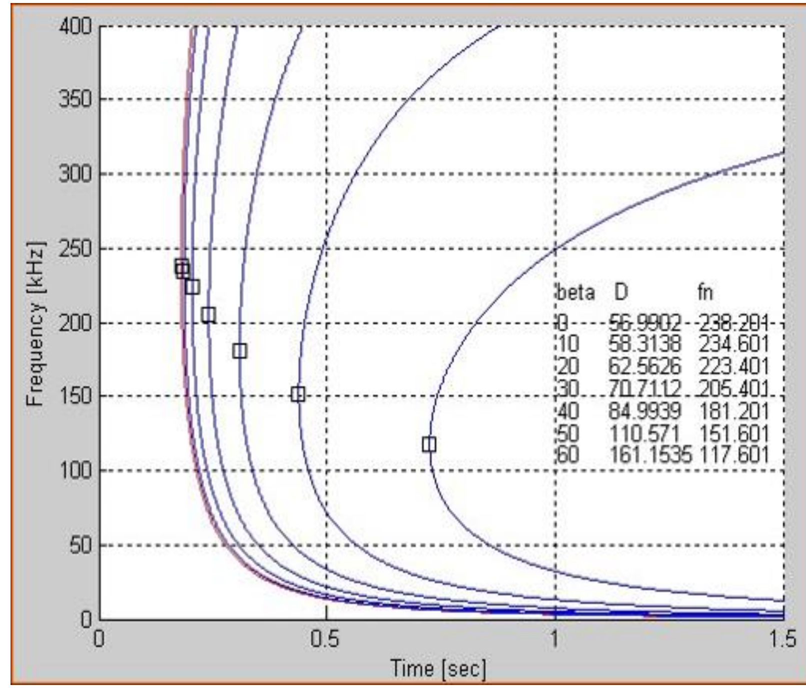
model parameters:

wp, wb, distance, beta



the propagation factors:

$$k_x = \frac{1}{c}\sqrt{\omega^2 - \frac{\omega\omega_b\omega_p^2\sqrt{4\left(\omega^2-\omega_p^2\right)^2\cos^2\beta + \omega^2\omega_b^2\sin^4\beta} - \omega^2\omega_p^2\left[\omega_b^2\sin^2\beta - 2\left(\omega^2-\omega_p^2\right)\right]}{2\left[\omega_b^2\omega_p^2\cos^2\beta + \omega^2\left(\omega_2 - \omega_b^2 - \omega_p^2\right)\right]}},$$

$$\alpha_x = \frac{1}{c}\sqrt{\omega^2 - \frac{\omega\omega_b\omega_p^2\sqrt{4\left(\omega^2-\omega_p^2\right)^2\cos^2\beta + \omega^2\omega_b^2\sin^4\beta} + \omega^2\omega_p^2\left[\omega_b^2\sin^2\beta - 2\left(\omega^2-\omega_p^2\right)\right]}{2\left[\omega_b^2\omega_p^2\cos^2\beta + \omega^2\left(\omega_2 - \omega_b^2 - \omega_p^2\right)\right]}}$$

time domain (electric) field:

$$E(t) = F^{-1}\left\{\left(E_1\cos\beta - E_3\sin\beta\right)\cdot e^{-j\frac{k_x}{\cos\beta}\cdot x}\right\},$$

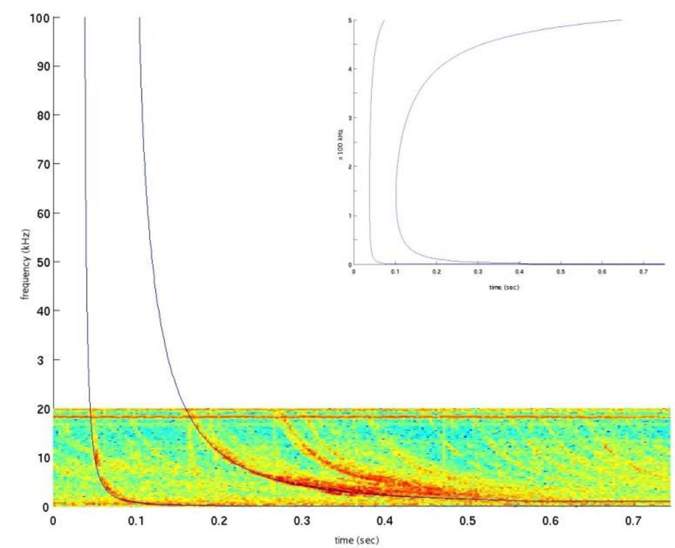
where

$$E_1 = M_{xw}E_3$$

$$E_3 = \frac{-Z_0 I_{x0}}{\left\{\left(\cos\beta + \frac{k_x}{k_0}\right) + M_{xw}\left(\sin\beta + \frac{k_x}{k_0}\tan\beta\right) + \left[\left(\cos\beta - j\frac{\alpha_x}{k_0}\right) + M_{xN}\left(\sin\beta - j\frac{\alpha_x}{k_0}\tan\beta\right)\right]\frac{M_{xw}\cos\beta - \sin\beta}{-M_{xN}\cos\beta + \sin\beta}\right\}}$$

$$M_{xw} = \frac{-c^2k_x^2\tan\beta}{\omega_p^2 - \omega^2 + c^2k_x^2\tan^2\beta} \text{ and } M_{xN} = \frac{c^2\alpha_x^2\tan\beta}{\omega_p^2 - \omega^2 - c^2\alpha_x^2\tan^2\beta}$$

[*Ferencz et al*. 2001]



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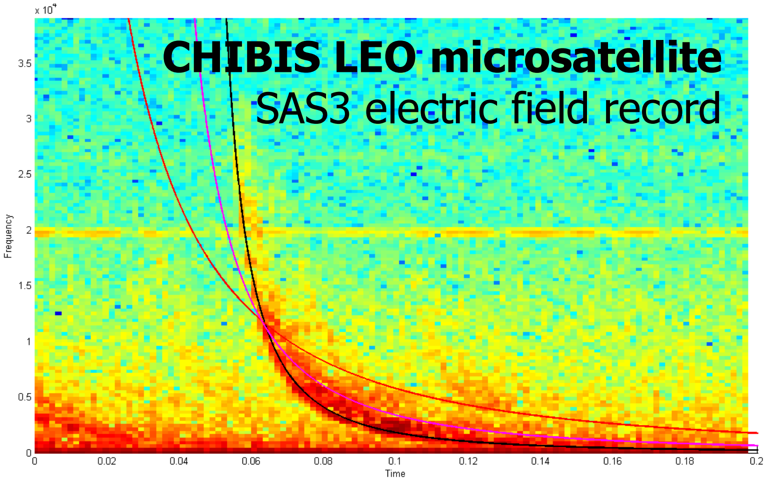
example case of **lsq bestfits** for the most probable entry *point* at the ionosphere bottomside



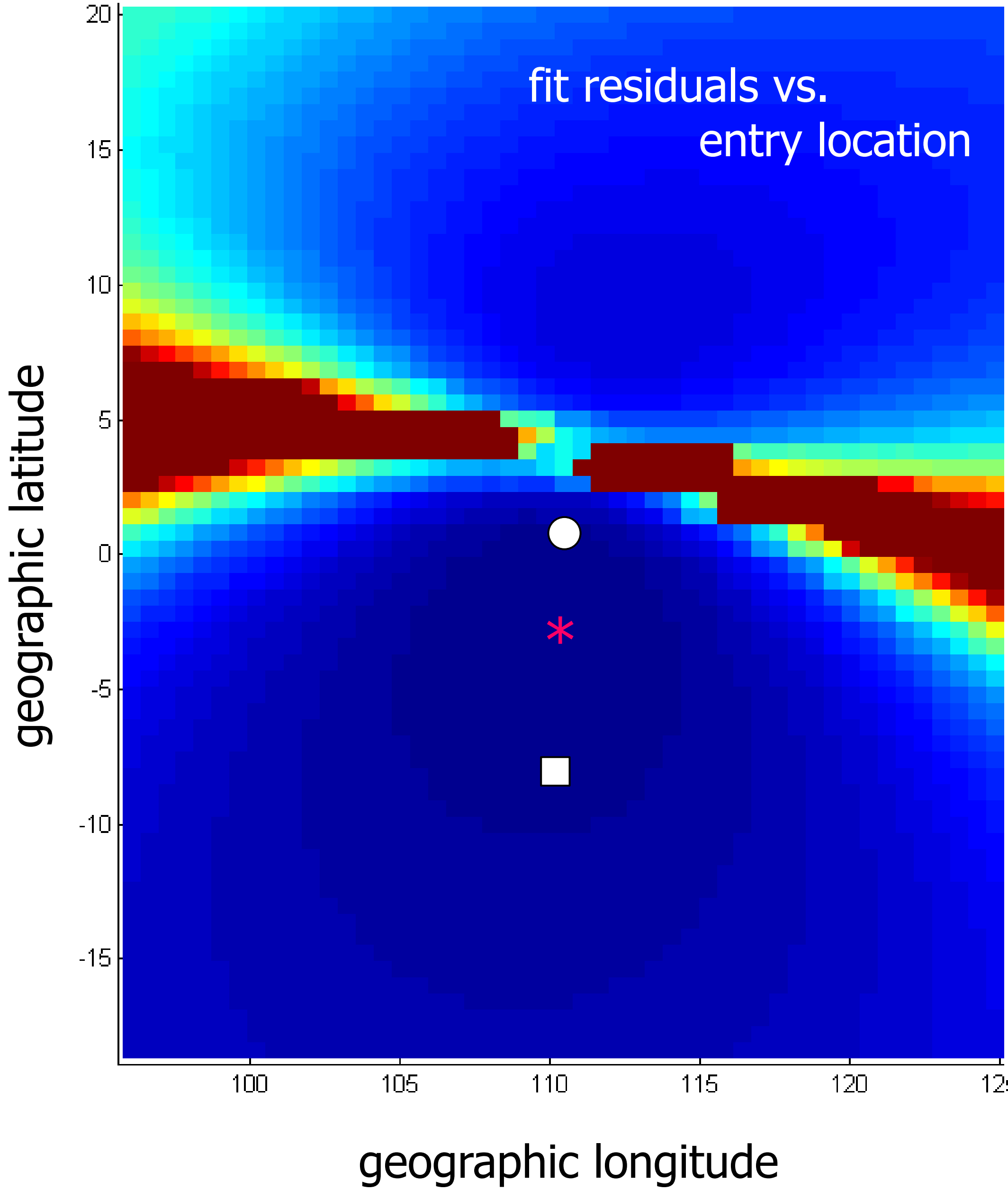
Simple concept, direct search,
medium fixed by IGRF & IRI,
free parameter is the location of the starting point only

sub-satellite **o**:
110.36 E; 1.11N
geom.lat: 6.74S, L: 1.09,

best fit *,

field line footprint @100km □:
110.27E; 7.99S

whistler dispersion: 2.7 $s^{1/2}$



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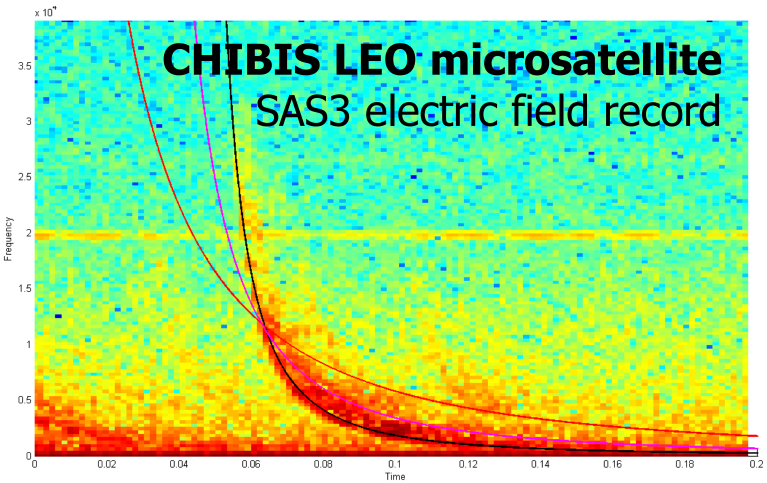

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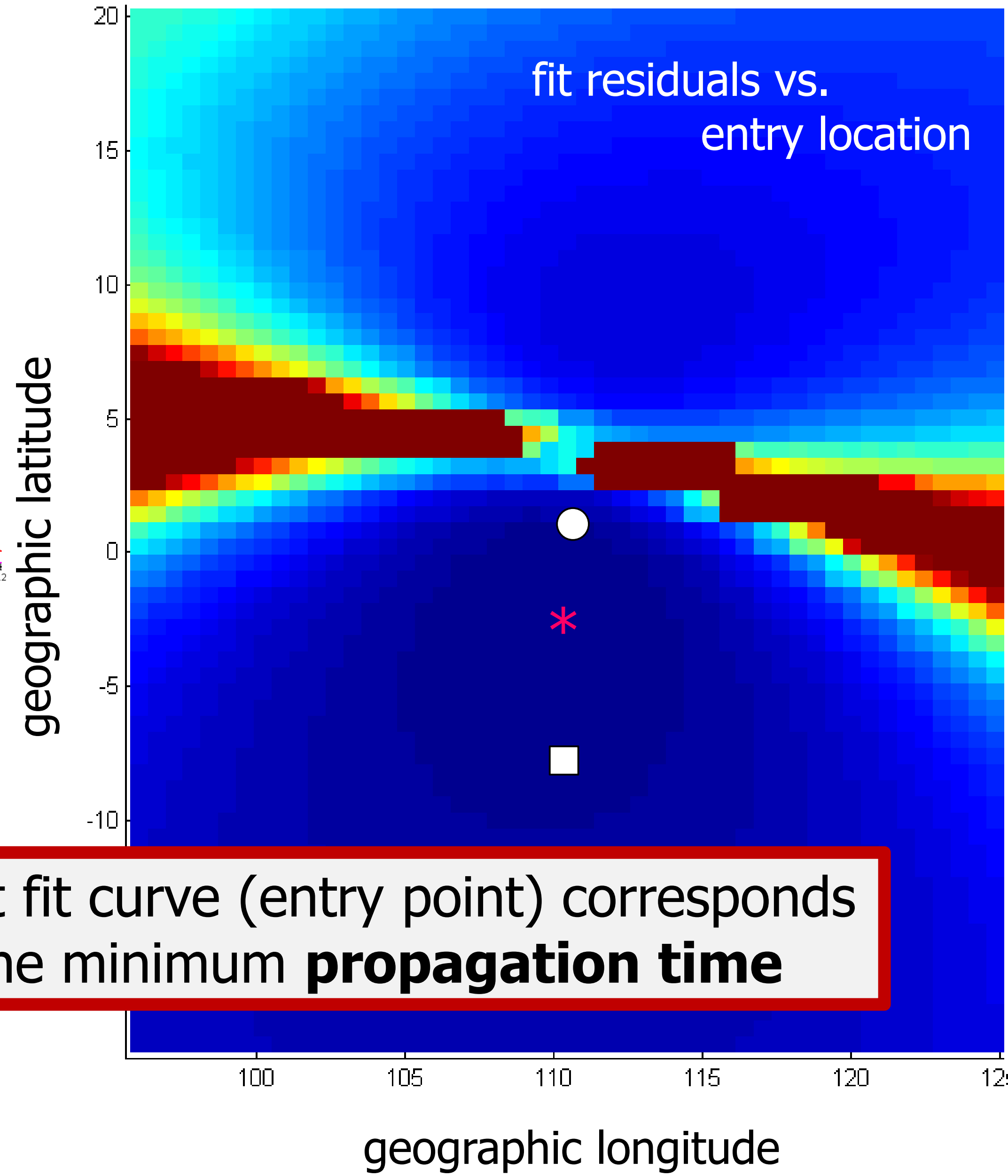
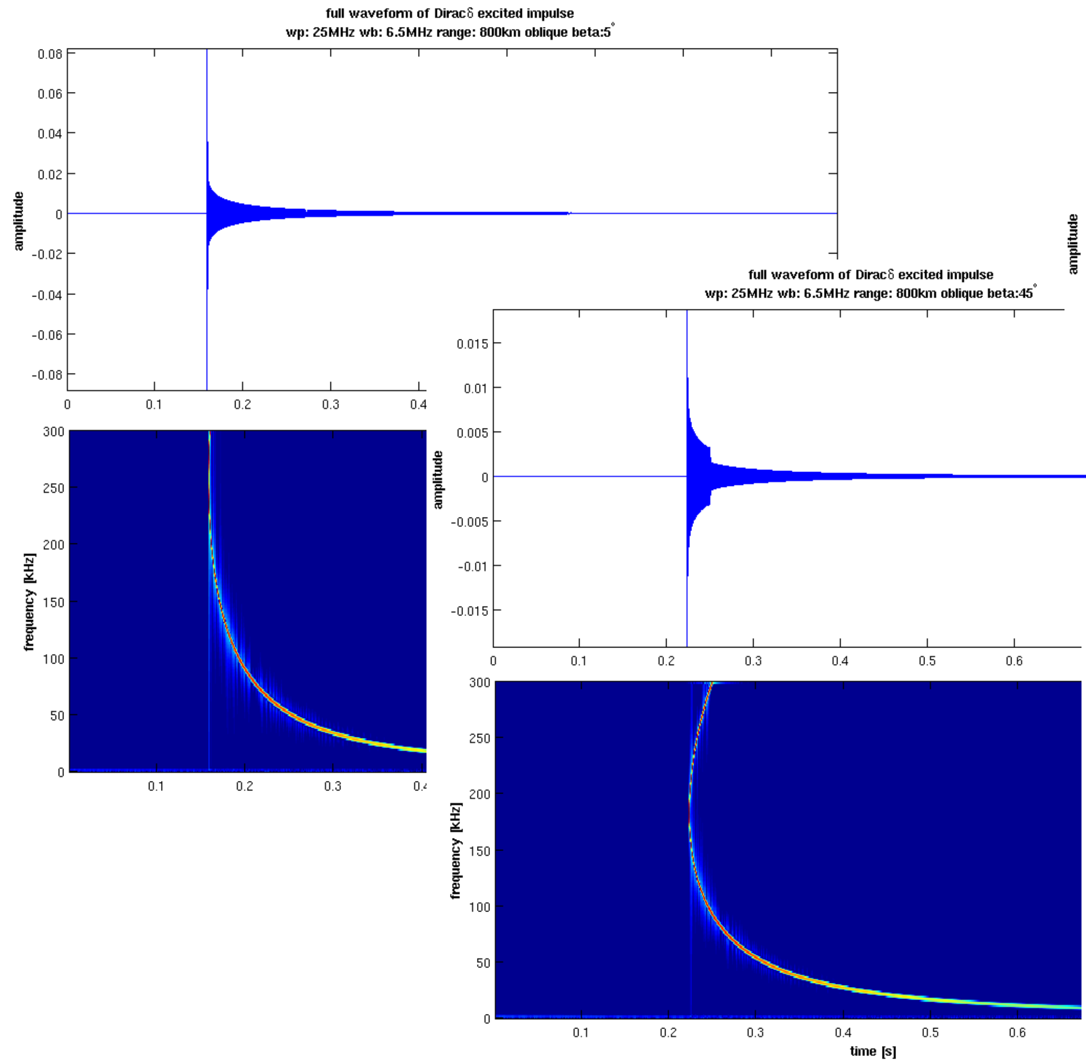
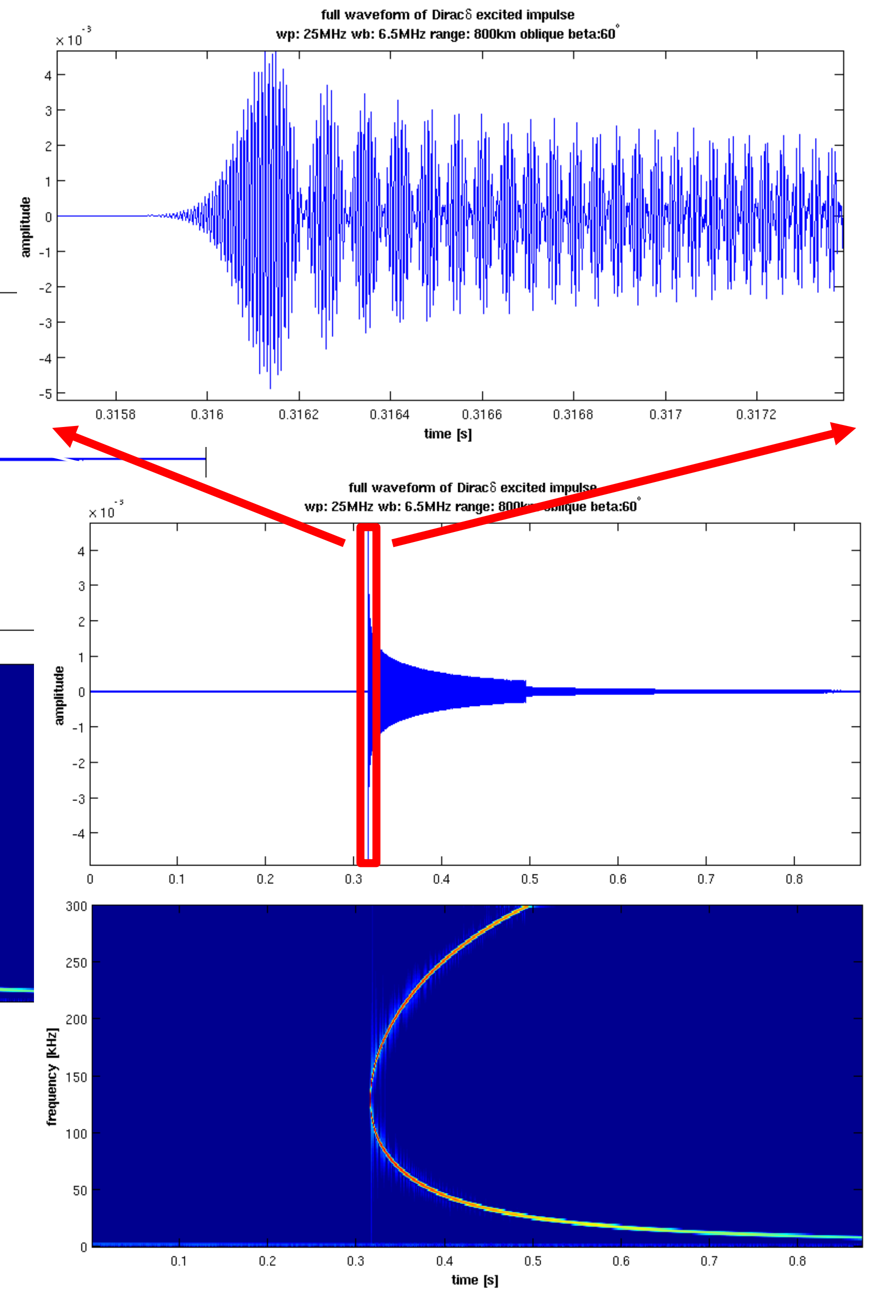
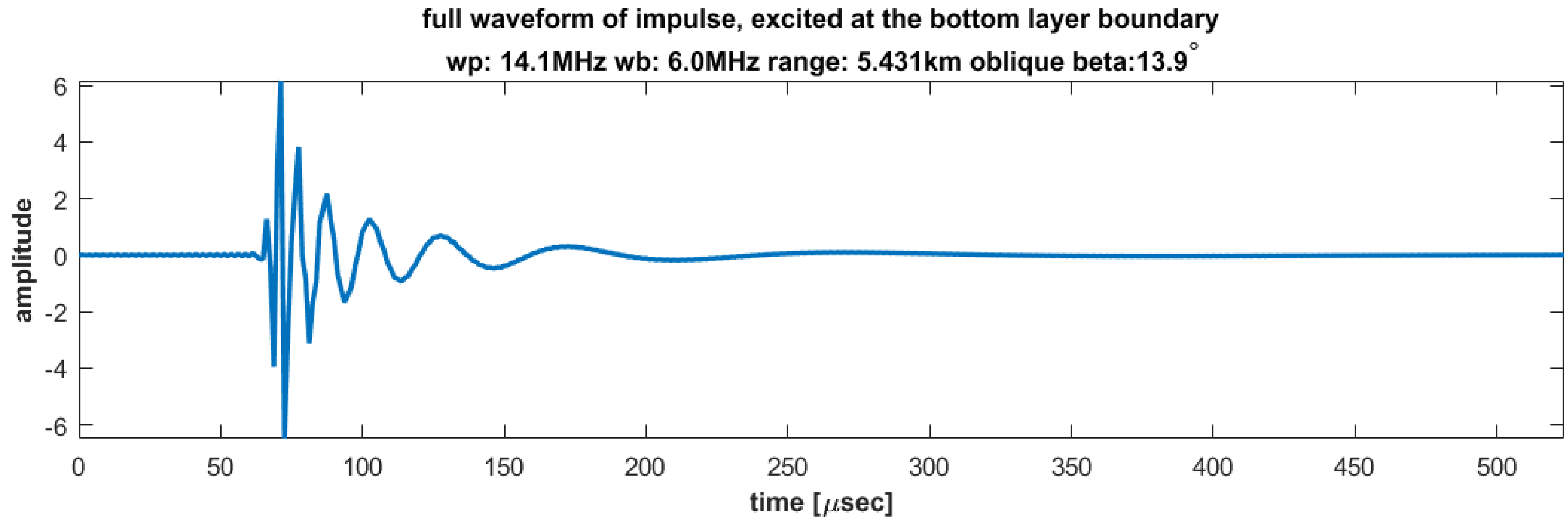


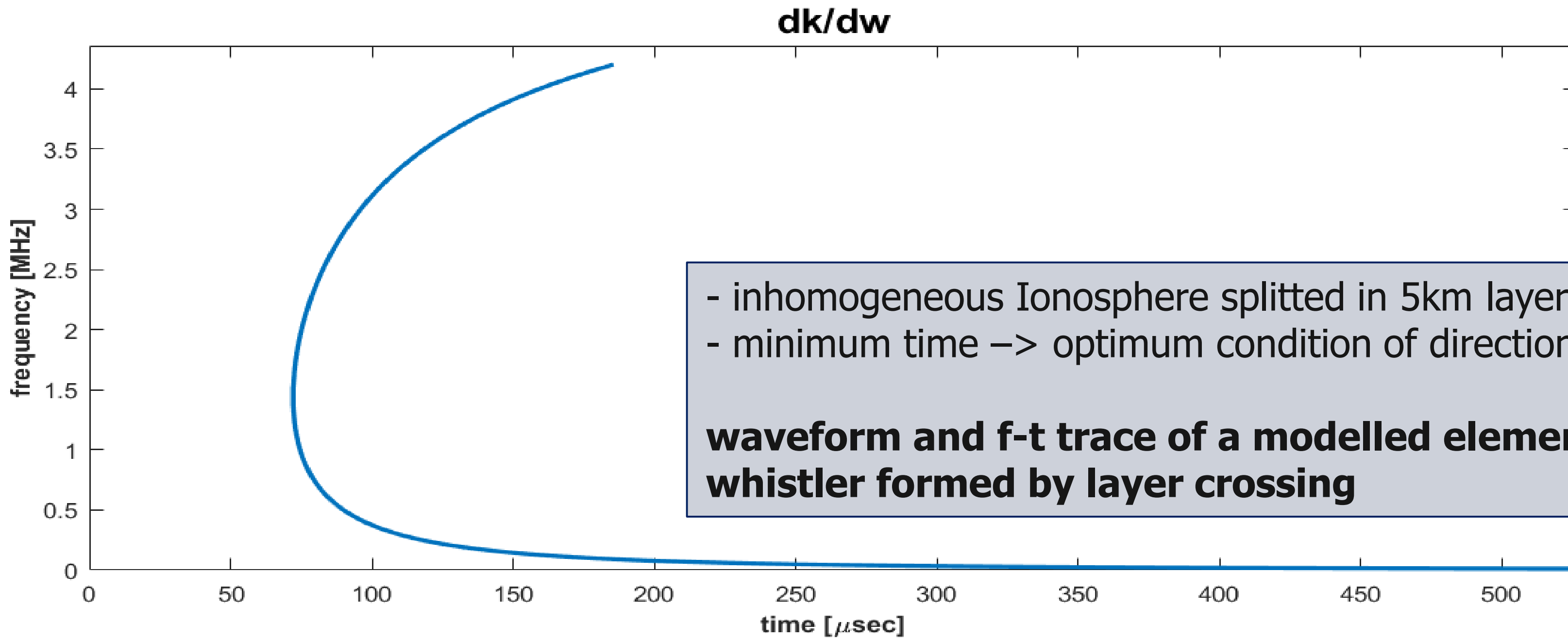
Best fit curve (entry point) corresponds to the minimum **propagation time**





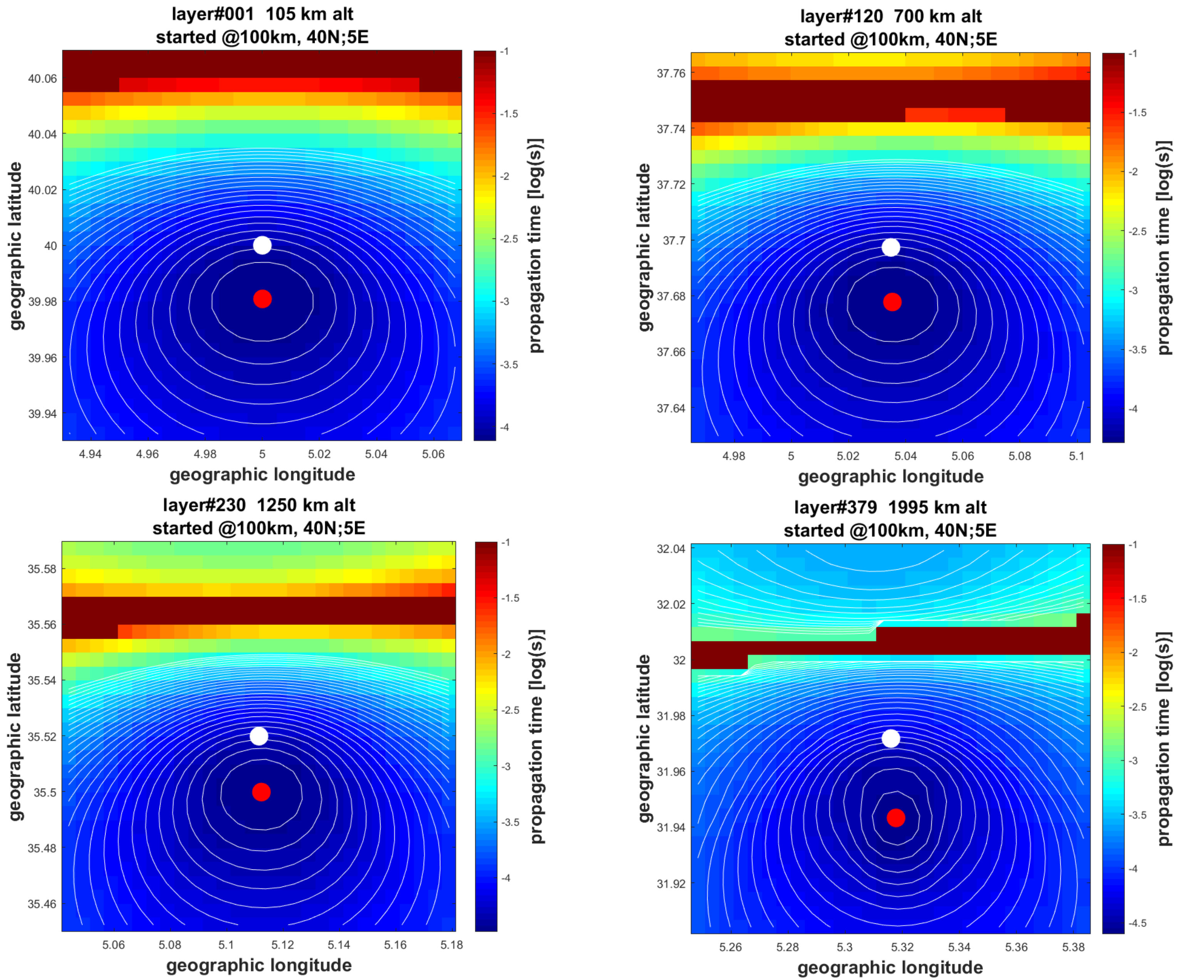
prop. time of the impulse :=
occurrence of the wave amplitude (energy),
time of whistler nose



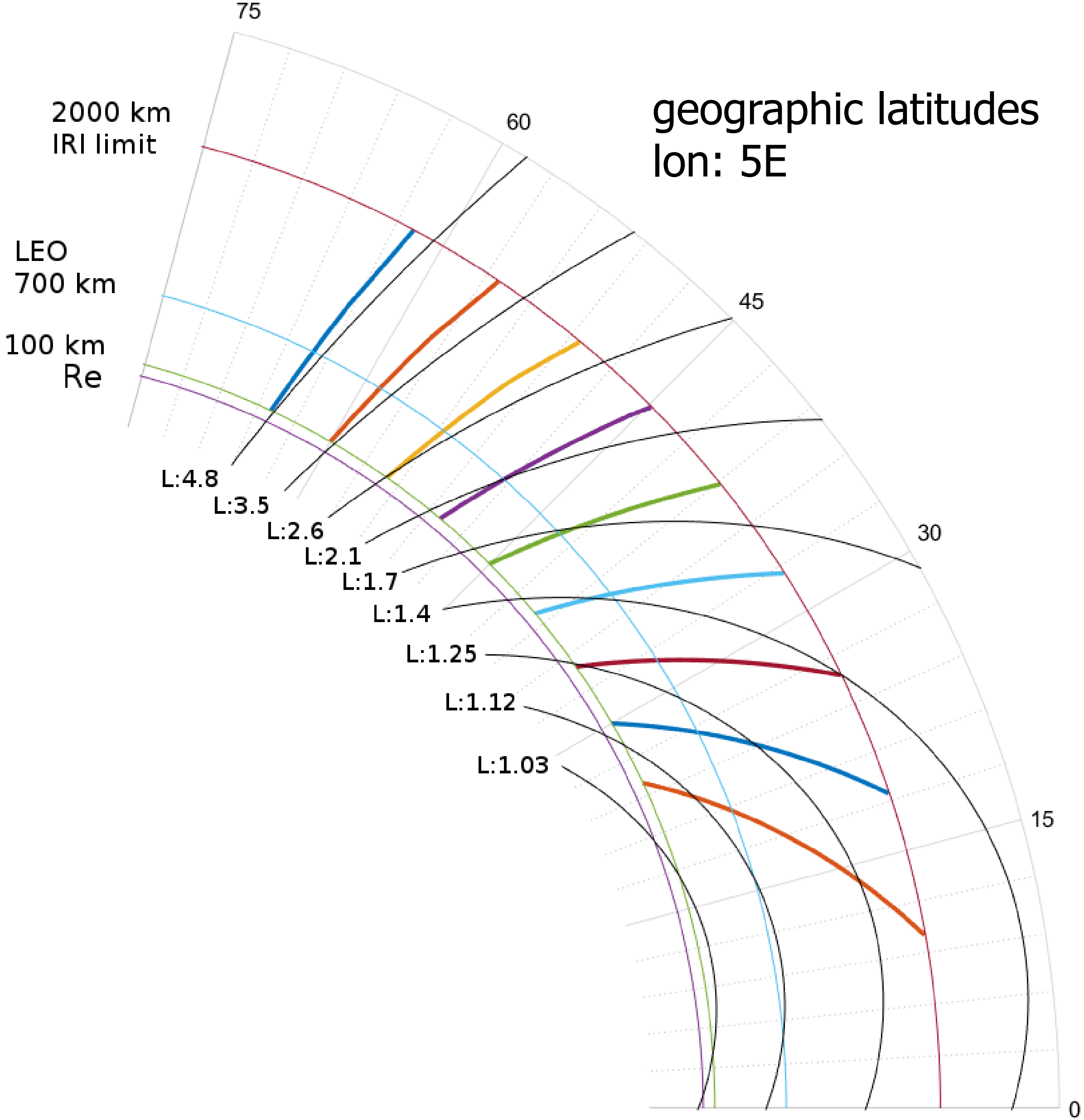


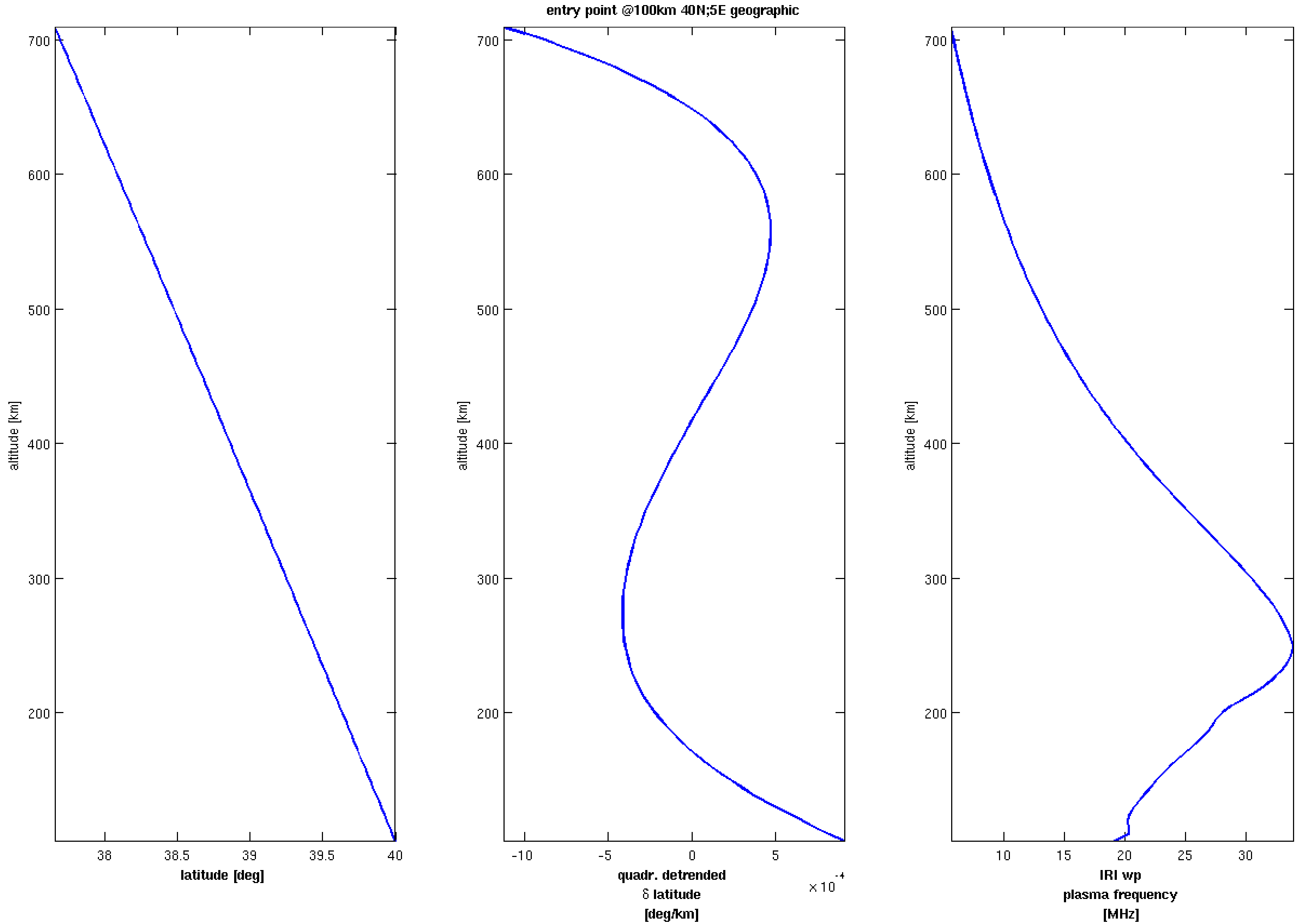
- inhomogeneous Ionosphere splitted in 5km layers
- minimum time –> optimum condition of directions

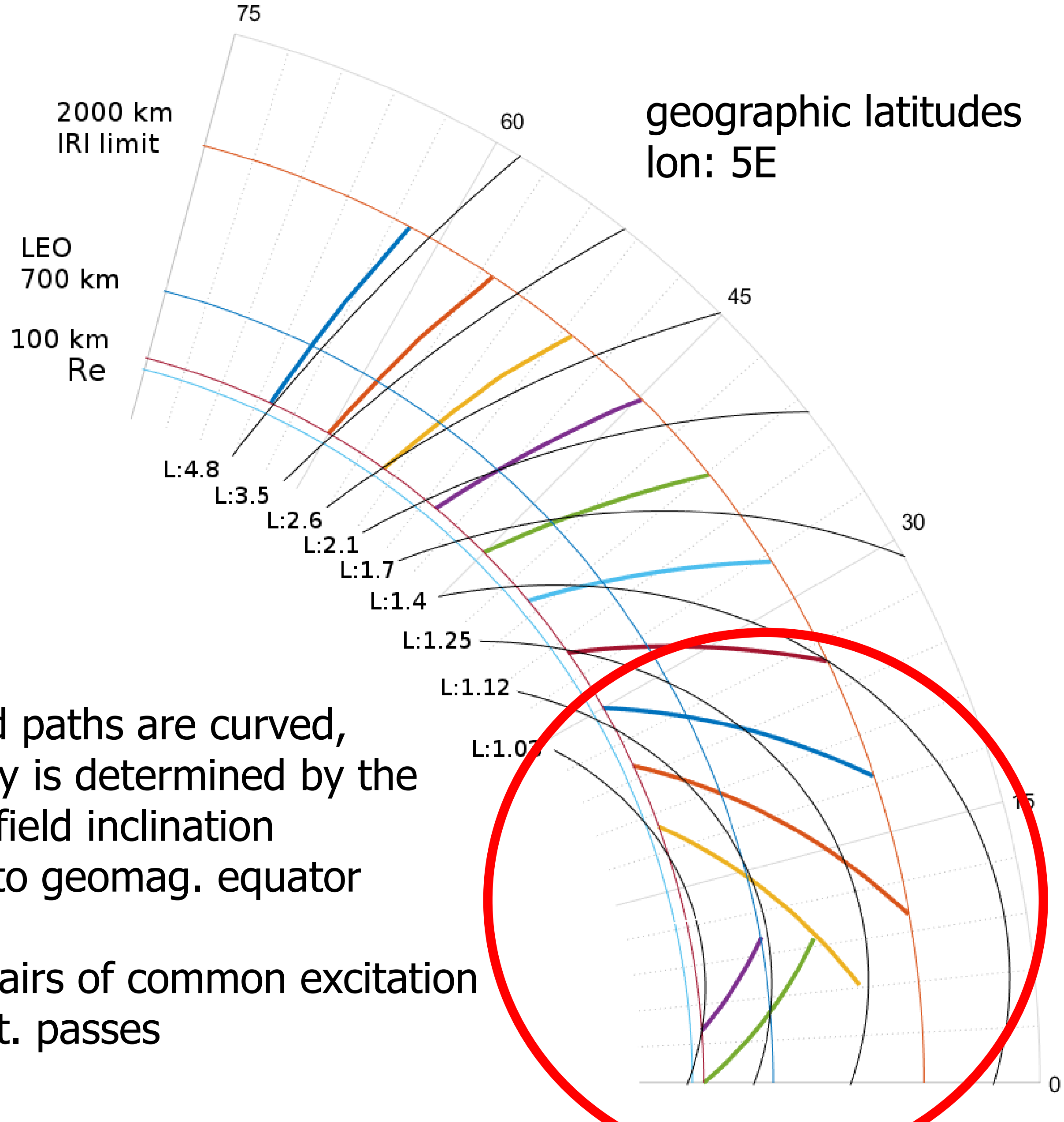
waveform and f-t trace of a modelled elementary whistler formed by layer crossing



Optimum parameter fields of 5km thin layers at different altitudes of a model path

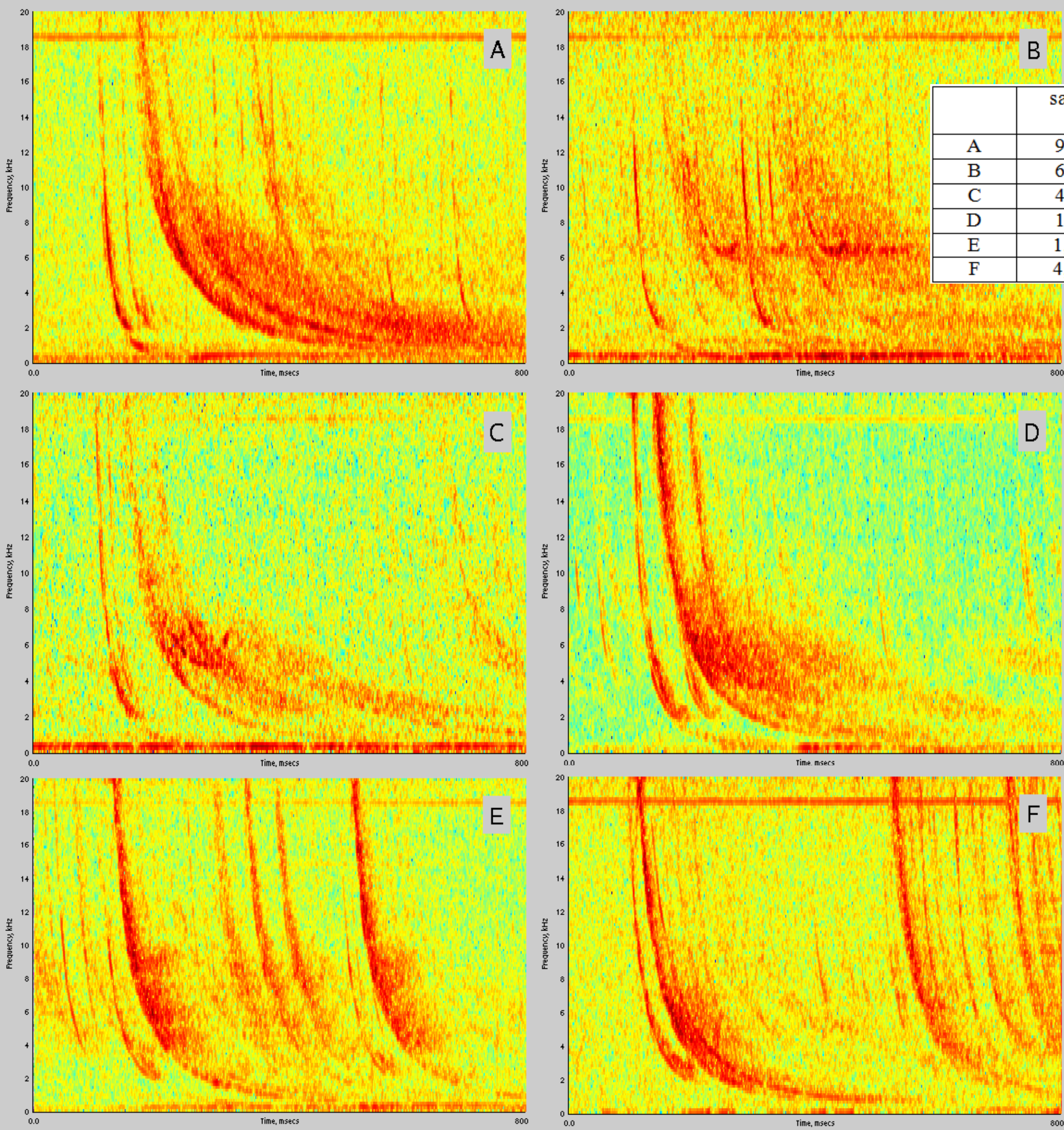

75
60
45
30
15
0
geographic latitudes
lon: 5E
2000 km
IRI limit
LEO
700 km
100 km
Re
L:4.8
L:3.5
L:2.6
L:2.1
L:1.7
L:1.4
L:1.25
L:1.12
L:1.03


entry point @100km 40N;5E geographic
altitude [km]
latitude [deg]
38
38.5
39
39.5
40
700
600
500
400
300
200
quadr. detrended
δ latitude
[deg/km]
×10^-4
-10
-5
0
5
IRI wp
plasma frequency
[MHz]
10
15
20
25
30



- the resulted paths are curved,
- the topology is determined by the
  magnetic field inclination
- symmetric to geomag. equator

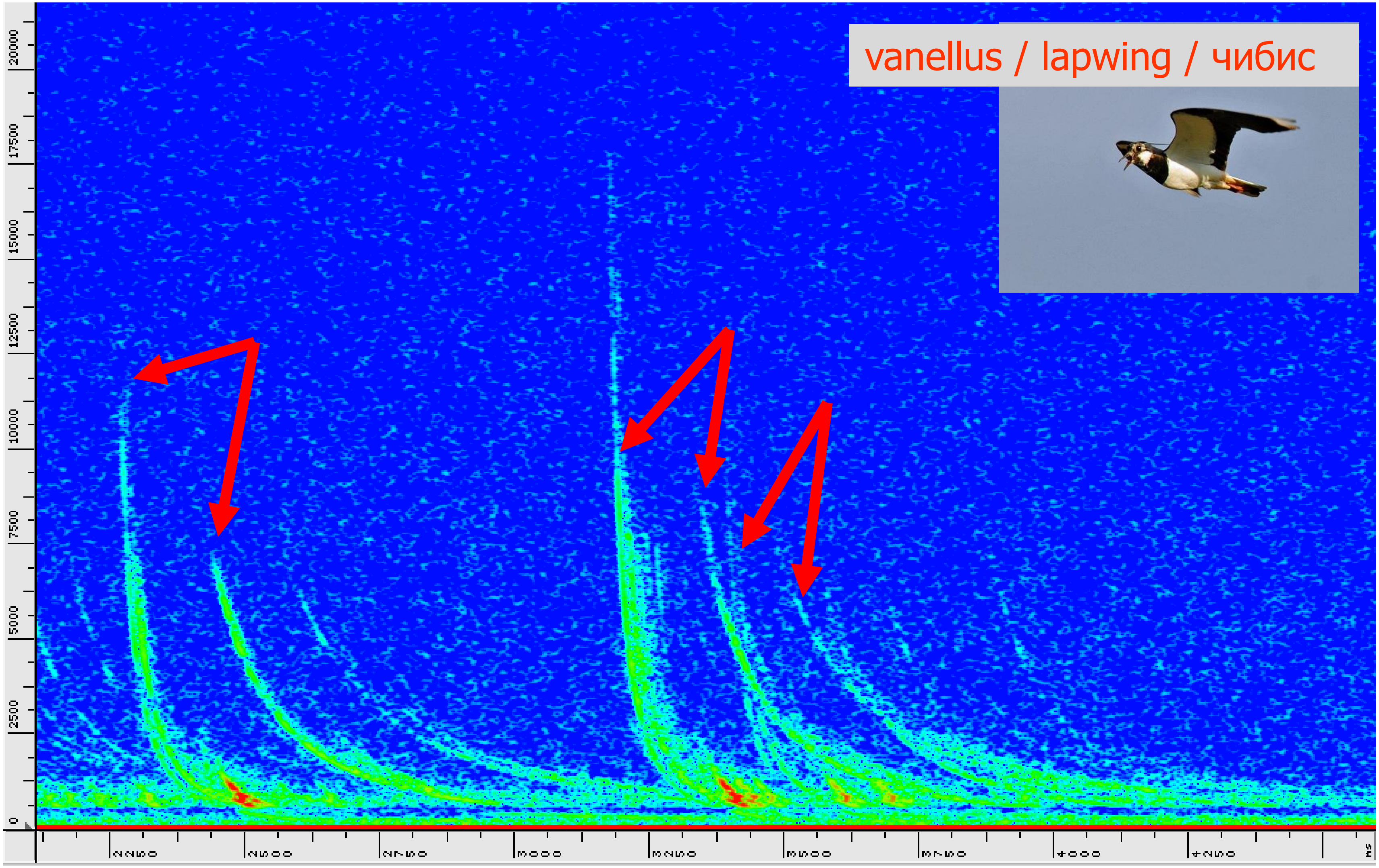
-> whistler pairs of common excitation
   at low lat. passes



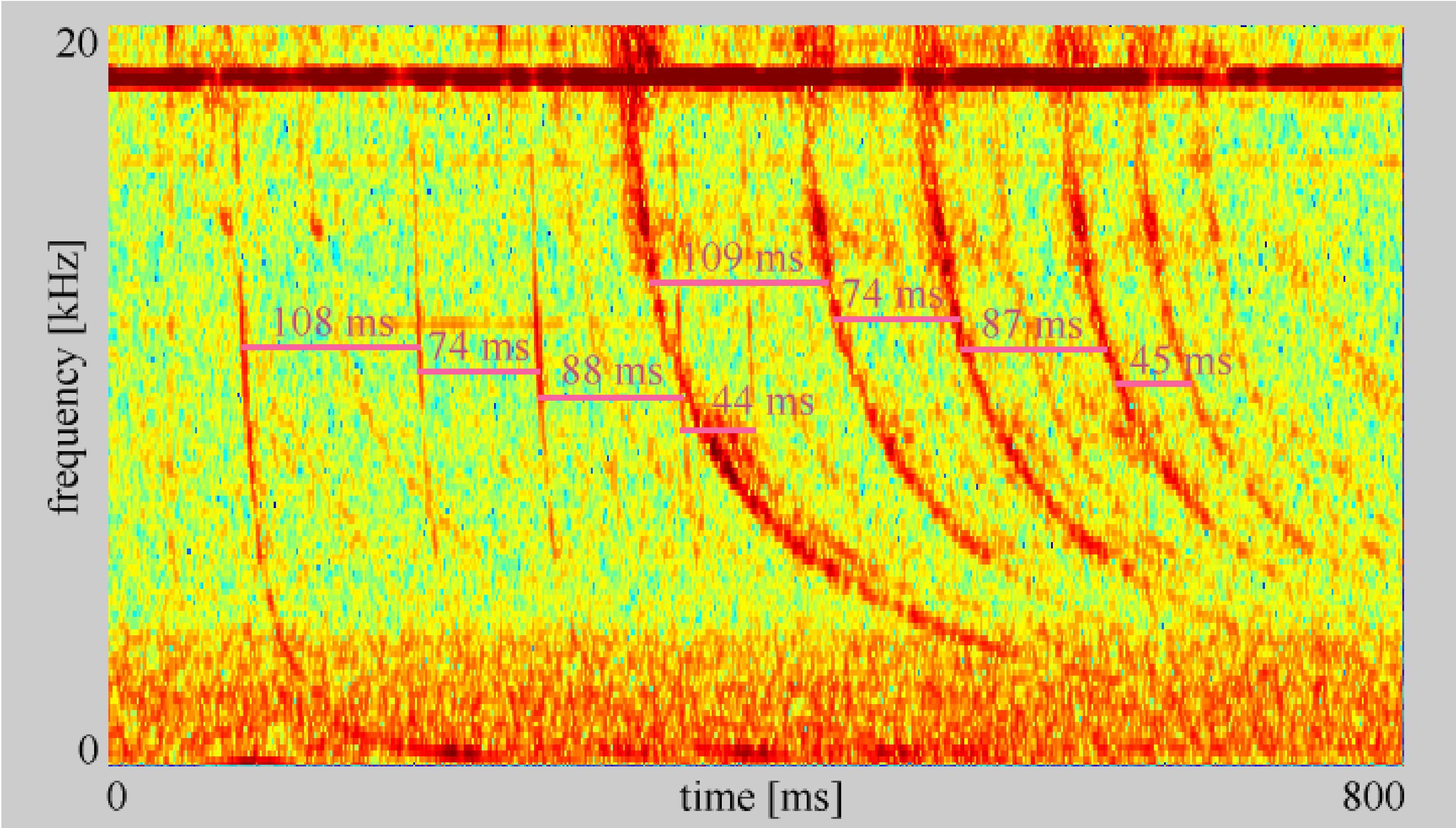
	satellite position geographic	orbit altitude	satellite position geomagnetic	L
A	9,4° S;128,4 °E	721,0 km	18,4° S;200,4 °E	1,24
B	6,2° S;127,7 °E	719,6 km	14,9° S;199,5 °E	1,19
C	4,2° S;127,2 °E	718,7 km	12,7° S;198,9 °E	1,17
D	1,5° S;126,7 °E	716,6 km	9,7° S;198,3 °E	1,15
E	1,7° N;126,0 °E	716,5 km	6,2° S;197,5 °E	1,13
F	4,1° N;125,5 °E	715,6 km	3,3° S;197,0 °E	1,12

Sequence of whistler pairs recorded at low latitude pass

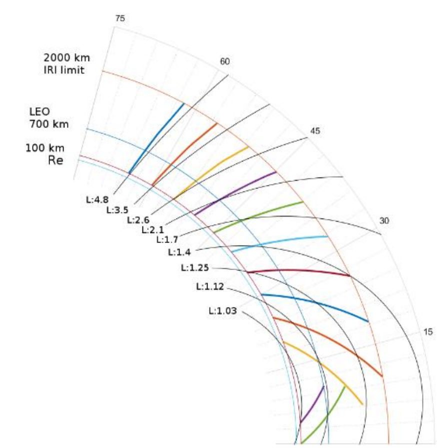
DEMETER VLF ICE
orbit 714, 20th Aug. 2004.

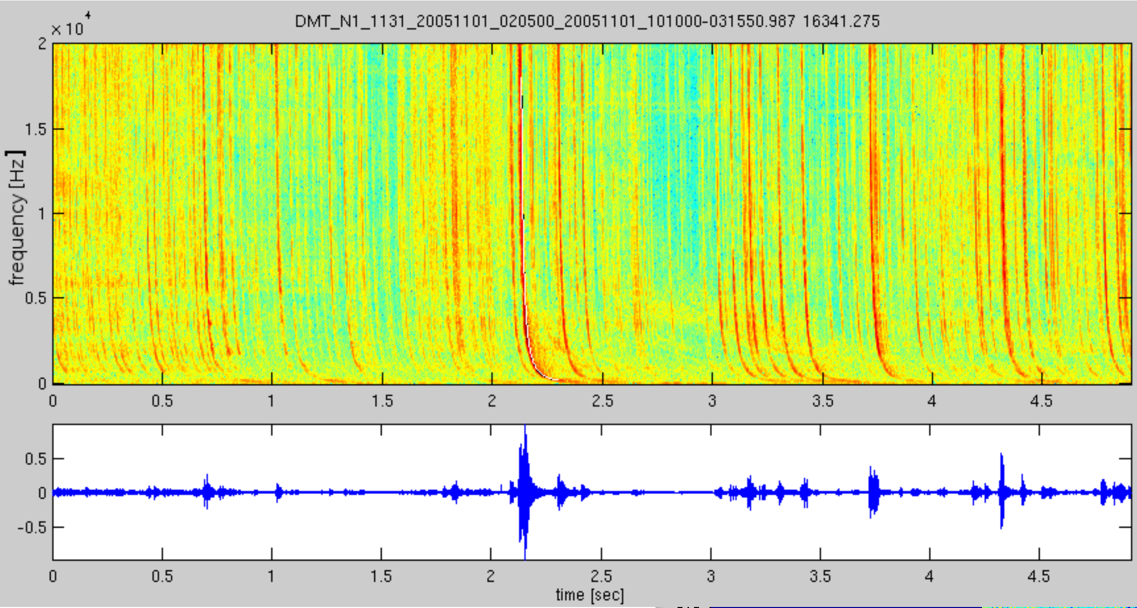


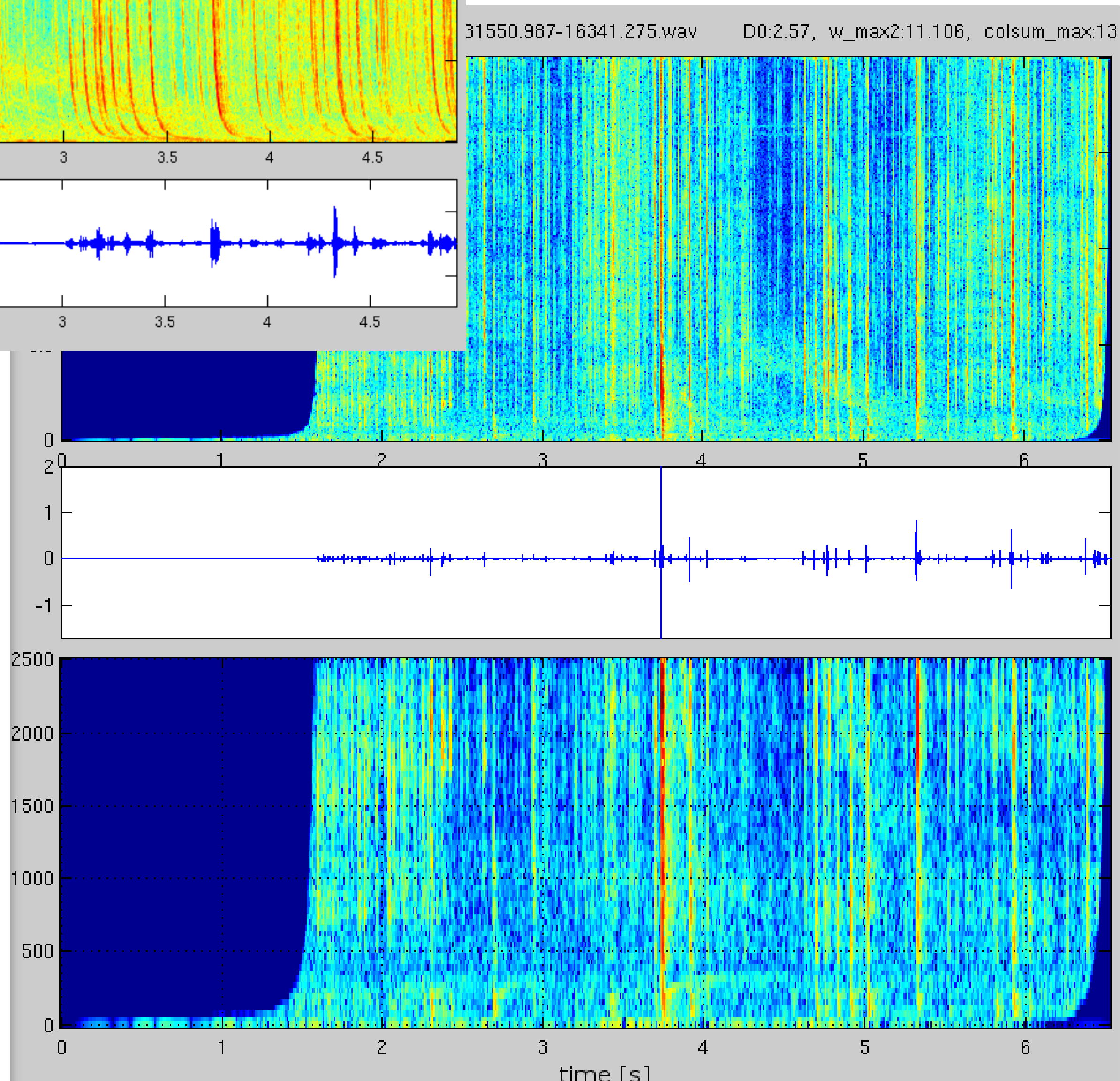
low-latitude whistler pairs, CHIBIS-M, electric sensor (ch0)
2012.12.01. 18:51:03UT 93.48E; 8.87N L=1.08



DEMETER ICE VLF 13.10.2004 12:03:38.7 UT
geographic: (45.14 N ; 144.18 E) geomagnetic: (36.53 N ; 210.97 E), L: 1.72







Fractional hop (0^+) whistlers exhibit the same shape at a given satellite LEO location (or fall in known, distinct categories)

Removal of the prop. effect (dechirping) by *one set of medium parameters* for all frequencies *works <-> separate paths of RT concept?*

Comparison of model (calculated directions) to the wave records

Multi-component analysis in LEO satellite recordings,

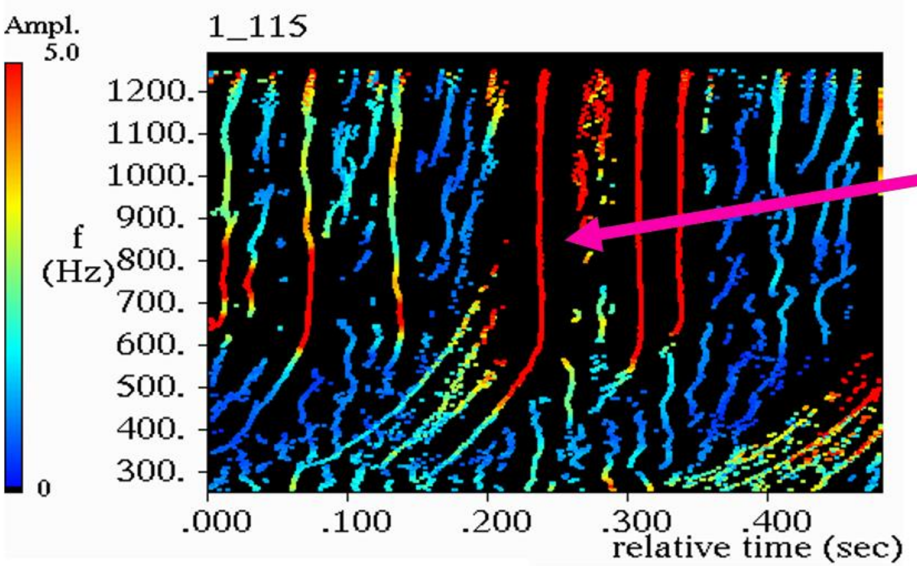
- scaling -> trace f-t points
- whistler model fit -> whistler parameters
- matched filtering -> *instanteneous, amplitude and phase data sequence,* characterizing the selected coherent signal

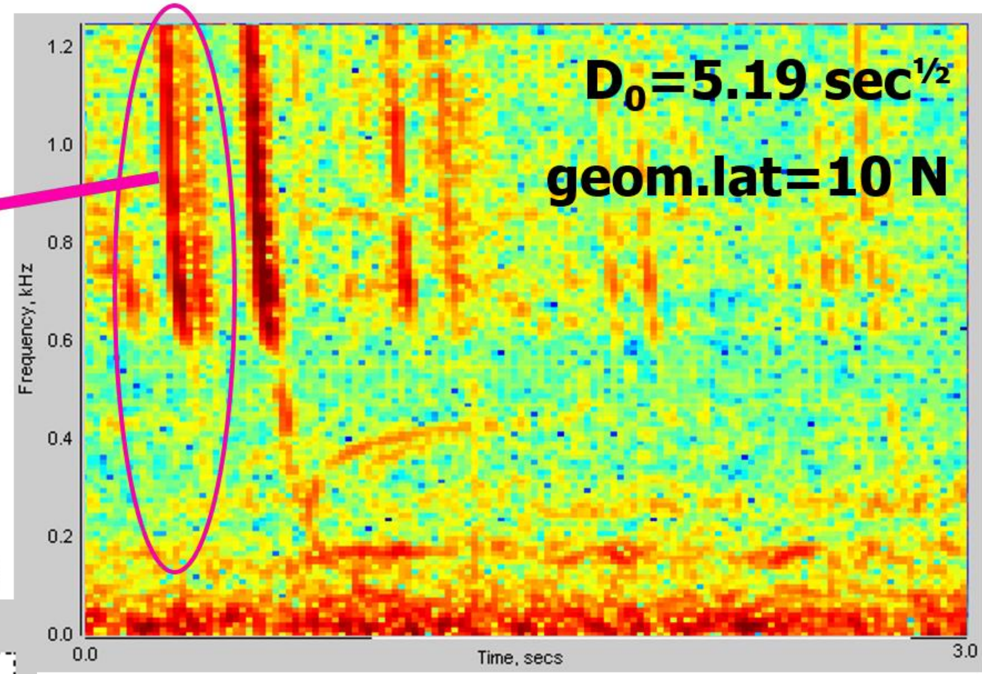
-> Poynting vector from 6 independent signal amplitudes vs. freq
-> ***k*** prop. factor,

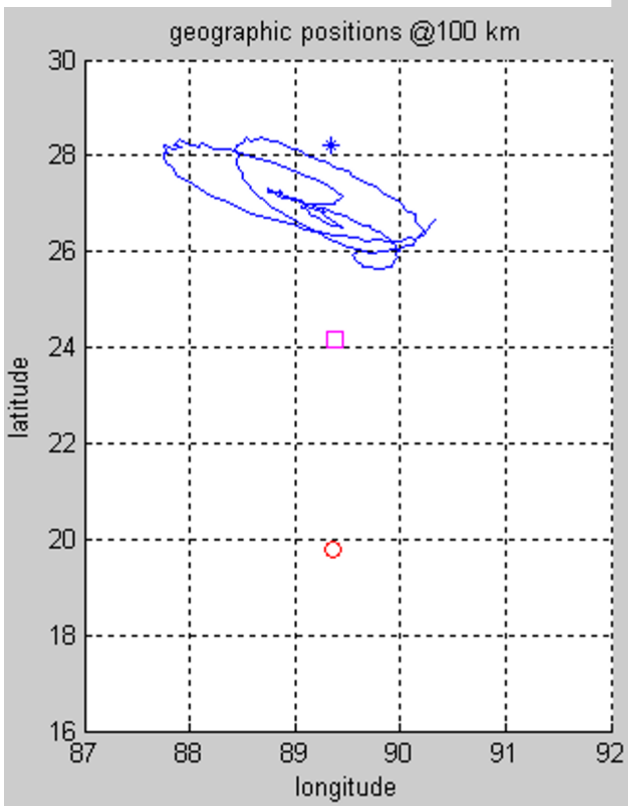
$$\boldsymbol{k} \parallel \boldsymbol{B}(t1) \times \boldsymbol{B}(t2)$$

or

-> direct spectral matrix method by means of Means (1972),

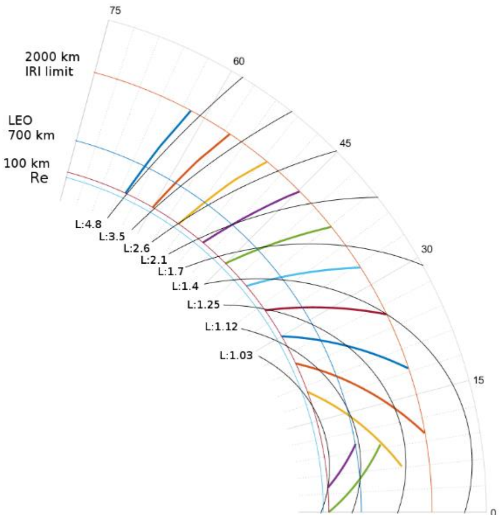




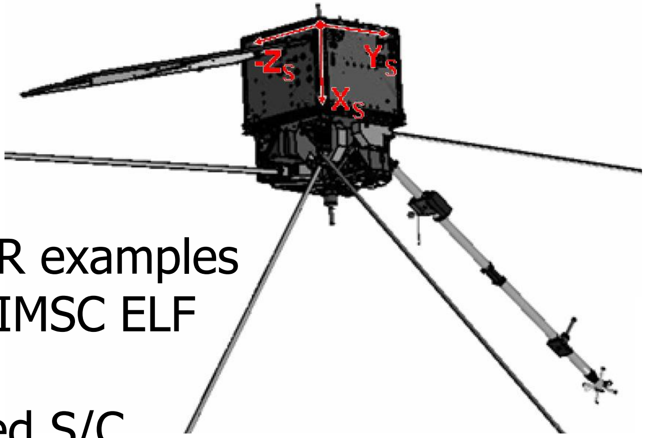


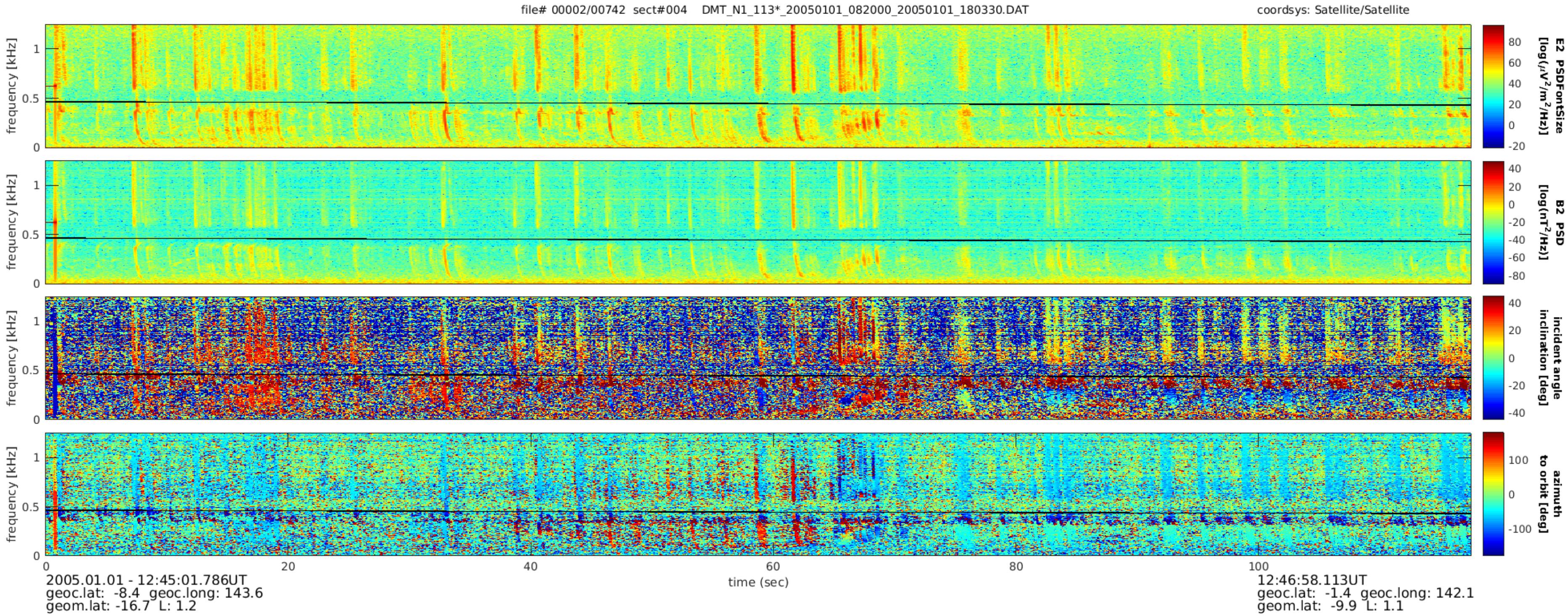
Demeter ICE ELF
2004.10.01. 16.04.25 19.76N 89.37E 701.1km

Blue curve represents the projected ***k(f)*** at the lower ionosphere, (**o**) (□) (*) symbols sign the position of the subsatellite, best fit result of the UWB modeling, and the footprint of the geomagnetic field line, respectively.

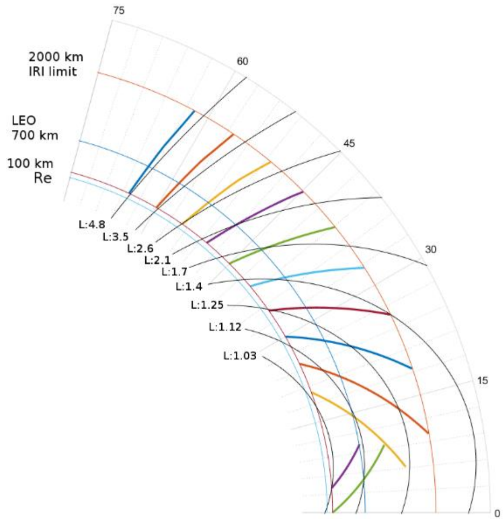


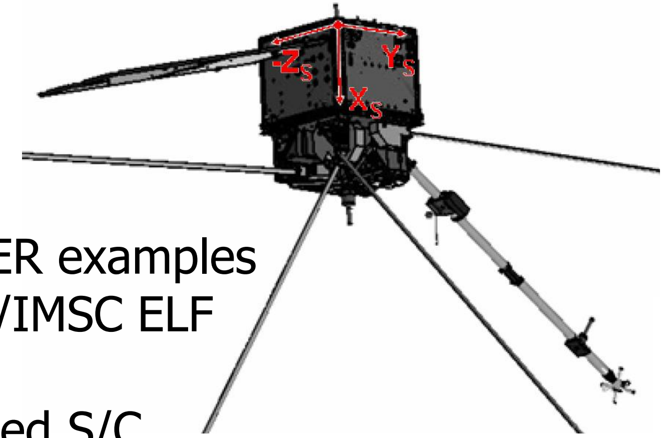
LEO DEMETER examples
6 comp. ICE/IMSC ELF
fs:2500Hz
3axis stabilized S/C





Incident direction varies according to the modelled lat. dependent oblique paths





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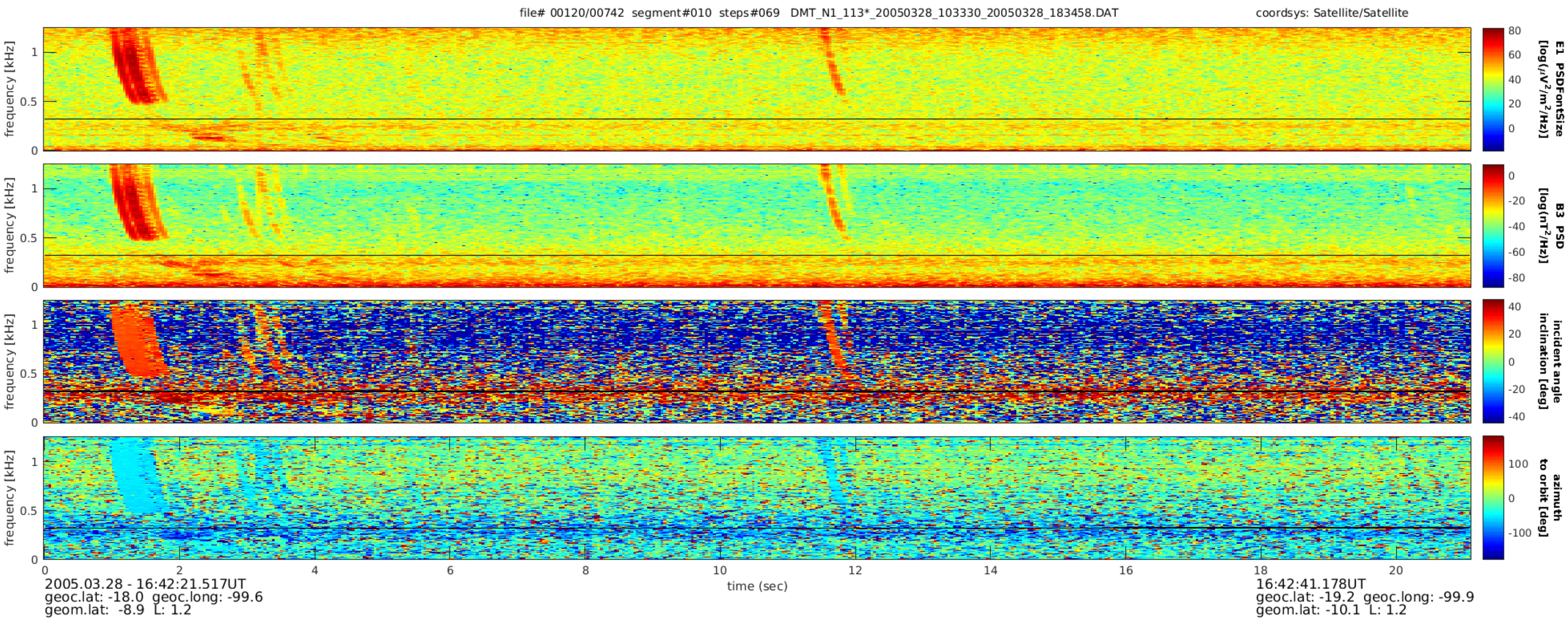
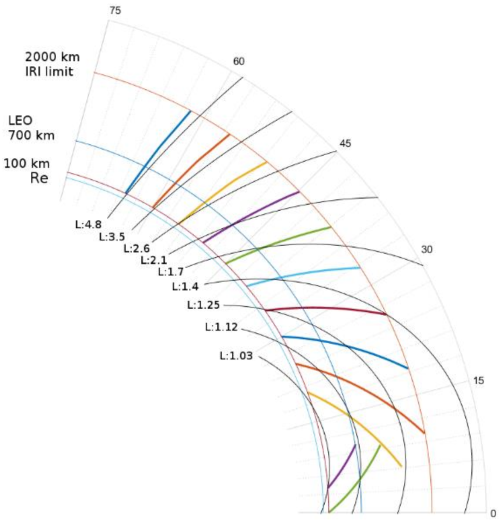
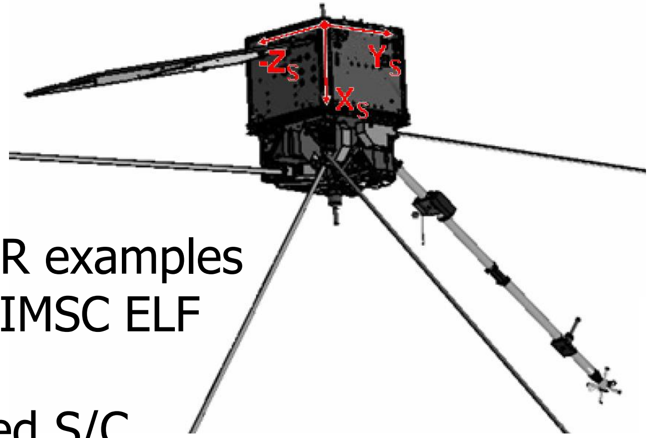


Incident directions do not exhibit significant change vs. freq, supporting the concept of one common path of the whole impulse.





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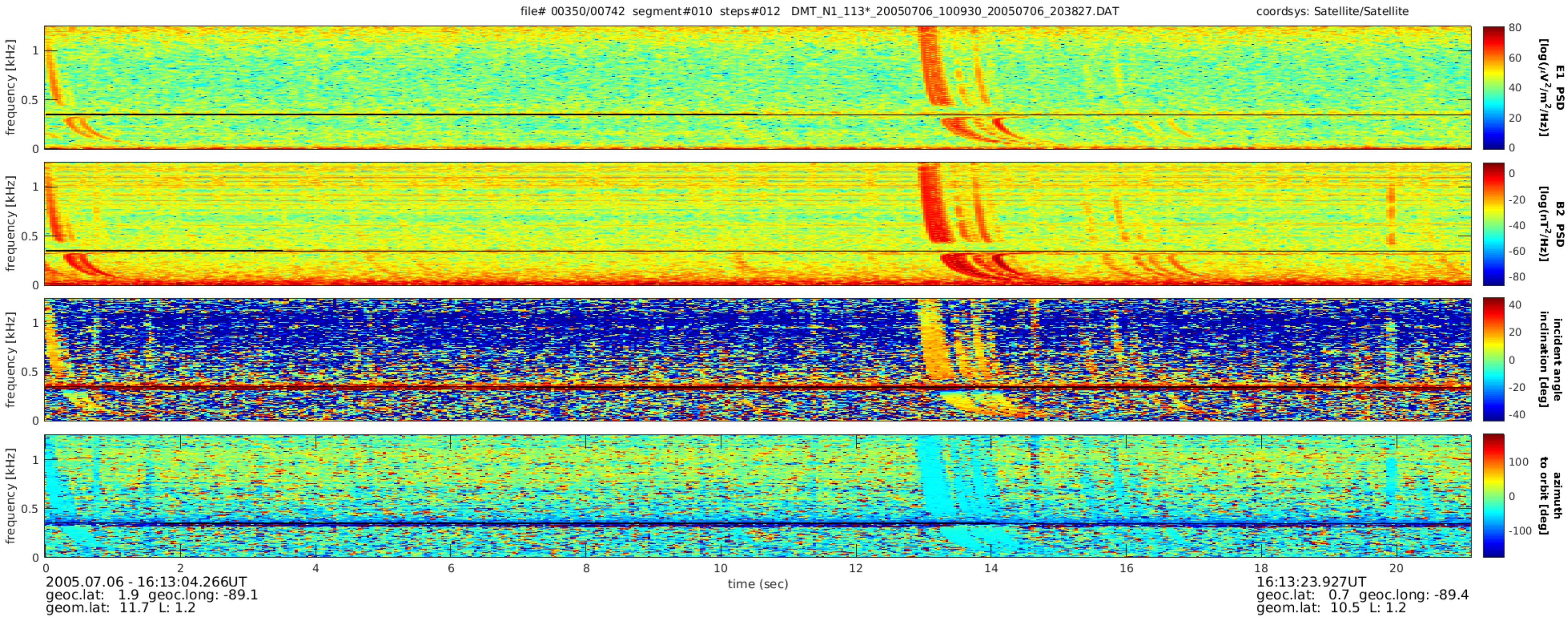
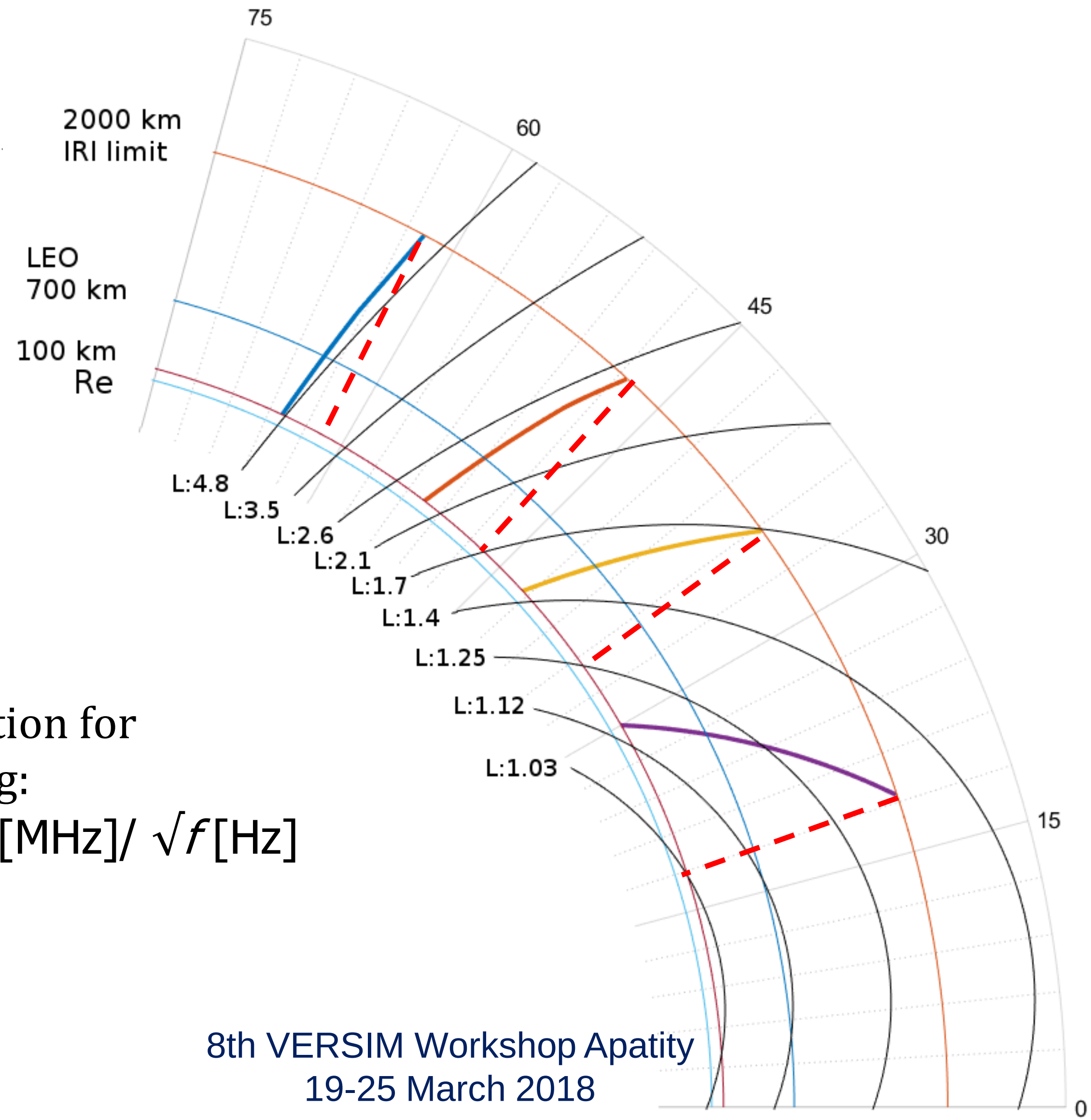


Incident directions do not exhibit significant change vs. freq, supporting the concept of one common path of the whole impulse.

Latitude dependent **propagation time** in the ionosphere is

- (almost) negligible in hop whistler inversion (Park, 1972*),
- may be significant correction factor in fractional-hop whistler inversion (e.g. RBSP/VAP),
- fundamental parameter in LEO whistler inversion, future ionosphere monitoring.



* simple time correction for ionosphere crossing:

$$t_{iono}[s] \cong 0.7 * f_0F2\,[\mathrm{MHz}] / \sqrt{f}\,[\mathrm{Hz}]$$

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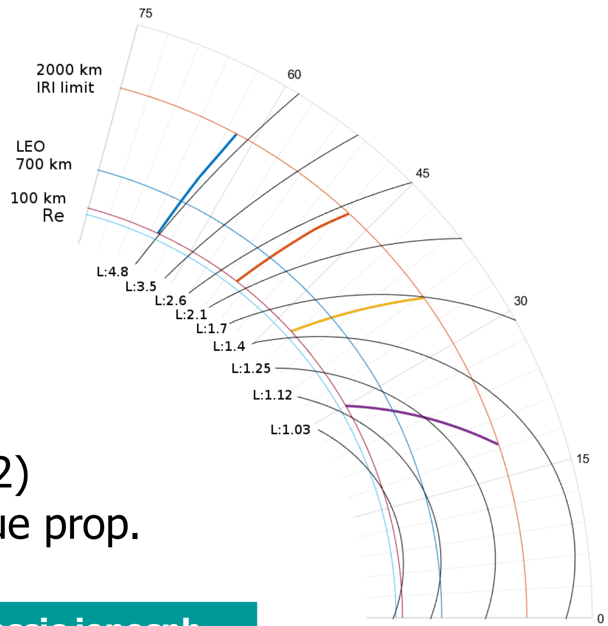

2004.08.20. 13.56 UT

Classic time correction of cross-ionosphere propagation (Park, 1972) much underestimates real values, due to neglecting effect of oblique prop.

path start @100km	path end @700km	path dip @700km	obliqe angle @700km	oblique prop. time of 5kHz	classic ionosph. prop. correction
65.0N; 5E	64.08N;5.11E	74.85°	4.6°	**36.0 ms**	**29.2 ms**
52.5N; 5E	51.03N;5.06E	65.86°	6.9°	**39.8 ms**	**34.5 ms**
42.5N; 5E	40.39N;5.04E	51.51°	11.1°	**48.8 ms**	**35.4 ms**
30.0N; 5E	26.55N;5.06E	35.4°	20.4°	**88.8 ms**	**35.3 ms**

Conclusions:

- Applicaton of *UWB, real full wave* solution for impulse propagation in a stratified 3D Ionosphere yielded curved, *latitude dependent* paths according to a *minimum prop. time condition*. The resulted topology involves single entry point into the plasma, and *unique path* for the whole whistler – in contradiction to RT concept.

- Incident angles in multi-component LEO records correspond to and support the above wave oblique propagation picture.

- This modelling of the unducted, oblique impulse propagation in the anisotropic plasma yielded significantly different propagation time values than has been used as time correction of regular whistler analysis in the plasmasphere diagnostics.

- Realistic propagation models give the option of ionosphere diagnostics based on inversion of short path fractional hop whistlers recorded on board of LEO sats.

Thank you for your attention !

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