Remote sensing of the plasmasphere by VLF whistlers

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How can we monitor the electron/plasma densities in the plasmasphere?

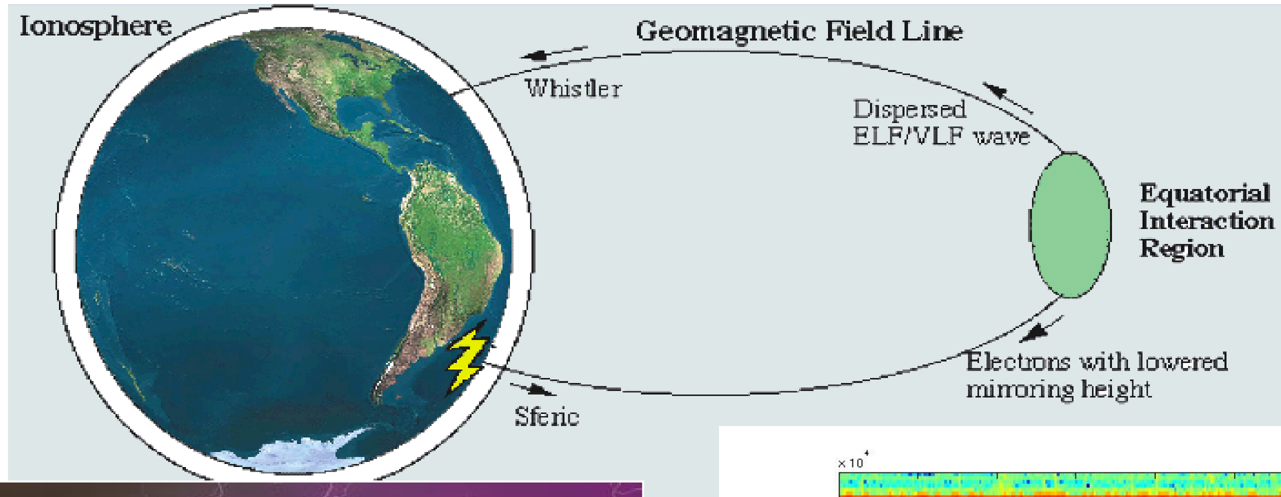
1) By in-situ (f_{uh}) measurements – perfect option, but no such data available in real time at the moment (Van Allen Probes are gone, Arase data are not available in real-time)

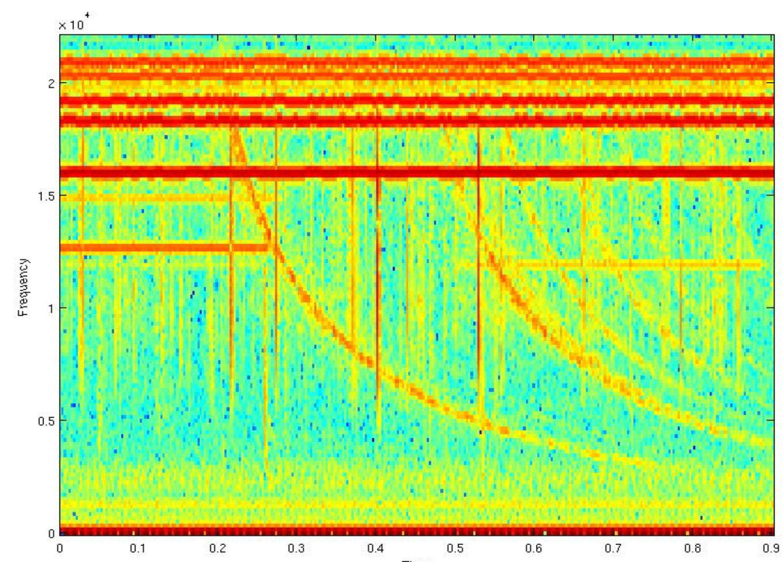
2) By ground based measurements:

- Using Field Line Resonances (plasma mass density → see Massimo Vellante's lecture on Thursday)
- Using VLF whistlers...

Question 1: what are the whistlers?

Whistlers are radio waves generated by terrestrial lightnings





Question 2: why whistlers?

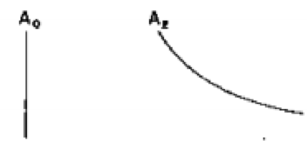
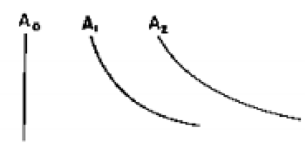
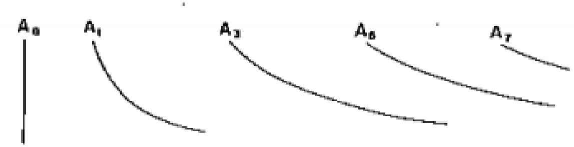
Whistlers are radio waves generated by terrestrial lightnings

Classification of whistlers (the "Zoo") (Helliwell - book, 1965)

Note the wording

TABLE 4-1

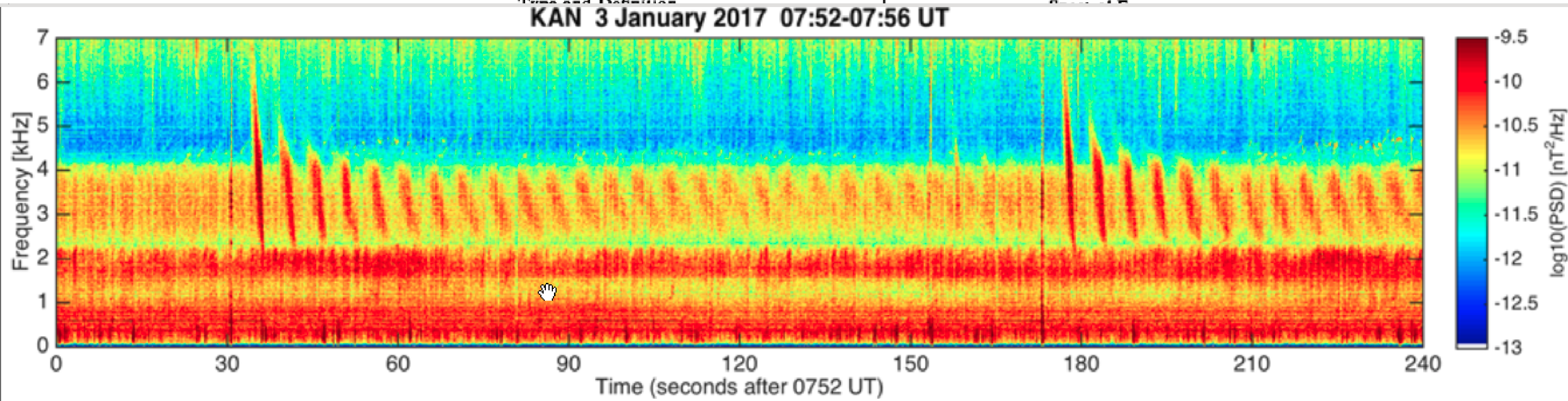
WHISTLER TYPES

Type and Definition	Spectral Form
I. *One-hop (short)* A whistler that has traversed one complete path through the ionosphere. Fig. 4-3.	
II. *Two-hop (long)* A whistler that has traversed in sequence two complete paths through the ionosphere. The two paths may or may not be the same. Fig. 4-4*b*, trace B_2.	
III. *Hybrid* A combination of a one-hop and a two-hop whistler originating in the same source. Fig. 4-5*a*.	
IV. *Echo train* A. Odd order: A succession of echoes of a one-hop whistler. Delays usually in ratio 1:3:5:7, etc. Components called one-hop, three-hop, five-hop, etc. Fig. 4-7*c*, *d*.	
B. Even order: A succession of echoes of a two-hop whistler. Delays usually in ratio 2:4:6:8, etc. Components called two-hop, four-hop, six-hop, etc. Fig. 4-7*a*, *b*.	

Classification of whistlers (the "Zoo") (Helliwell - book, 1965)

TABLE 4-1

WHISTLER TYPES

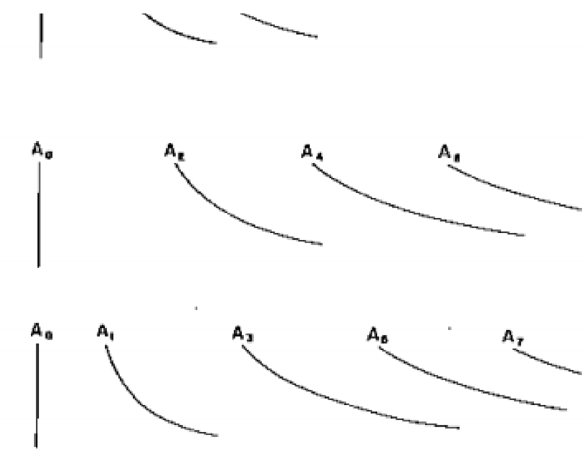


4-5*a*.

IV. *Echo train*

A. Odd order: A succession of echoes of a one-hop whistler. Delays usually in ratio 1:3:5:7, etc. Components called one-hop, three-hop, five-hop, etc. Fig. 4-7*c*, *d*.

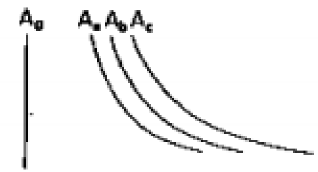
B. Even order: A succession of echoes of a two-hop whistler. Delays usually in ratio 2:4:6:8, etc. Components called two-hop, four-hop, six-hop, etc. Fig. 4-7*a*, *b*.



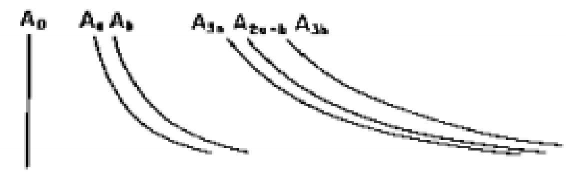
Classification of whistlers (the "Zoo") (Helliwell - book, 1965)

V. *Multiple-component*

A. Multipath: A whistler with two or more components, each of which has traversed a different path through the ionosphere. Figs. 4-11, 4-12, 4-15*d*.

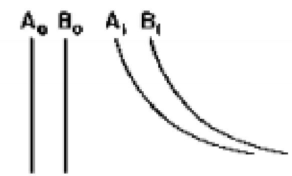


B. Mixed-path: A multiple whistler of two or more hops in which combinations of the basic one-hop paths occur. Fig. 4-13.



VI. *Multiple-source (multiflash)*

Two or more whistlers closely associated in time, but having different sources. Fig. 4-16.

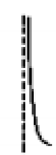


VII. *Nose*

A whistler whose frequency–time curve exhibits both rising and falling branches. The delay is a minimum at the nose frequency f_n. Figs. 4-17, 4-19, 4-20.

VIII. *Fractional-hop*

A whistler that has completed only a fraction of a one-hop path (often observed from a probe or satellite). Fig. 4-22.



Classification of whistlers (the "Zoo") (Helliwell - book, 1965)

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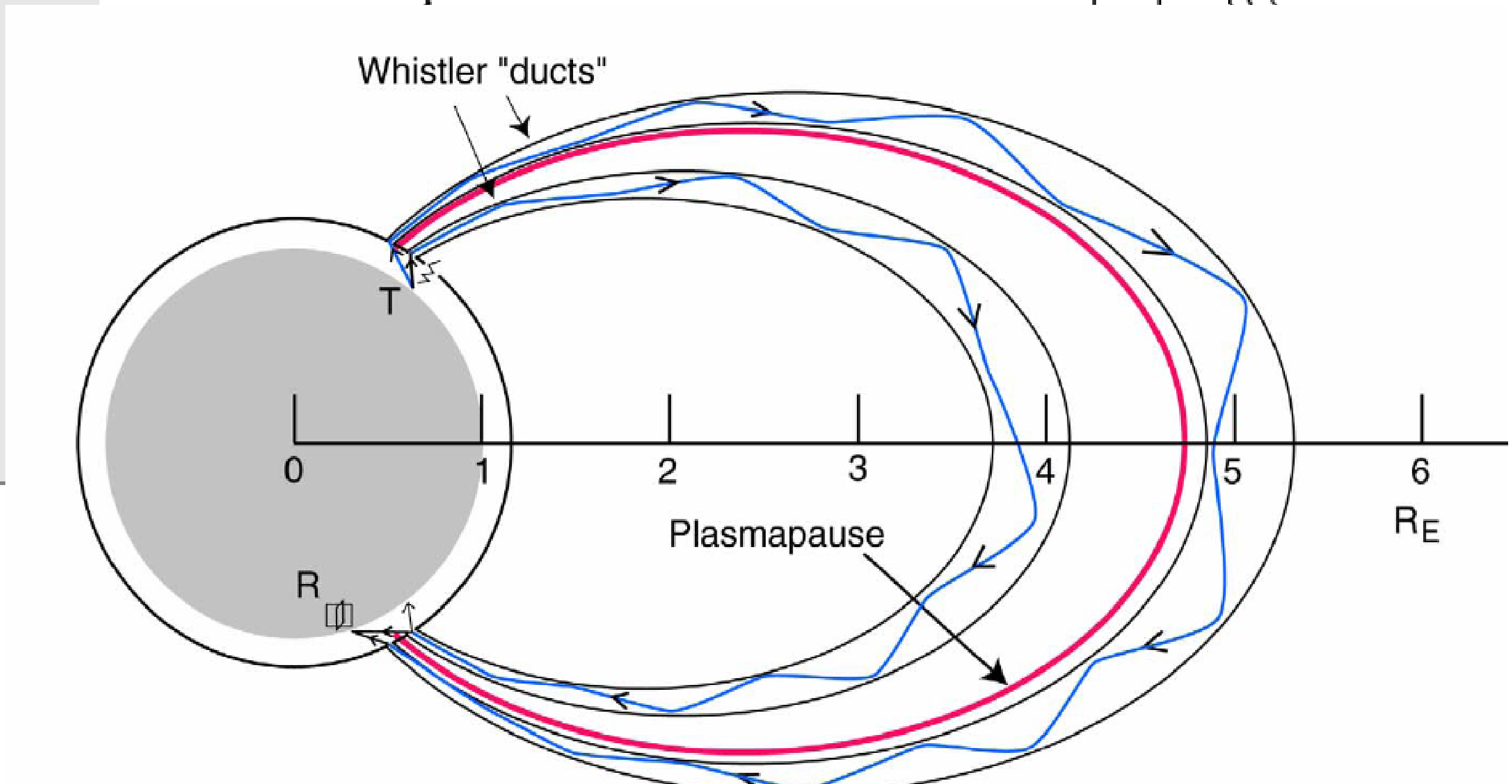

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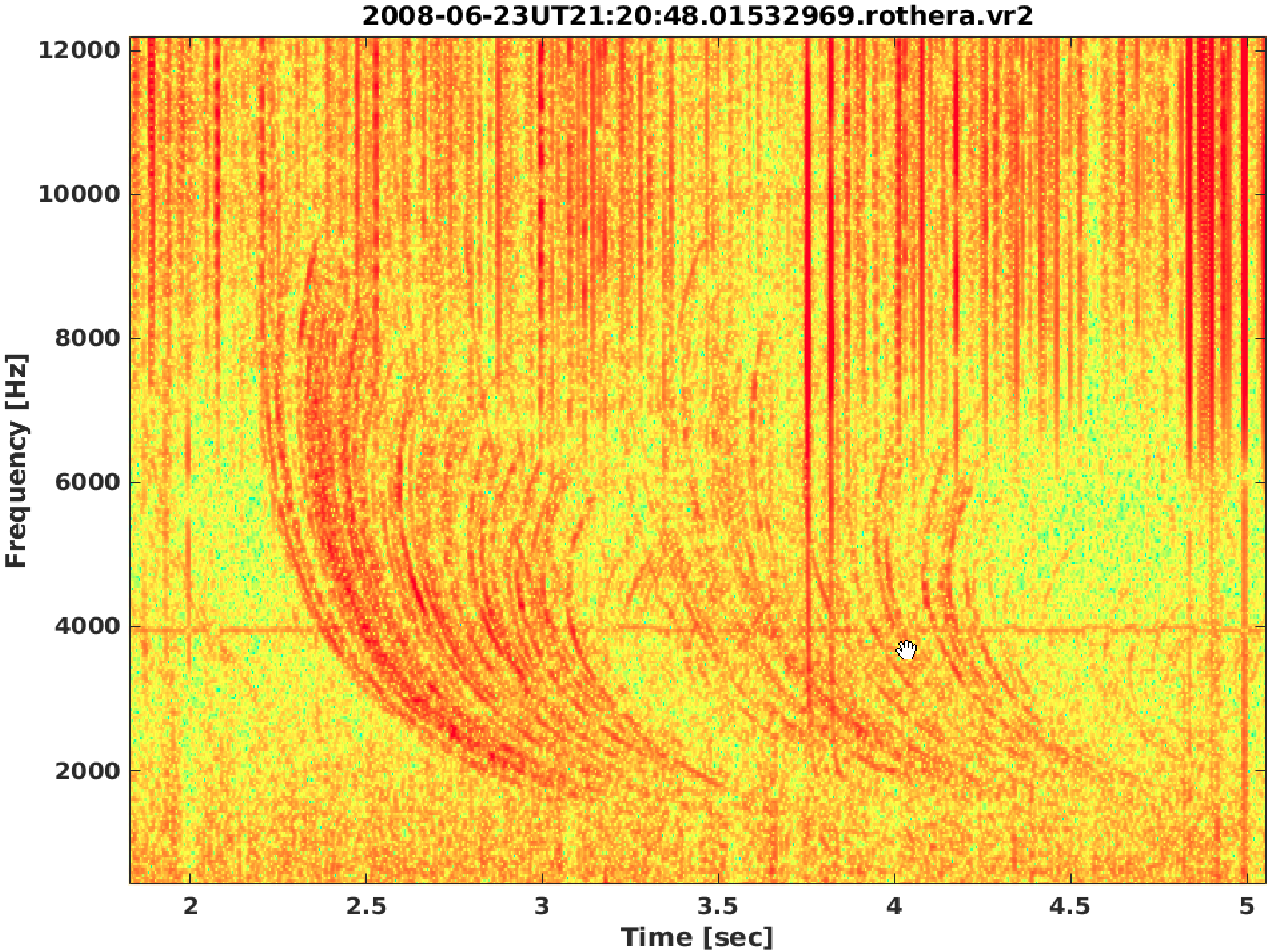
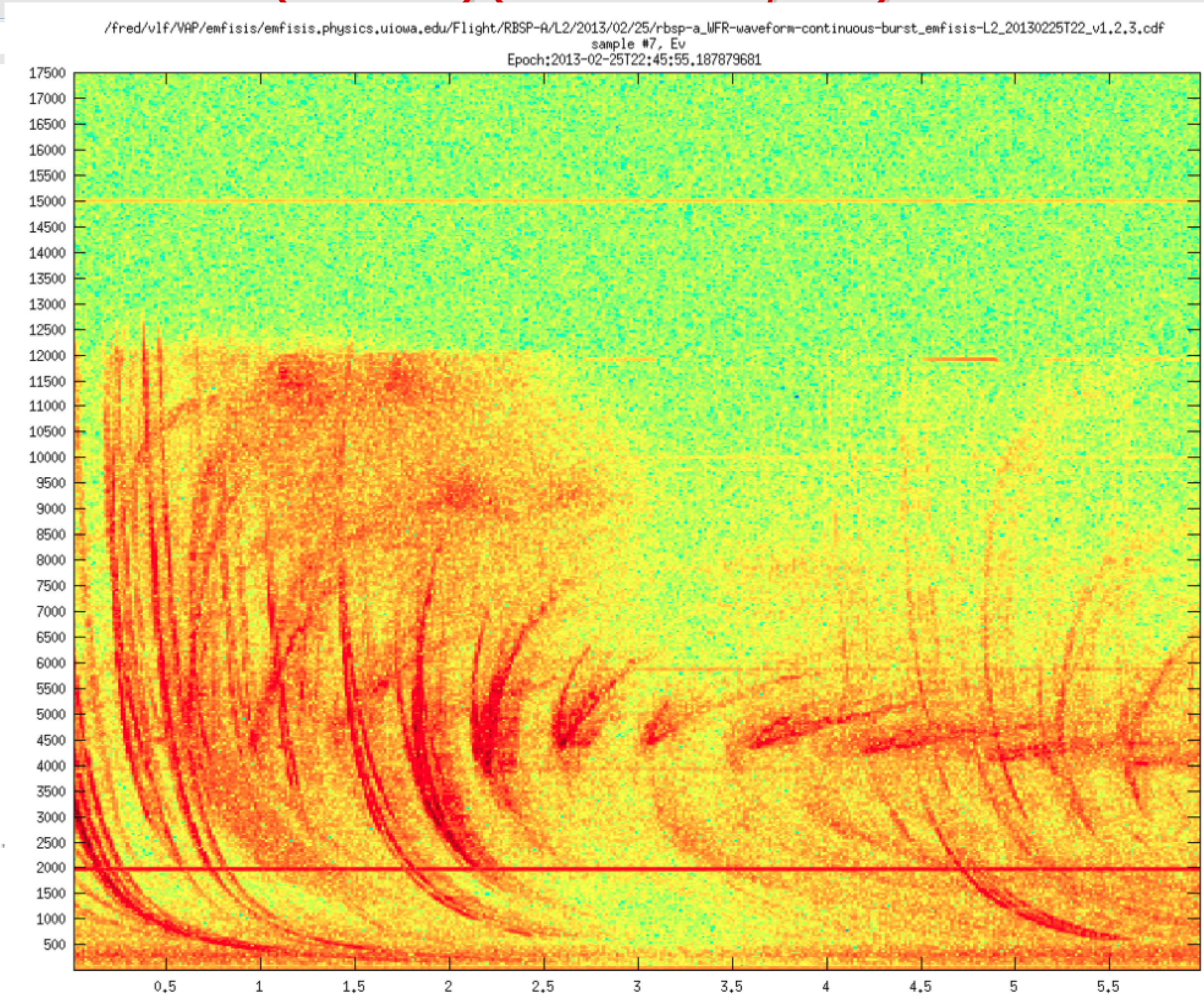
Classification of whistlers (the "Zoo") (Helliwell - book, 1965)



Classification of whistlers (the “Zoo”) (Helliwell - book, 1965)



1886 Sonnblick, High Altitude Observatory, Austria (cf. Hertz experiment, 1887): whistling noise on 22km long telephone line

A brief history

1919 Barkhausen, WWI: spy on enemy communications – or 'heard the grenades fly'
”musical tones produced by repeated reflexion between the earth and the ionosphere of waves from a distant lightning flashes”

1935 Eckersly

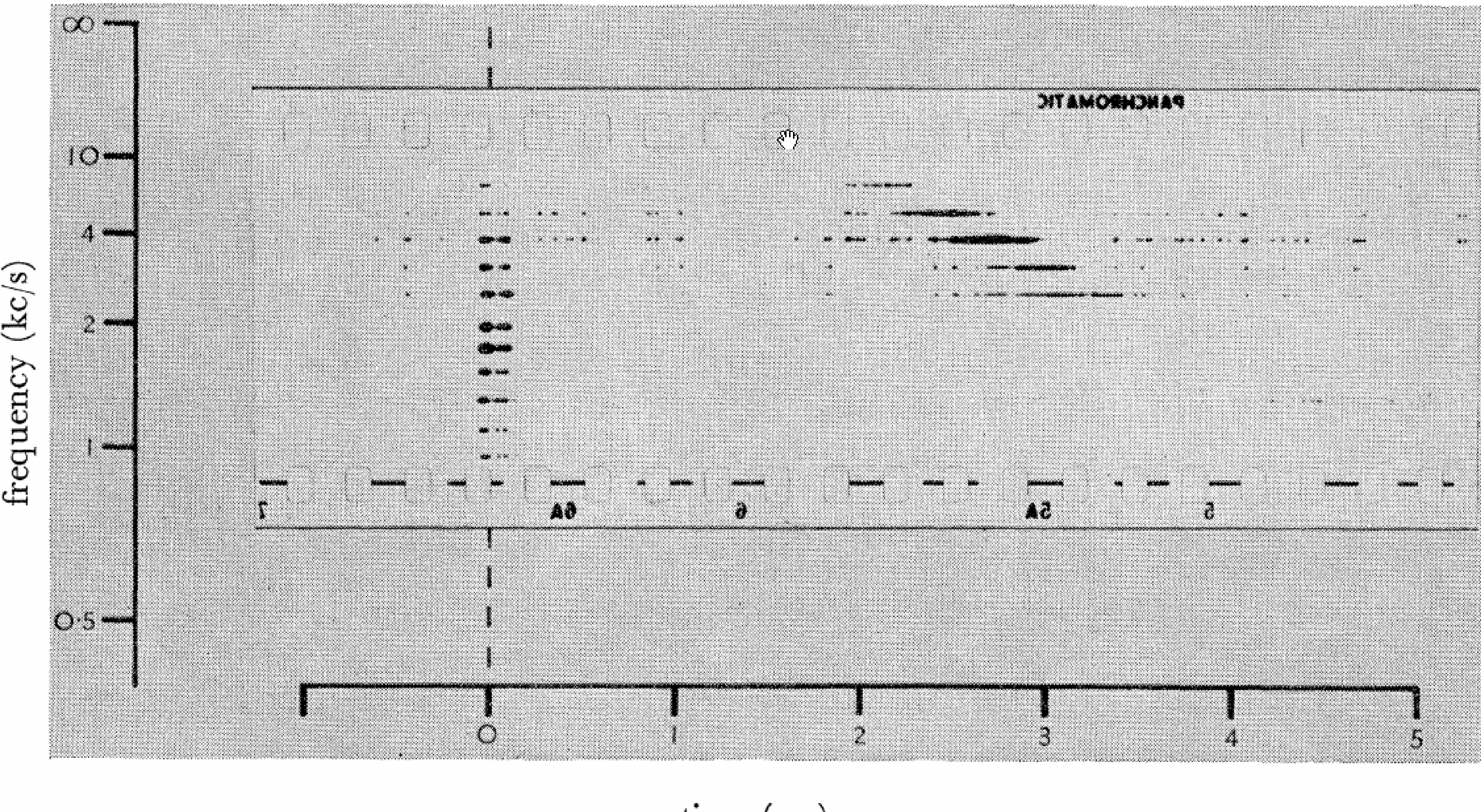
predicted that at a time (t) after the atmospheric the frequency (f) of the whistler should obey the relation $(f)^{-\frac{1}{2}} = t/D$. This result had been confirmed in the case of a single analysis

1953 L. R. O. Storey: origin and propagation of whistlers, *plasmasphere (there is something above the ionosphere):*

On the whole, then, the evidence supports the view that the ionization through which the whistlers travel is of extra-terrestrial origin. It must be admitted, however, that the electron densities required at great heights are uncomfortably large.

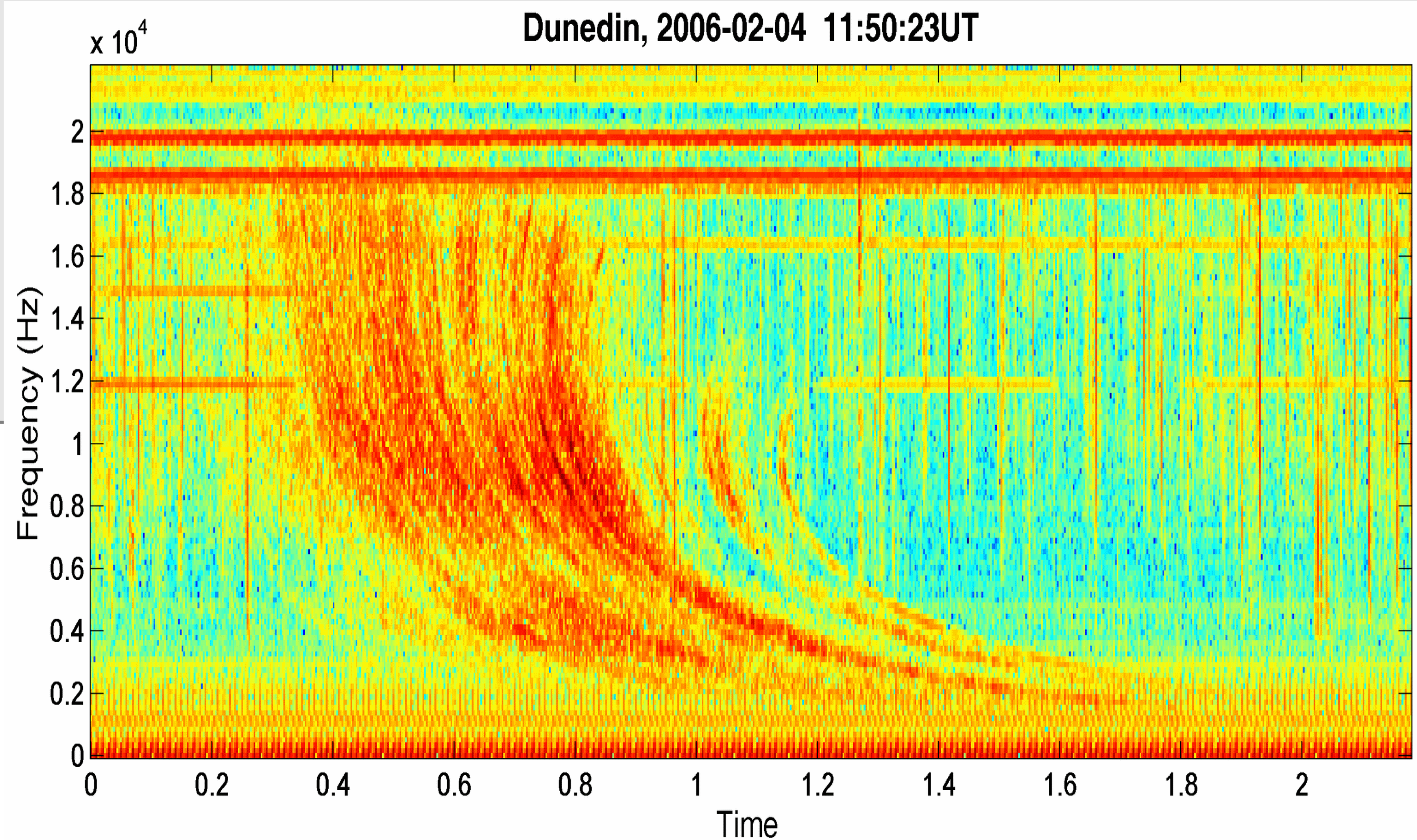
The “uncomfortable large” density was ~400 electron/cm^3

A brief history

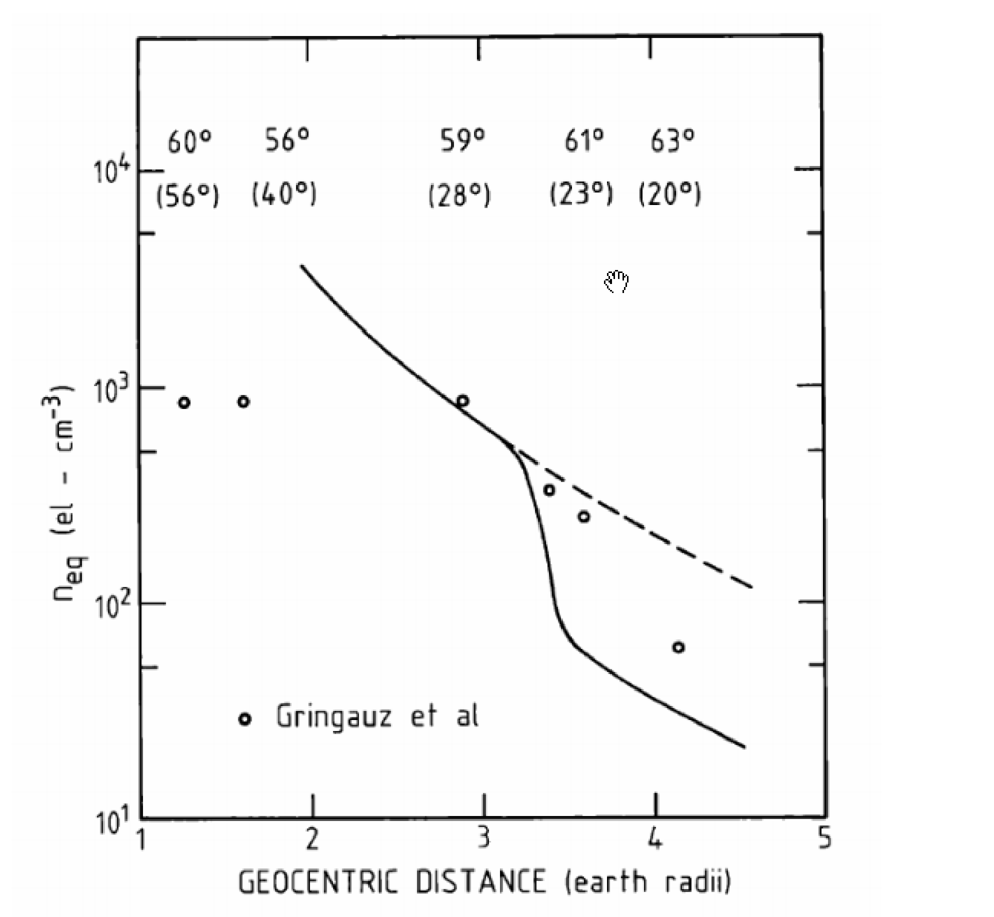


A brief history

1956 R. Helliwell: *nose whistlers*



1963 D. Carpenter *plasmapause*



A brief history

1972 C.G. Park

the first practical guide

METHODS OF DETERMINING ELECTRON CONCENTRATIONS IN

THE MAGNETOSPHERE FROM NOSE WHISTLERS

by

C. G. Park

January 1972

Technical Report No. 3454-1

Question 2: why whistlers?

Whistlers are radio waves generated by terrestrial lightnings

1. ***Nose*** frequency
2. ***Dispersion***

From ***1.*** + ***2.*** => where & what

Where did it travel in *plasmasphere*

What was the *plasma density* there

Assumption: Cold, uniform plasma, $T_i = T_e = 0$

Assuming an $\exp(i\vec{k}\cdot\vec{r})$ spatial dependence of $\vec{E}$ and defining a vector index of refraction

$$\vec{N} = \frac{c}{\omega}\vec{k},$$

the wave equation becomes

$$\vec{N} \times (\vec{N} \times \vec{E}) + \overleftrightarrow{K} \cdot \vec{E} = 0$$

The uniform plasma is isotropic in the x-y plane (i.e. $k_y = 0$).
If θ is the angle between $\vec{k}$ and $\vec{B}_0$ we then have

$$N_x = n\sin\theta \quad N_z = n\cos\theta \quad N_y = 0$$

The magneto-ionic theory → theory of whistlers

Assumption: Cold, uniform plasma, $T_i = T_e = 0$

$$\begin{pmatrix} S - N^2\cos^2\theta & -iD & N^2\sin\theta\cos\theta \\ iD & S - N^2 & 0 \\ N^2\sin\theta\cos\theta & 0 & P - N^2\sin^2\theta \end{pmatrix} \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} = 0$$

$$\begin{aligned} R &\equiv 1 - \sum_s \frac{\omega_{ps}^2}{\omega^2}\left(\frac{\omega}{\omega \pm \Omega_s}\right) \\ L &\equiv 1 - \sum_s \frac{\omega_{ps}^2}{\omega^2}\left(\frac{\omega}{\omega \mp \Omega_s}\right) \\ P &\equiv 1 - \sum_s \frac{\omega_{ps}^2}{\omega^2}. \end{aligned}$$

$$A'N^4 - B'N^2 + C' = 0.$$

Appleton-Hartree dispersion relation

$$\begin{aligned} A &= \frac{R+L}{2}\sin^2\theta + P\cos^2\theta \\ B &= RL\sin^2\theta + \frac{P(R+L)}{2}(1+\cos^2\theta) \\ C &= PRL \end{aligned}$$

The magneto-ionic theory → theory of whistlers

Longitudinal propagation (why?) + electrons only
(usual notation in whistler theory: n→ μ and Ω → ω_H

$$\mu^2 = 1 + \sum_j \frac{\omega_{p_j}^2}{\omega(\omega_{H_j} + c_j\omega)}$$

μ>>1 →

$$\mu^2 = \sum_j \frac{\omega_p^2}{\omega(\omega_H - \omega)}$$

group refraction index:

$$\mu_g = \frac{d(\mu\omega)}{(d\omega)}$$

group velocity:

$$v_g = \frac{c}{\mu_g} \cong 2c\frac{\omega^{1/2}(\omega_H - \omega)^{3/2}}{\omega_p\omega_H}$$

The magneto-ionic theory → theory of whistlers

Longitudinal propagation (why?) + electrons only
(usual notation in whistler theory: n→ μ and Ω → ω_H

travel time:

$$t(f) = \frac{1}{2c}\int_s \frac{f_p(s) f_H(s)}{f^{1/2}(f_H(s)-f)^{3/2}} ds + T_{wg1} + T_{i1}(f) + T_{i2}(f) + T_{wg2}$$

Dispersion → f_p → n_e

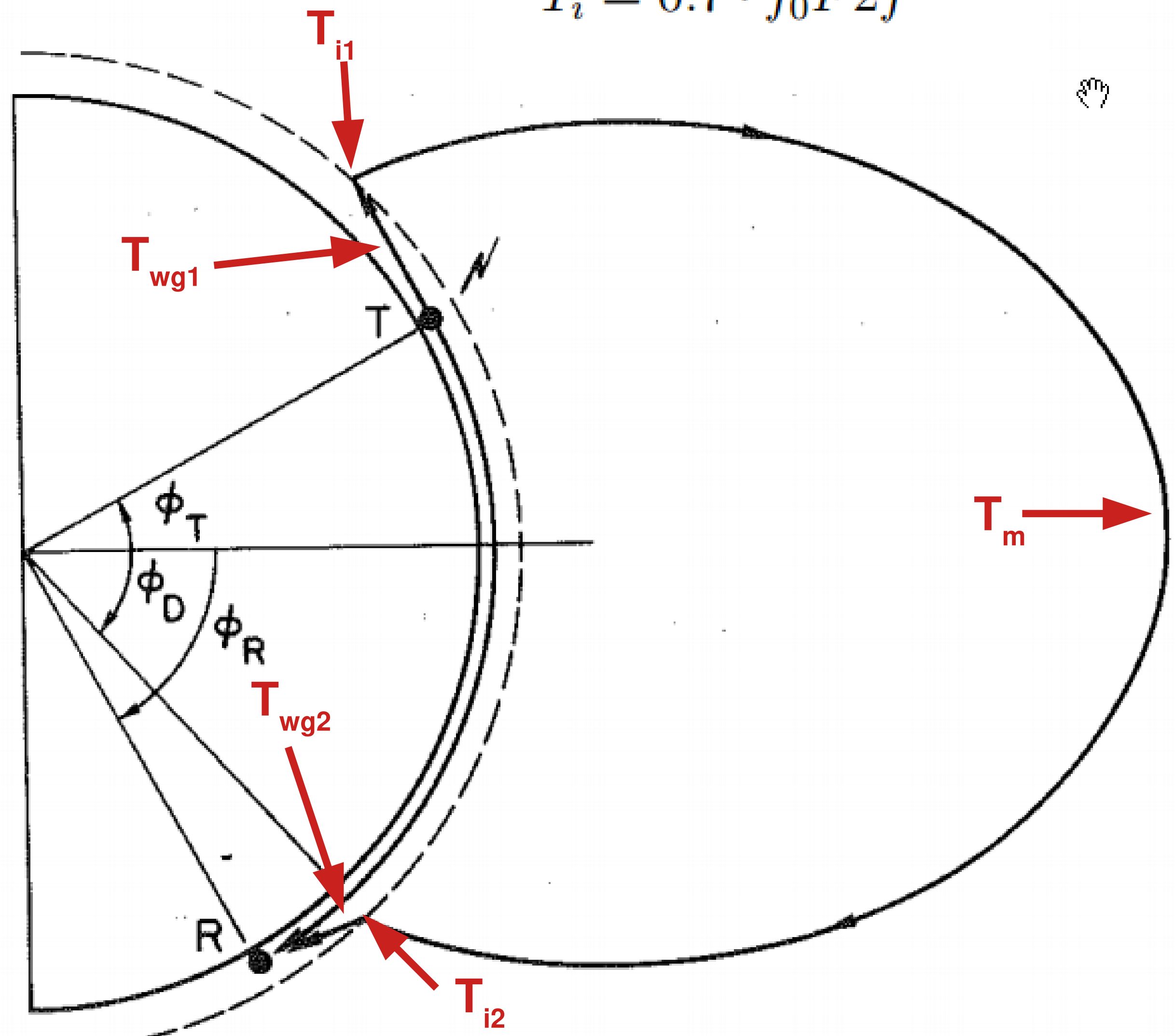
Nose frequency → f_H → field line (L-value)

The magneto-ionic theory → theory of whistlers

Longitudinal prop
(usual notation in

travel time:

$$T_i = 0.7 \cdot \overline{f_0F2}f^{-1/2}$$



Longitudinal propagation: ***why?***

A detour: the number of whistlers inside the plasmasphere are significantly higher than those of reaching the ground again → Transmission through the ionosphere:

1. waves propagating through the ionosphere from below, start to propagate along the local magnetic field line

2. waves reaching the ionosphere from above may propagate through, when they arrive to the top of the ionosphere with small wave normal angle. The majority of the waves are reflected back and never reach the ground again – propagating obliquely and thus cannot be used to estimate the electron density

The magneto-ionic theory → theory of whistlers

Longitudinal propagation: ***why?***

1. Because only the longitudinally propagating whistlers reaches the ground
2. Those whistlers propagate in density ***ducts*** (density enhancement/depletion or gradient)

The evidences:

- the existence of discrete traces in multiple-path (MP) whistler groups
- the integral relationship of the members of an echo train
- the existence of upper cutoff frequency of whistler traces at ½ f_{Heq}

1961 R.L. Smith: ray-tracing in density *crest:*

there is an upper cutoff frequency = $f_H/2$

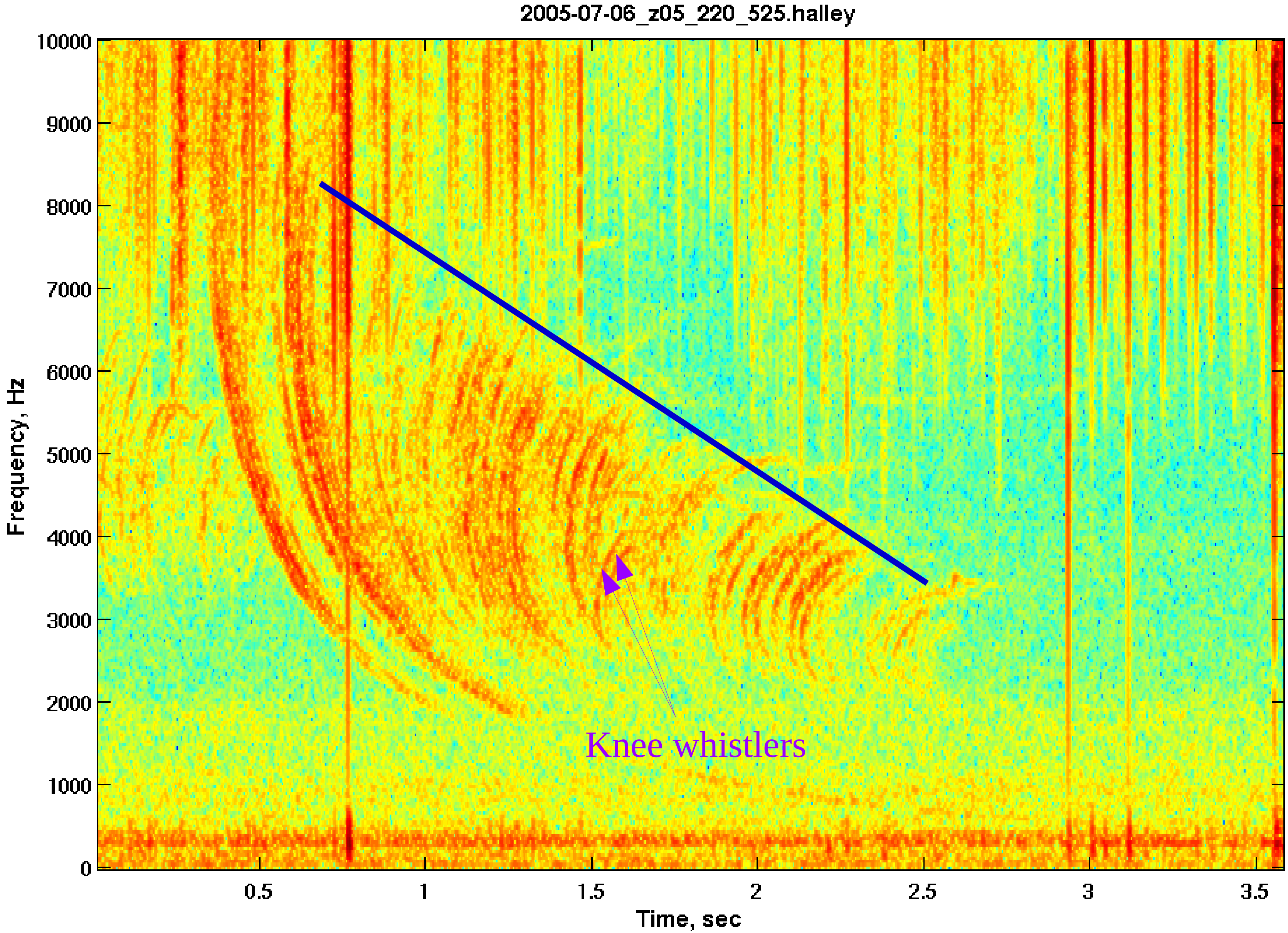
(density *trough:* there is a lower cutoff frequency $= f_H/2$)

Lo

1.

2.

Th
- tl
- tl
- tl



Traditional whistler inversion procedure

Whistler inversion model:

1) Wave propagation model (Appleton/Hartree dispersion relation)
2) Magnetic field model (central dipole → IGRF)
3) Field-align electron density distribution:
   - Physics based models (Diffusive Equilibrium models)
   - Experimental models based on in-situ measurements (Polar PWI, IMAGE RPI)

The procedure (*in theory*):

- Use the travel time integral to calculate the travel times for a model whistler
- Compare it with measured travel times

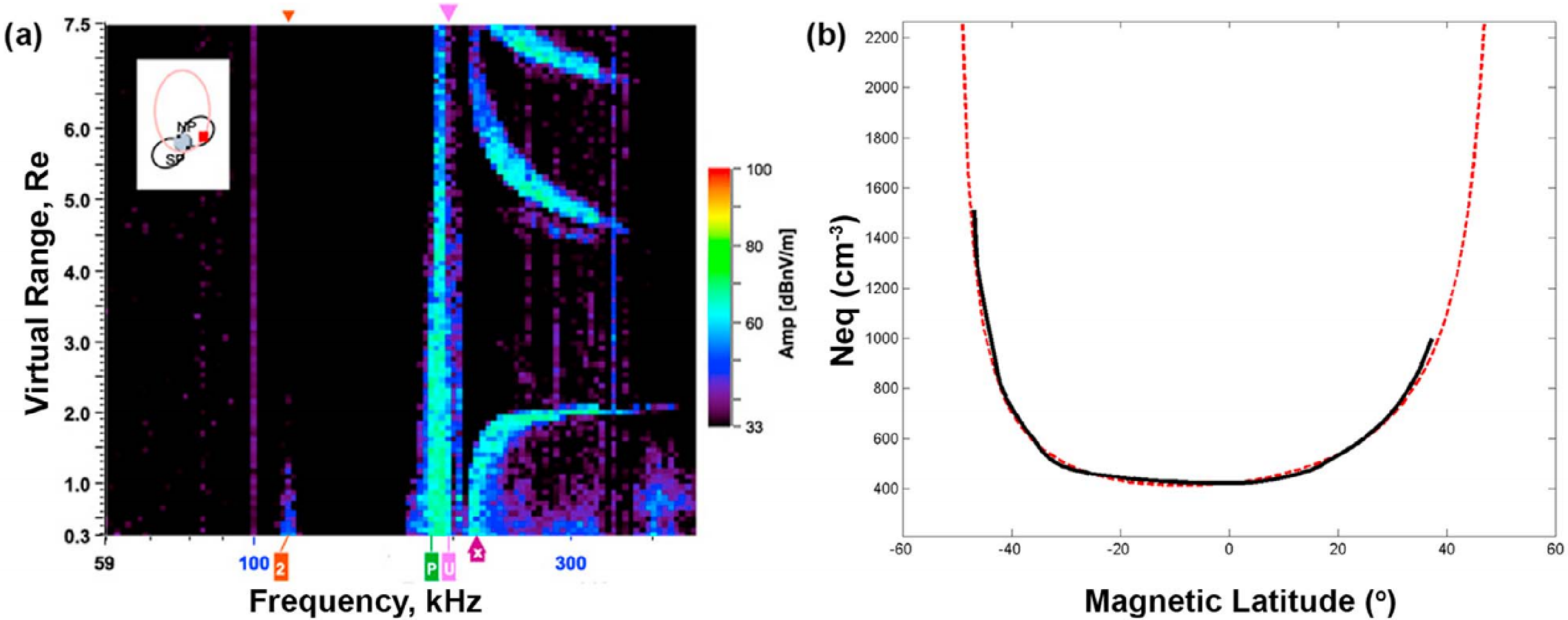


Figure 1. RPI measurements on 12 June 2002, 04:17 UT, MLT = 19.94, L = 2.94. (a) Plasmagram – color-coded echo amplitude as a function of frequency and virtual range in Earth radii made with BinBrowser [*Galkin et al.,* 2008]. The labels denote: second gyrofrequency harmonic, plasma and upper hybrid resonances, and local X mode cutoff frequency, respectively. The insert displays the IMAGE satellite orbit, with the satellite location marked by the red dot, and $L = 4$ field lines. (b) Electron density distribution as a function of magnetic latitude with solid line denoting the field-aligned density profile inverted from the traces shown in Figure 1a. The dashed red line is a least squares fit of the equation (1) to the RPI density profile, with $\alpha = 1.081$, $\beta = 0.678$ and $\gamma = 0.297$.

Traditional whistler inversion procedure

[17] The final result of the empirical plasmaspheric density model along a field line can be expressed as:

$$N(L,\lambda) = N_{eq}(L)\cdot\cos^{-(0.75\pm0.08)}\left(\frac{\pi}{2}\cdot\frac{(1.01\pm0.03)\lambda}{\lambda_{INV}}\right), \qquad (2)$$

$$N_{eq}(L) = 10^{((4.4693\pm0.0921)-(0.4903\pm0.0315)\cdot L)},$$

where N_{eq} is the equatorial density and $\lambda < \arccos((8371/(L^*R_E))^{-0.5})$ (this condition is to ensure that the model is applicable to altitudes above 2000 km).

The procedure (*in practice*):

- starts with ***detection of the whistler traces***

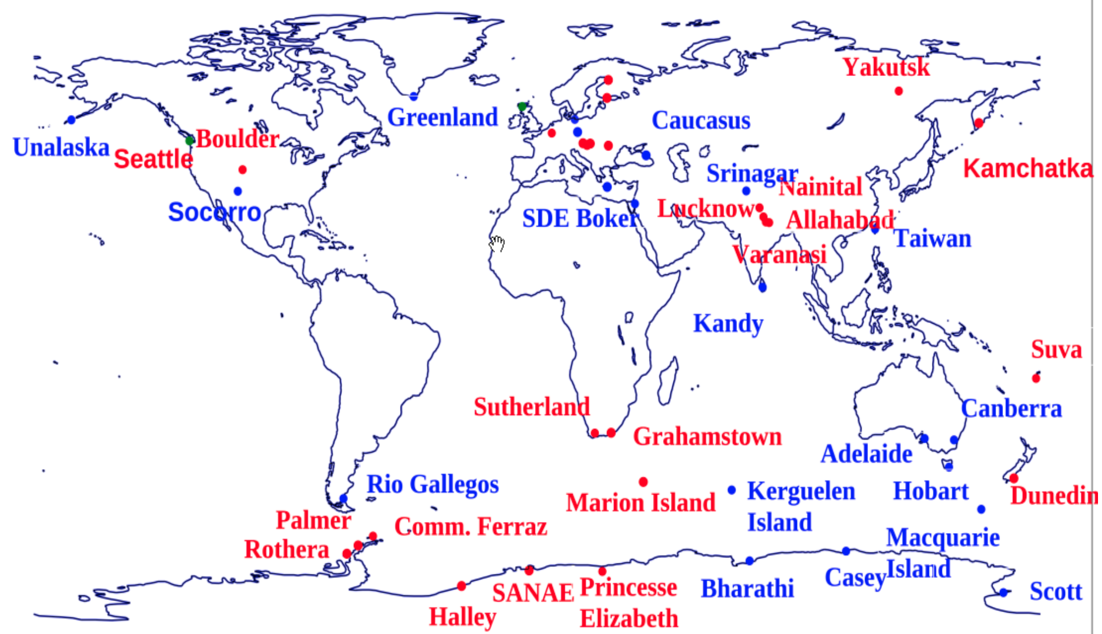
By 2D image correlation

The procedure (*in practice*):

- ***but first we need whistlers ->***

Traditional whistler inversion procedure

Automatic Whistler Detector and Analyzer Network (AWDANet)
a worldwide network of automated whistler receivers

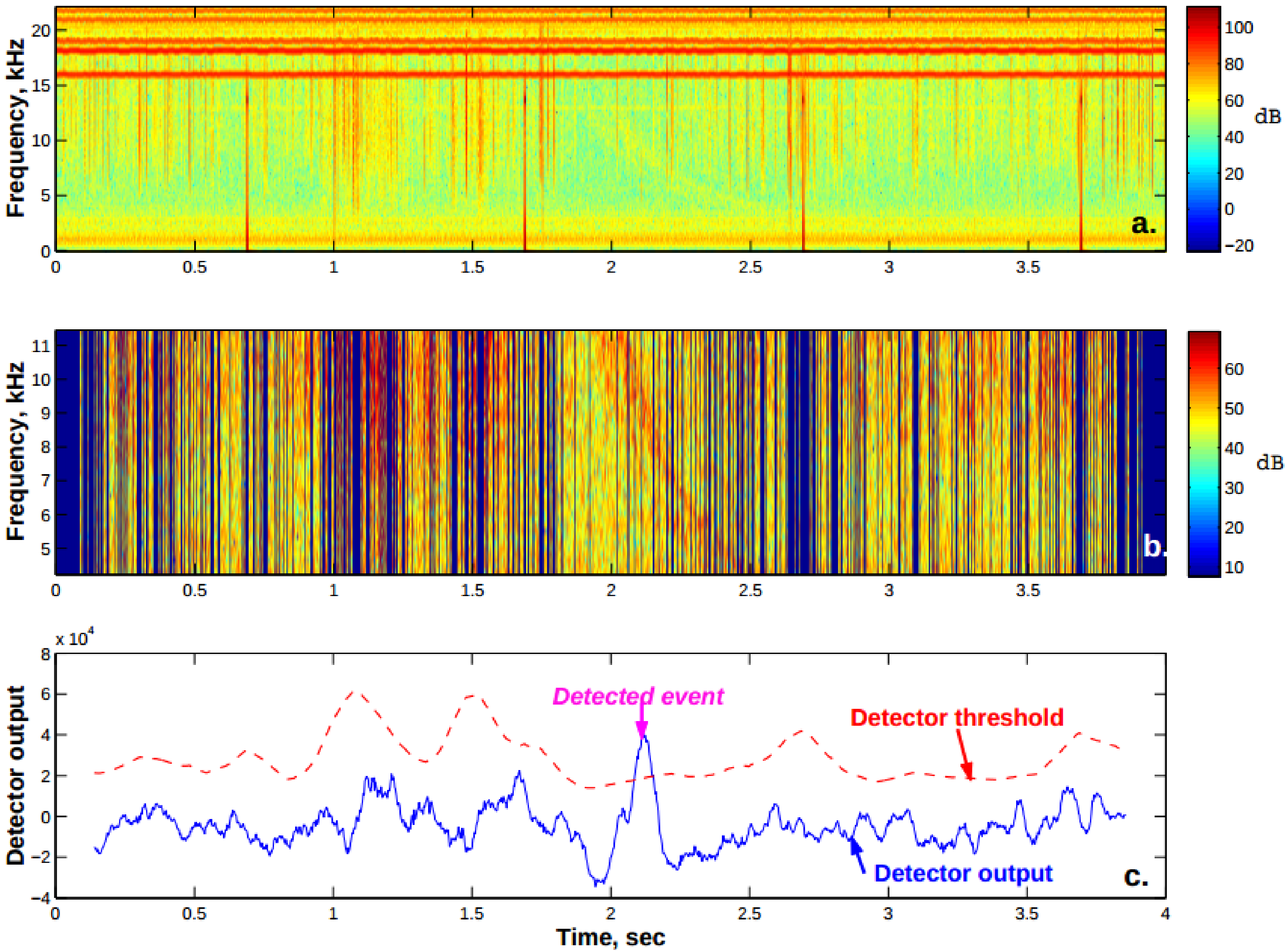


Traditional whistler inversion procedure

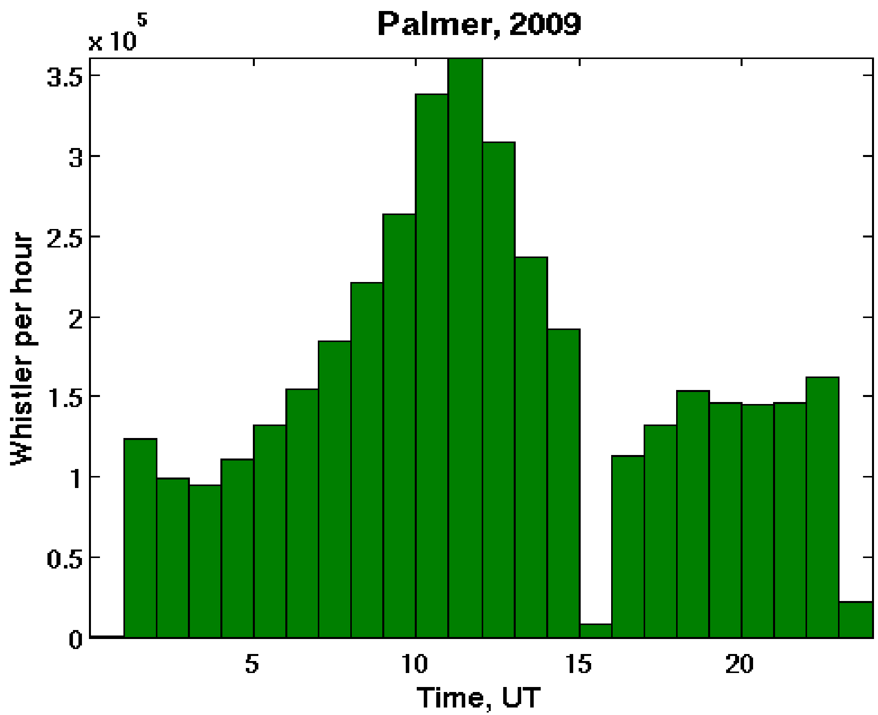
The p

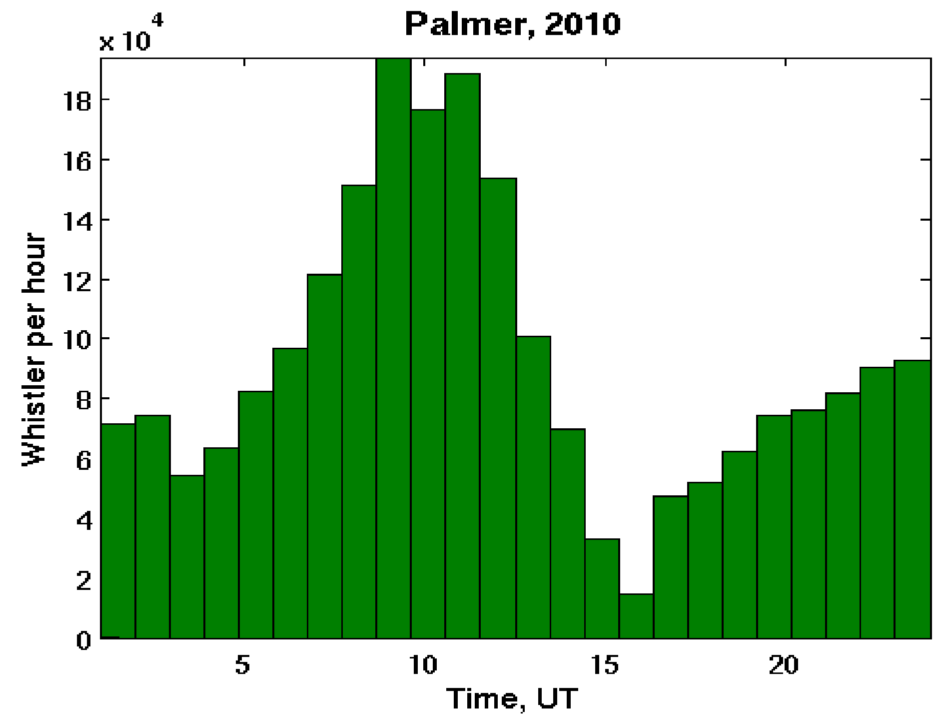
- star

By 2D



Traditional whistler inversion procedure





3.8 million events
11.3 million traces

2.2 million events
6.3 million traces

Traditional whistler inversion procedure

The procedure (*in practice*):

- starts with ***detection of the whistler traces***

Or by artificial intelligence (neural network) – see later and in Vijay Harid´s lecture later today

Traditional whistler inversion procedure

The procedure (*in practice*):

- and continues with ***scaling of the whistler traces***

Either by hand (very labour intensive and tiresome) or by artificial intelligence (neural network) – see later and in Vijay Harid´s lecture later today

Motto

Whistlers have been regarded as cheap and effective tools for plasmasphere diagnostic since the early years of whistler research...

Motto

...but it never became a real operational tool until recently since "reducing" whistler data to equatorial densities is very labor intensive

Is it still true?

- the answer is not simple

- original thoughts: detection is difficult, but inversion is easy (ready)

Outline

A. ***Route I***. Whistler inversion in ***frequency domain***

1. Traditional way
2. Virtual Trace Transformation (***AWDANet***)→ lesson learned: the ***detection*** is **easy** and ***solved***, but the ***inversion*** is **difficult**

B. ***Route II.*** Whistler inversion in time ***domain***

1. Reduction to sferic *or* dechirping

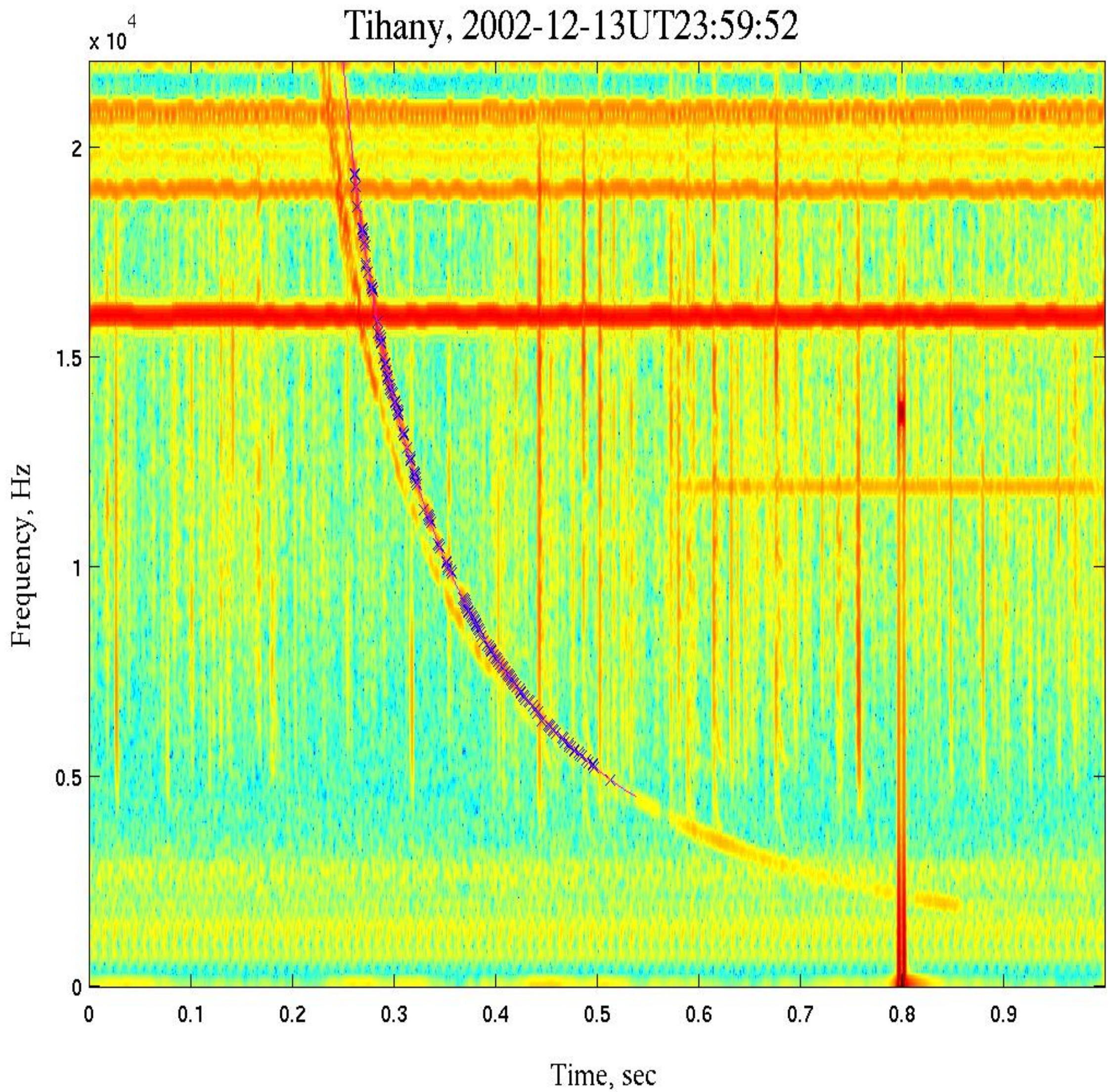
A. ***Route I***. Whistler inversion in ***frequency domain***

1. Traditional way:

- *Scaling* a whistler trace on spectrogram +
- Running inversion algorithm (e.g. Bernard, 1973; Tarcsai, 1975, Lichtenberger, 2009) → to obtain equatorial **electron density** and **L-value** of the field line (*assuming ducted, longitudinal propagation*) to invert the travel-time integral:

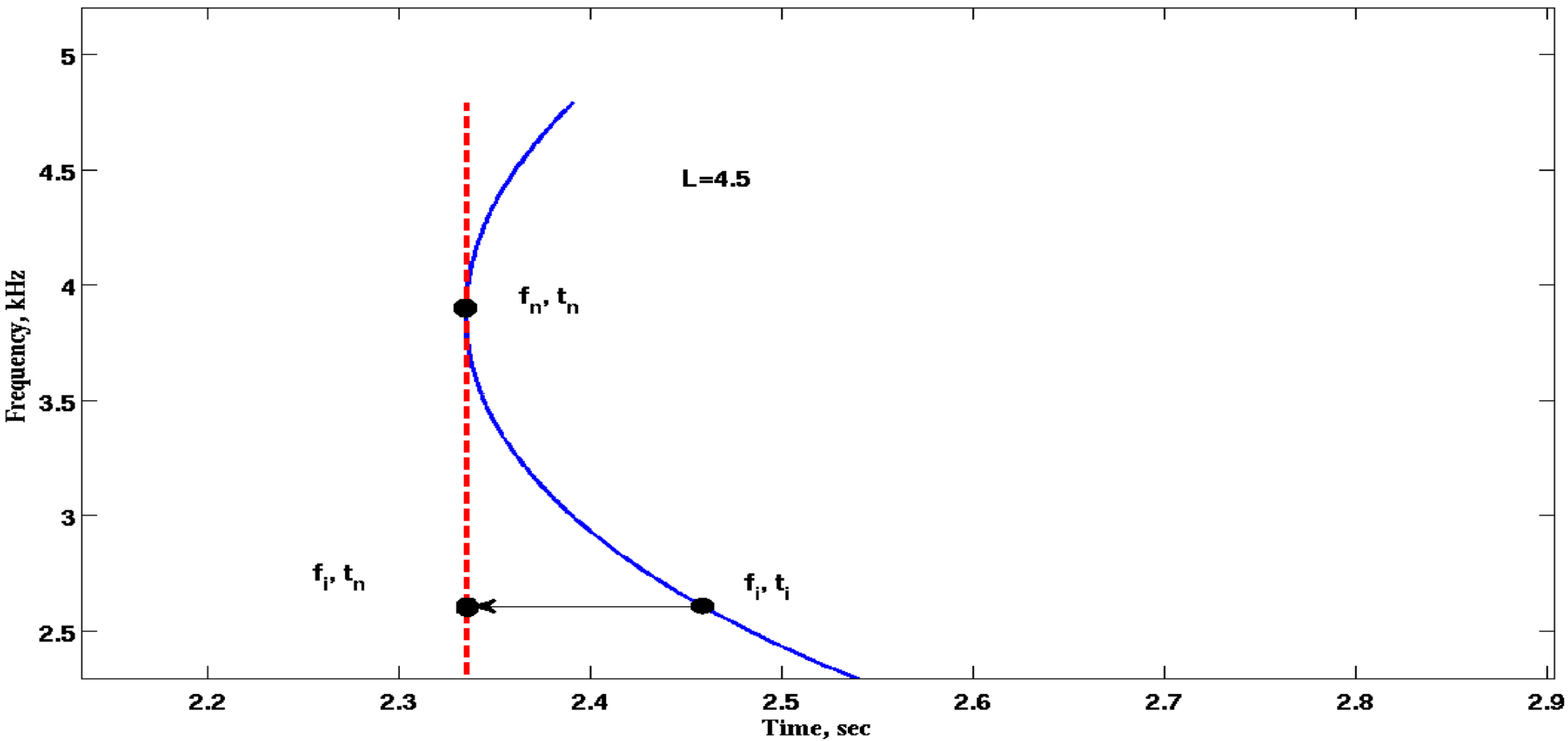
$$T_m(f) = \frac{1}{2c} \int_s \frac{f_p f_H}{f^{1/2}(f_H - f)^{3/2}} ds$$

Route I. Whistler inversion in *frequency domain:* 1. Traditional way



Virtual (whistler) Trace Transformation

[Lichtenberger, *JGR*, 2009]



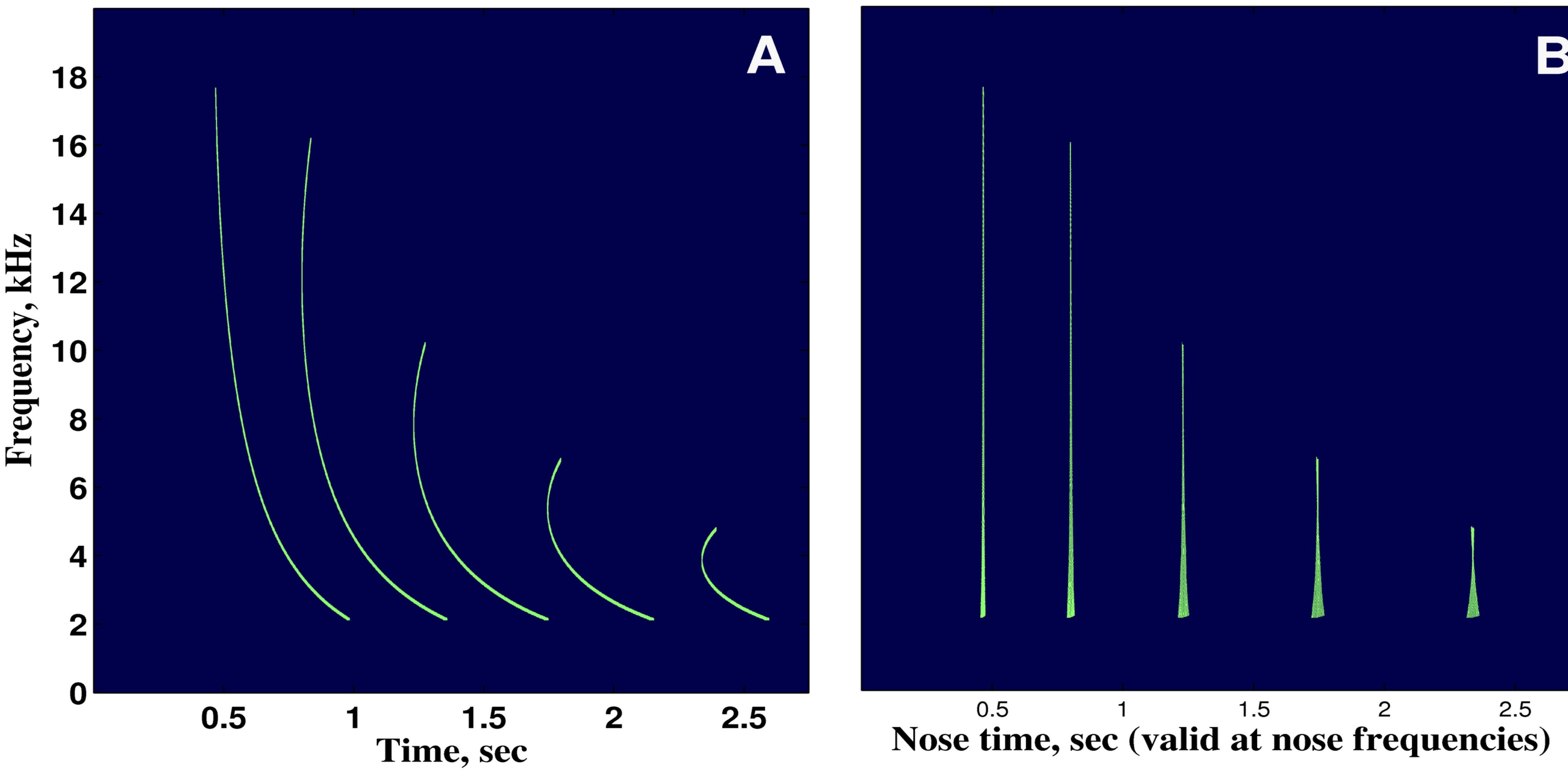
Multiple path whistler group model:

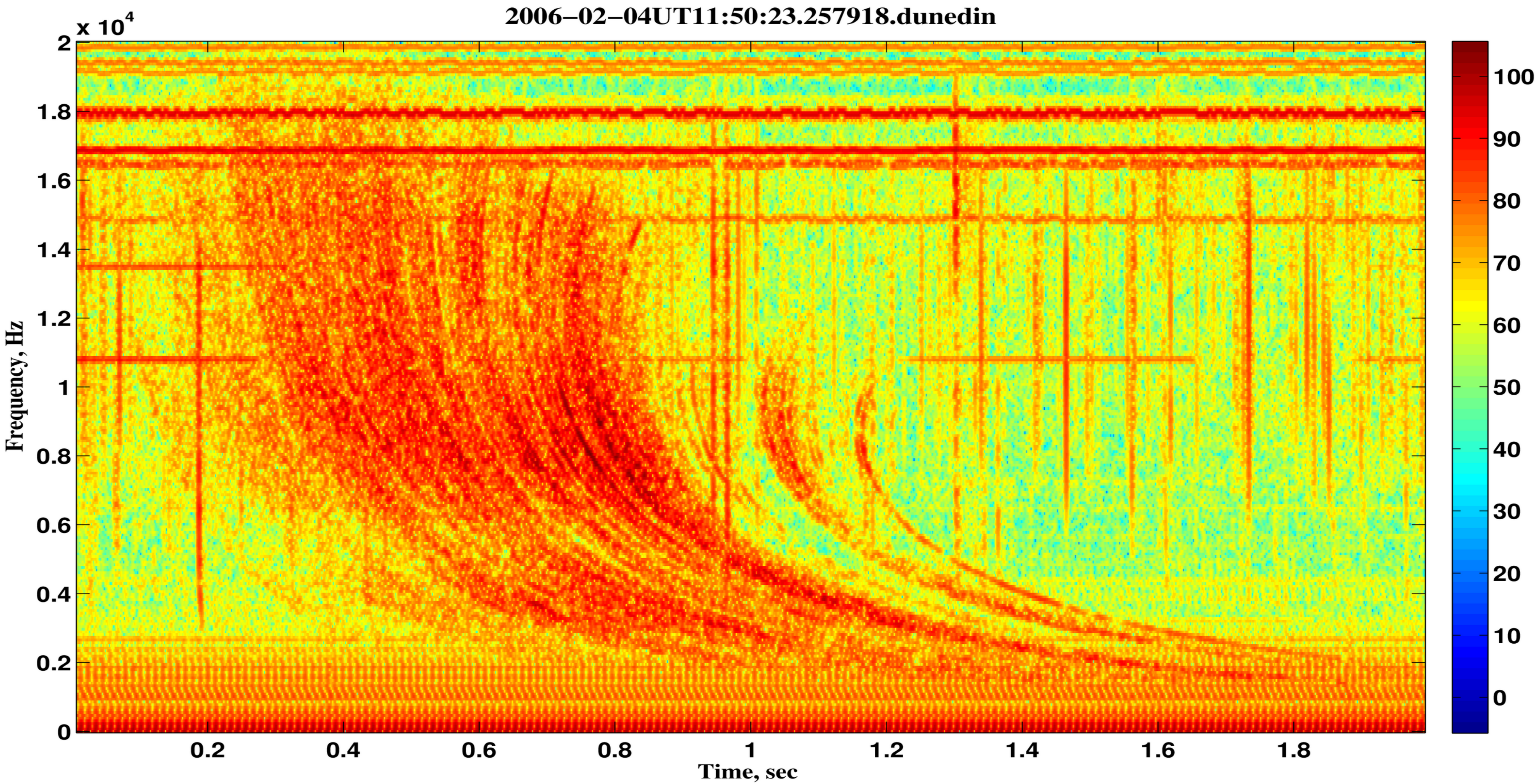
- A new, simplified equatorial electron density profile is introduced in a meridional section of the plasmasphere:

$$\log_{10} n_{eq} = A + B \cdot L$$

- *A* and *B* are constants for a MP group, but may vary to time and place.
- This approximation is valid between ~ $2 < L < \min(8, L_{pp})$, where L_{pp} is the location of plasmapause.
- Taking a pair of *(A,B),* the electron density in magnetic equator decreases monotonically. In principle, a whistler can propagate along each field line described by an *L* in this range with corresponding n_{eq} forming a ***virtual whistler continuum***. Of course, in reality only a few whistlers of that continuum may be real.

VTT – applied to model MP group

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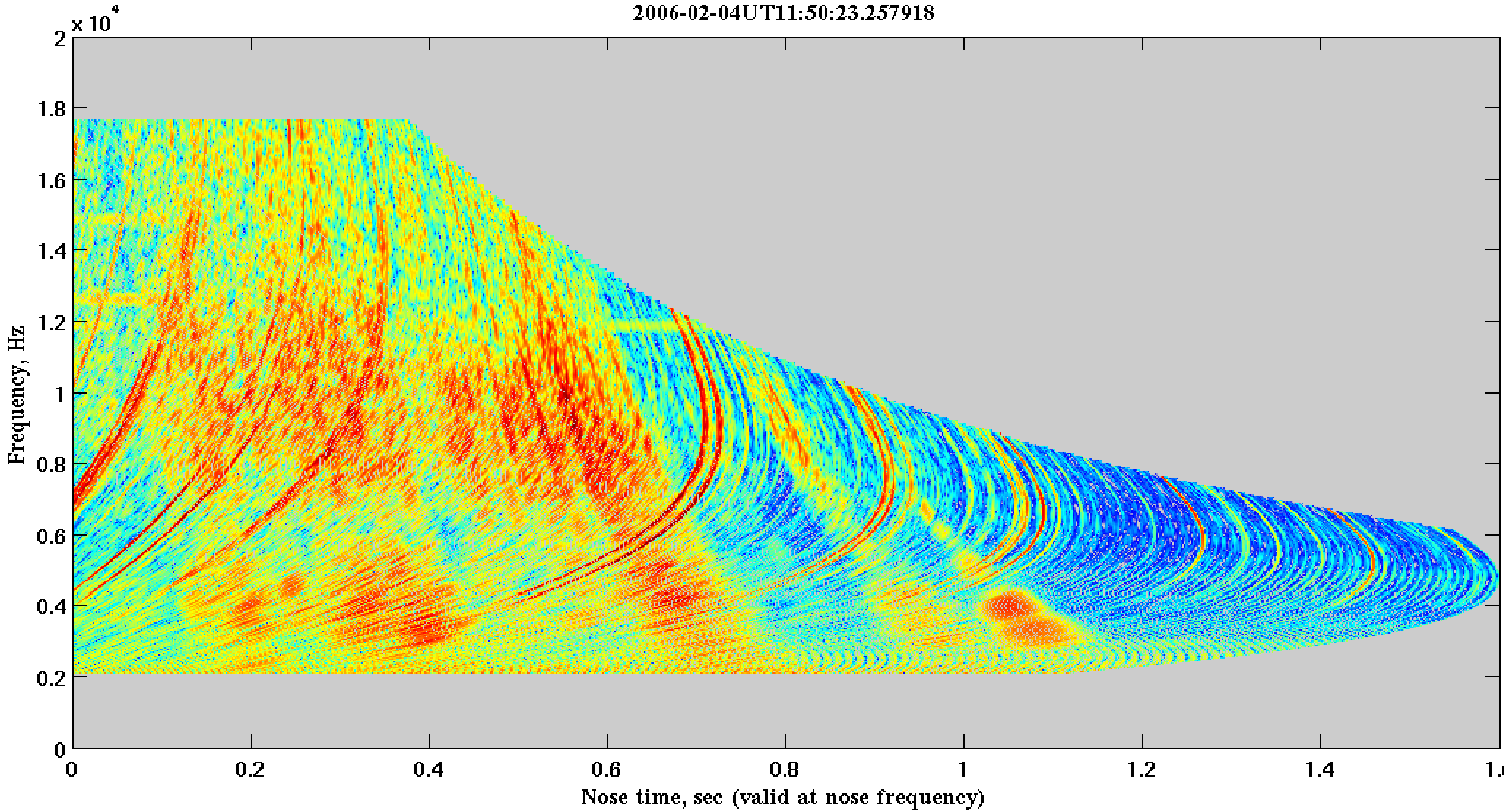
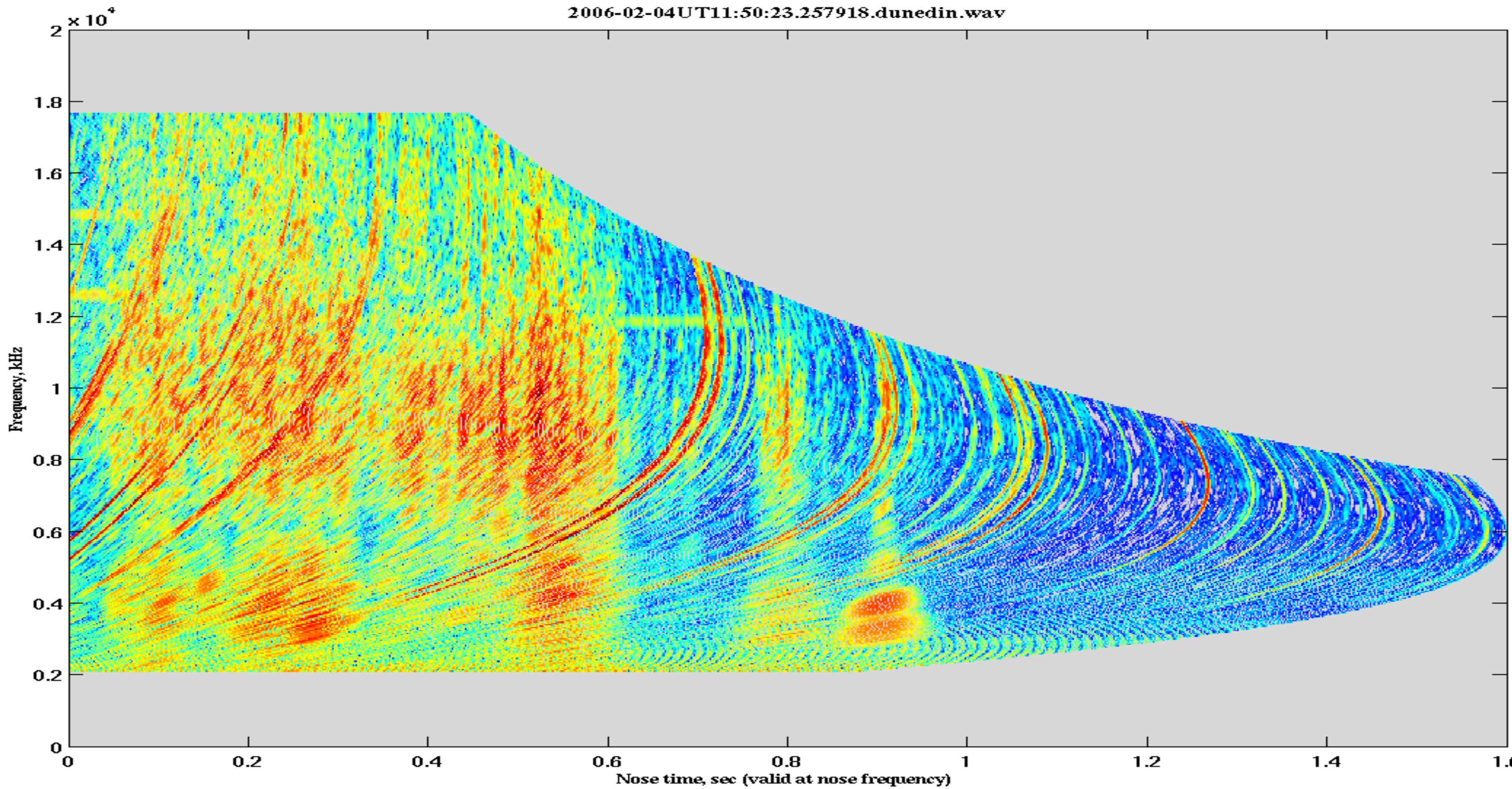
x 10^4
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Frequency, Hz
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Time, sec
100
90
80
70
60
50
40
30
20
10
0

VTT – unmatched parameters

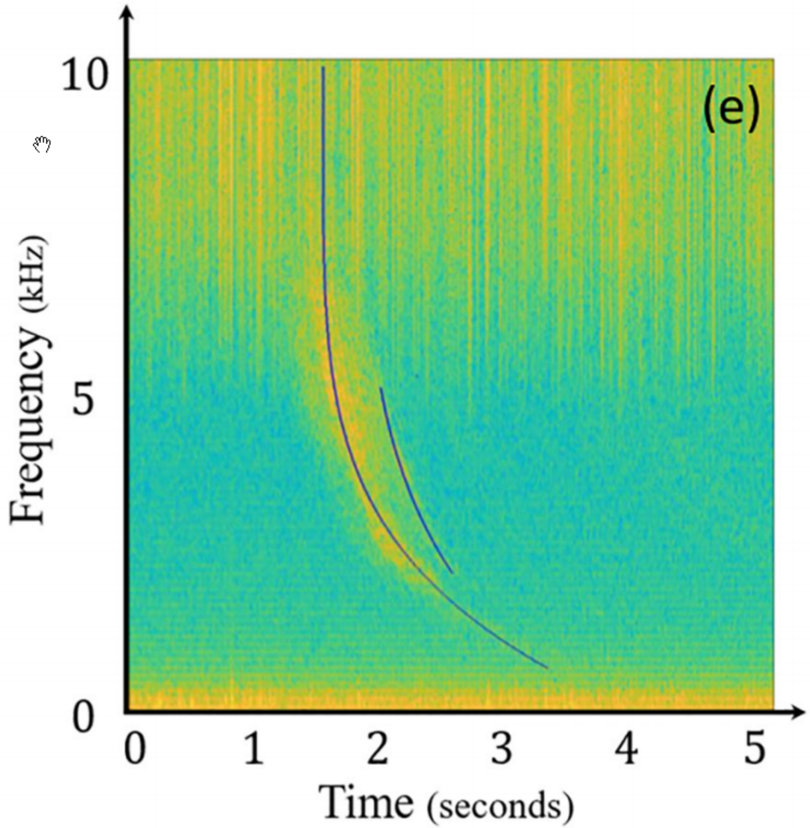


VTT – matched parameters

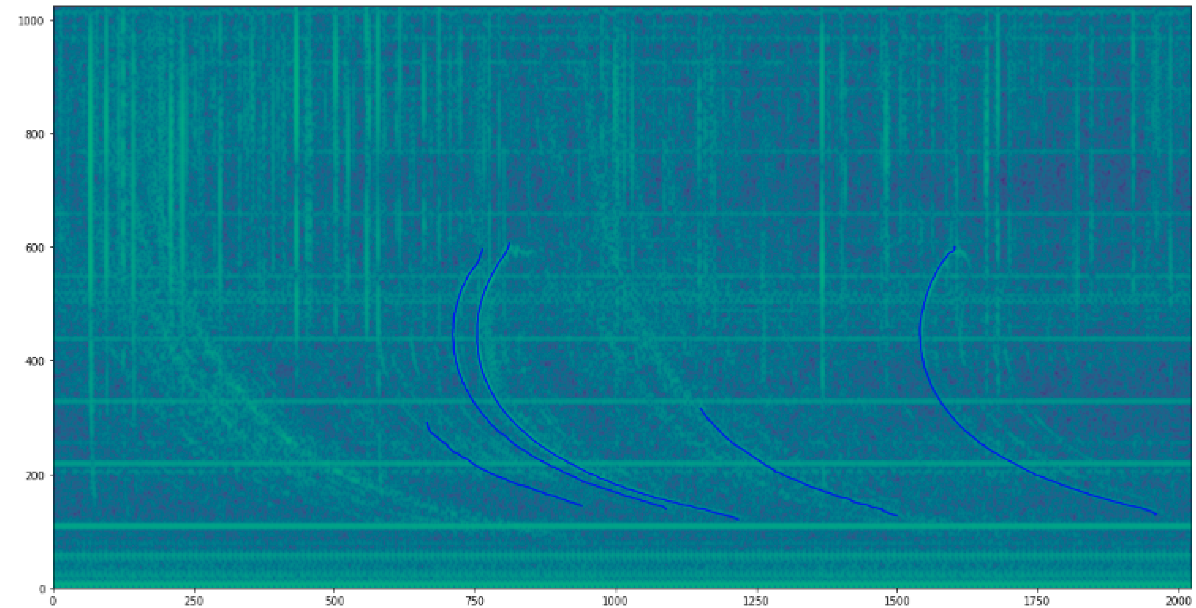


A. Route I. Whistler inversion in frequency domain

1. "Traditional way": using **Neural network** to "scale" whistlers



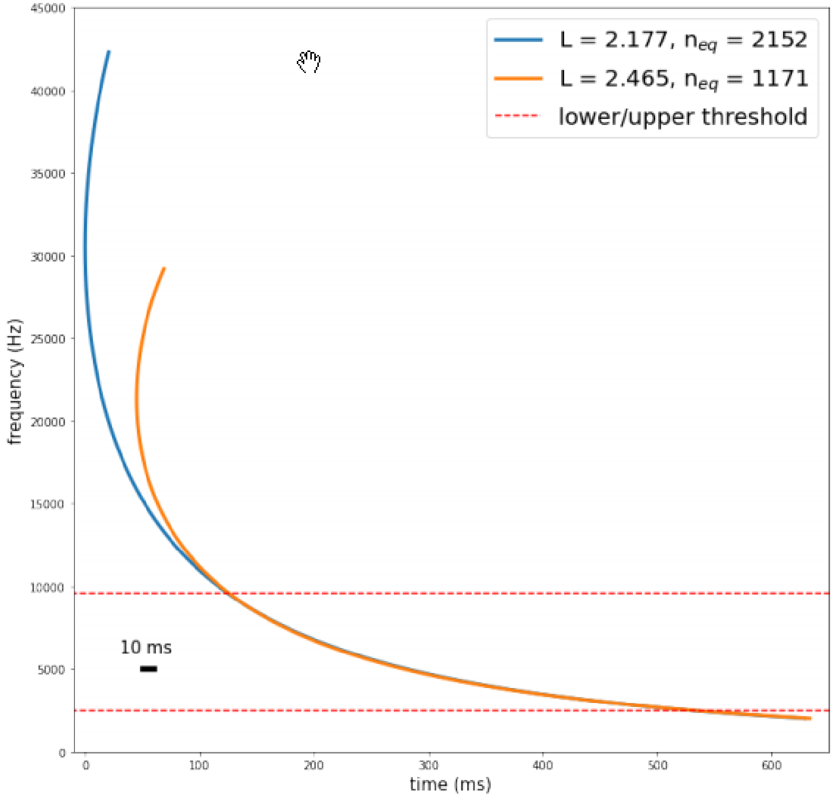
[Harid+, GRL, 2021:
Mask Scoring R-CNN

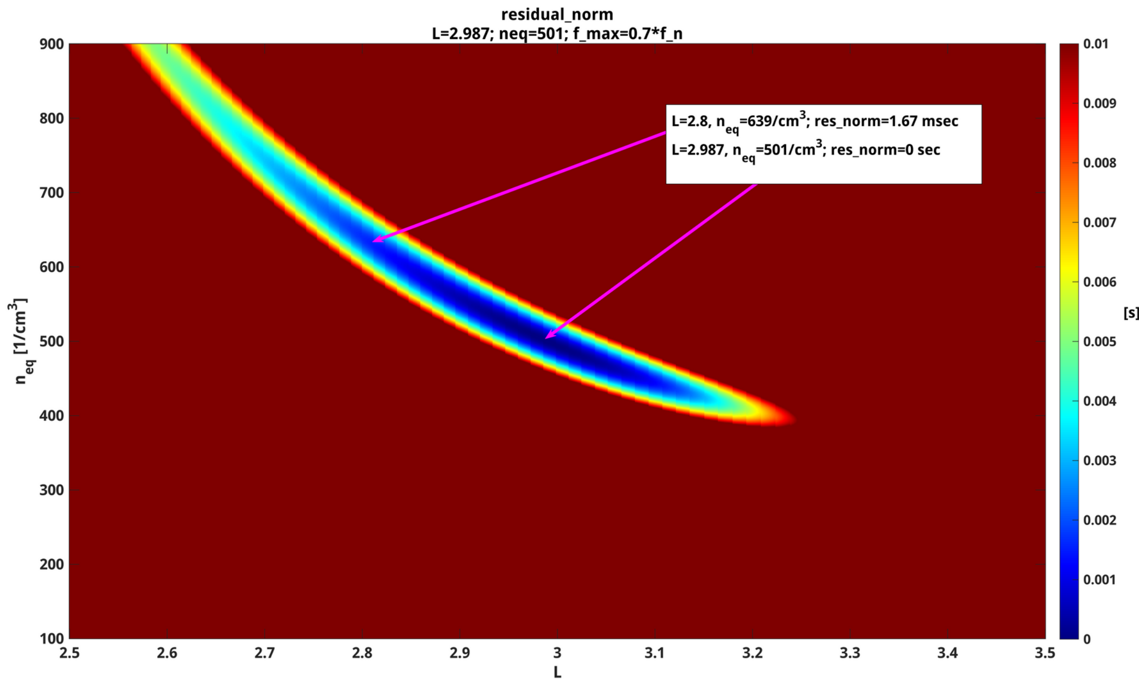


[Pataki+, JGR, under preparation:
Mask R-CNN + Pointrend

A. *Route I*. Whistler inversion in ***frequency domain***

1. "Traditional way": using **Neural network** to "scale" whistlers [Pataki+, JGR, 2022]

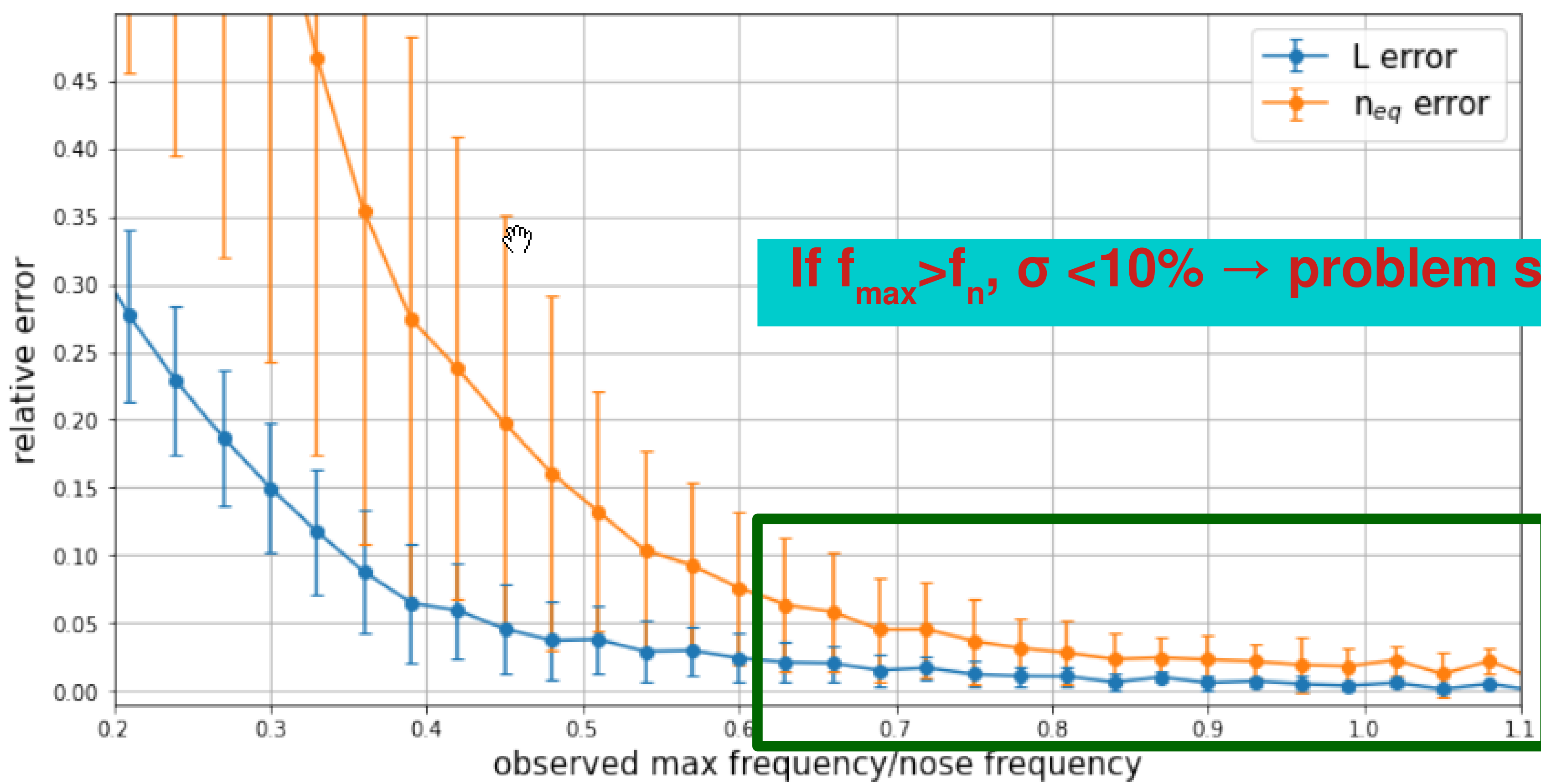




The uncertainty can not only be high, but its value is not known!

A. *Route I*. Whistler inversion in ***frequency domain***

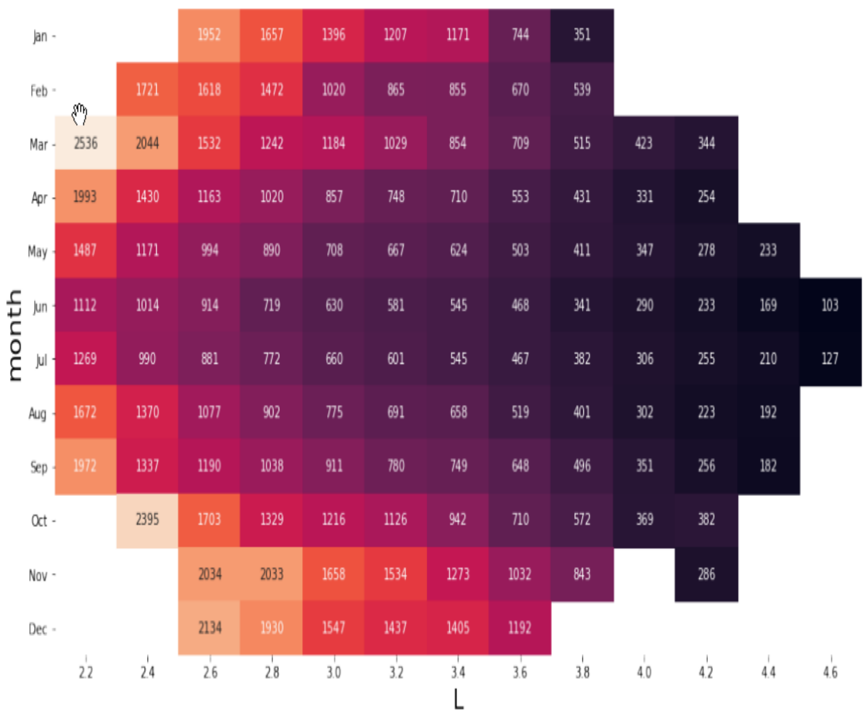
1. "Traditional way": using **Neural network** to "scale" whistlers [Pataki+, JGR, 2022]

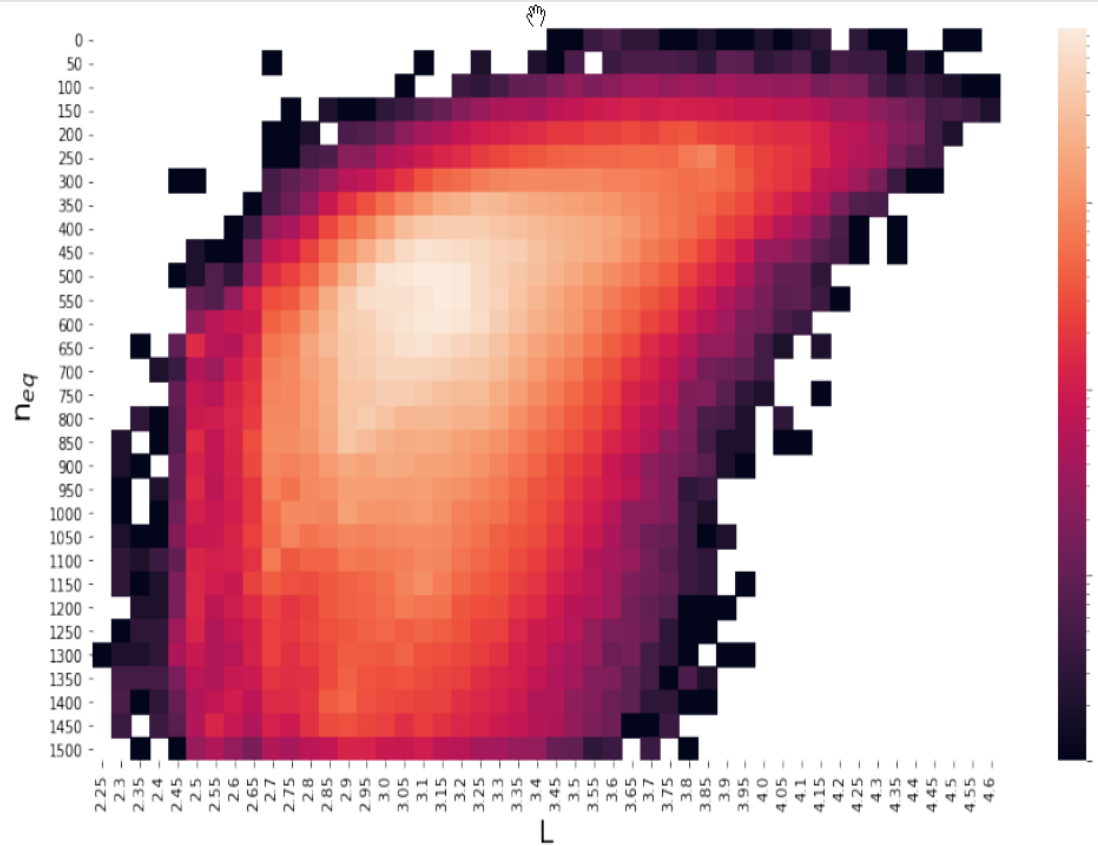


If $f_{max}>f_n$, σ <10% → problem solved?

A. *Route I*. Whistler inversion in ***frequency domain***

1. "Traditional way": using **Neural network** to "scale" whistlers
[Pataki+, JGR, 2022] – large scale statistical results for ***Rothera*** 2008-2016 (~300,000 events)





Statistical studies binning the occurrences

Route II. Whistler inversion in ***time domain:*** Reduction to sferic *or* dechirping

The idea:

Signal: $$\mathrm{a(t,f)}=\mathrm{a}_0\cos(2\pi ft+\alpha)=a_0\cos(\phi)$$

Let`s assume, that we know $\phi=\phi(f)$ along the propagation path

At the end of the propagation,

the Fourier transform of a: $\mathcal{A}(f,t_{end})=\mathcal{F}[a(f,t_{end})]$

De-chirped signal: $$\mathrm{a}_{dc}(t_{start},f)=\mathcal{F}^{-1}[\mathcal{A}(f)e^{-i\phi(f)}]$$

Route II. Whistler inversion in ***time domain:*** Reduction to sferic *or* dechirping

1. Appleton-Hartree dispersion relation for longitudinal propagation – refractive index:

$$\mu^2 = 1 + \frac{f_p^2}{f(f_H - f)}$$

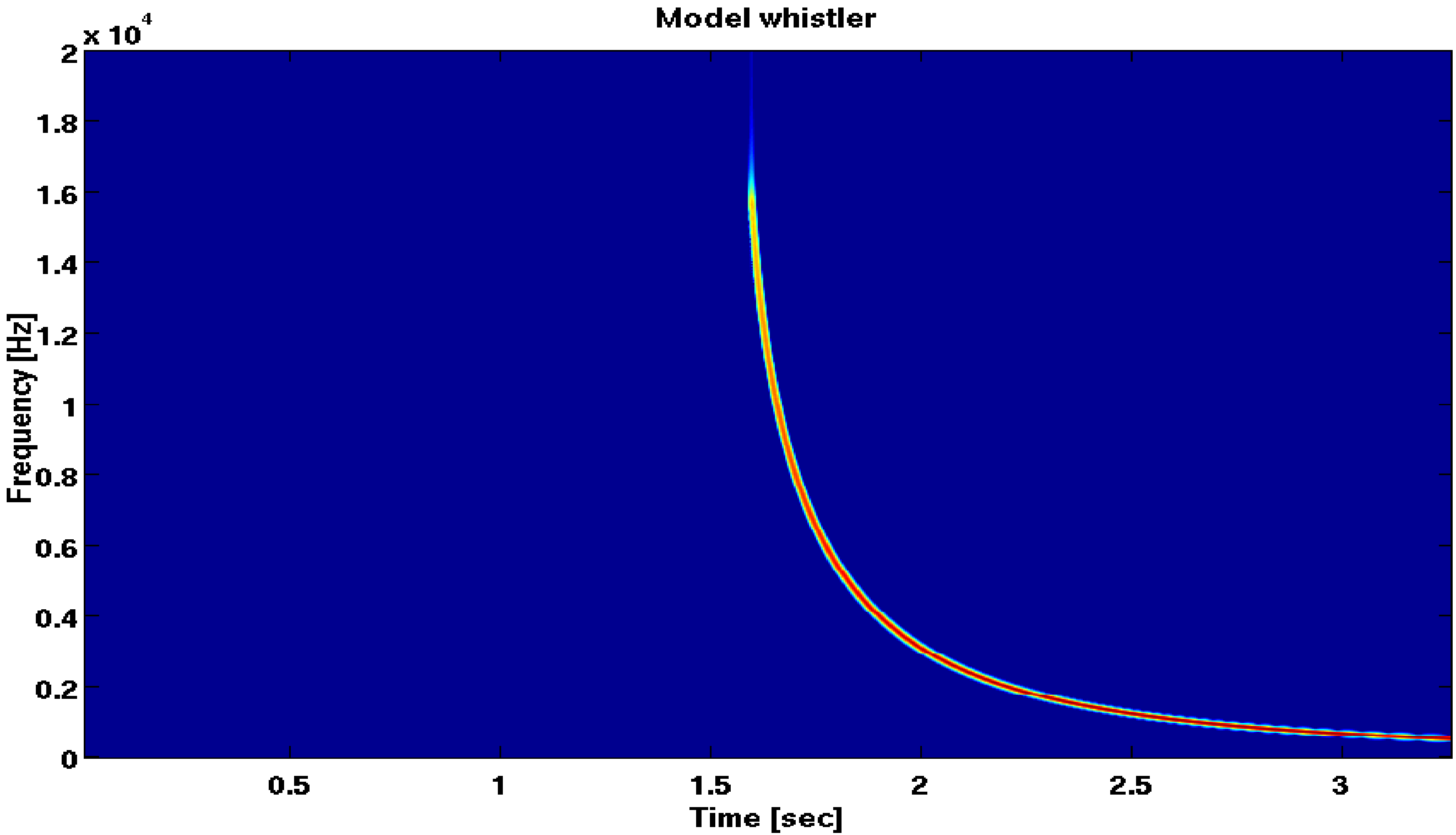
2. group-refractive index: $$\mu_g = \frac{d}{df}(\mu f)$$

3. group delay: $$\tau_g = -\frac{1}{2\pi}\frac{\partial\phi}{\partial f} \qquad \tau_g = \frac{1}{c}\int \mu_g ds$$

4. phase: $$\phi = \frac{2\pi}{c}\sqrt{(f)}\int \frac{f_p}{(f_H - f)^{1/2}} ds$$

In the ionosphere: $$f \ll f_p \ and \ f_H \approx const \Rightarrow \phi = D\sqrt{(f)}$$

Route II. Whistler inversion in *time domain:* Reduction to sferic *or* dechirping



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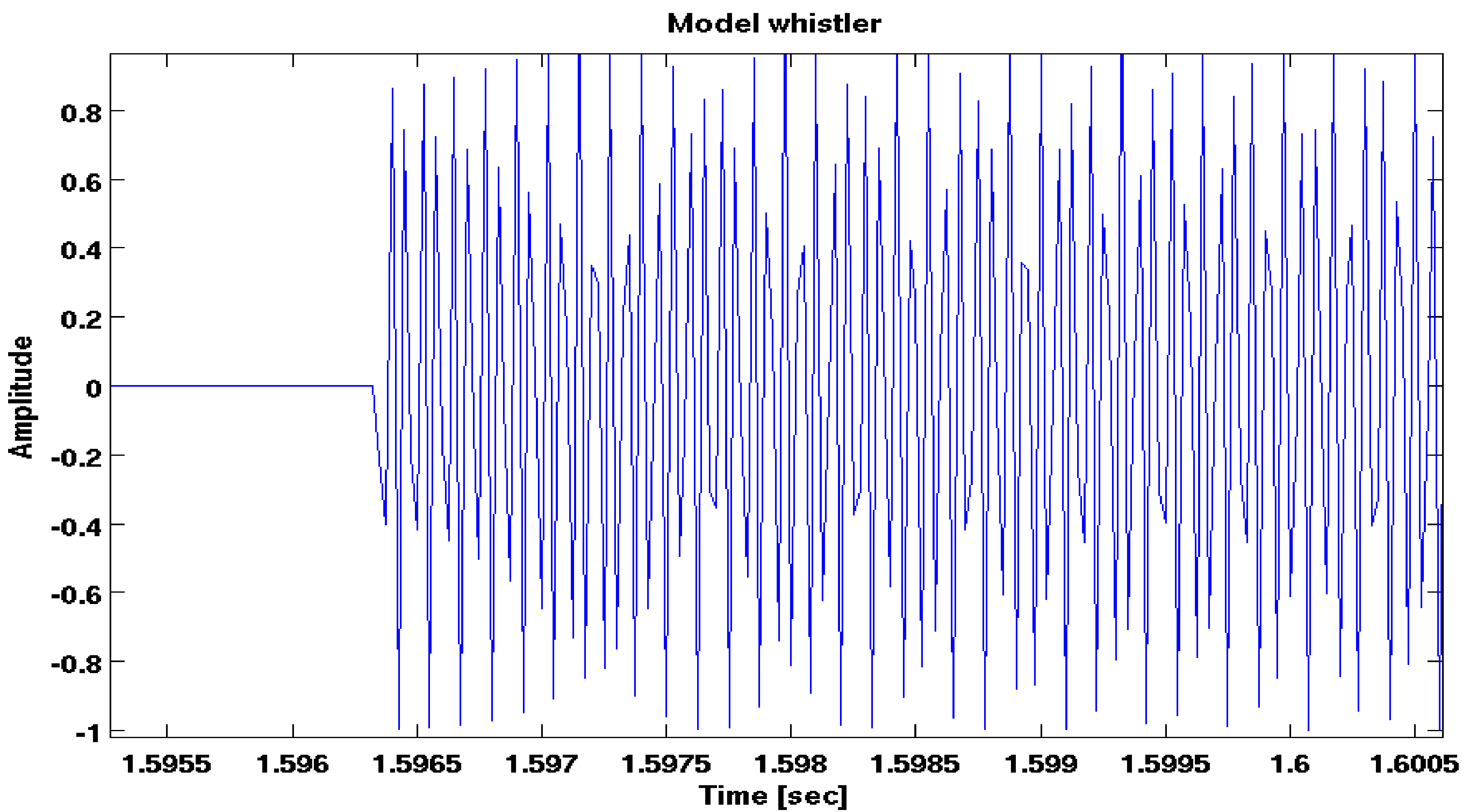

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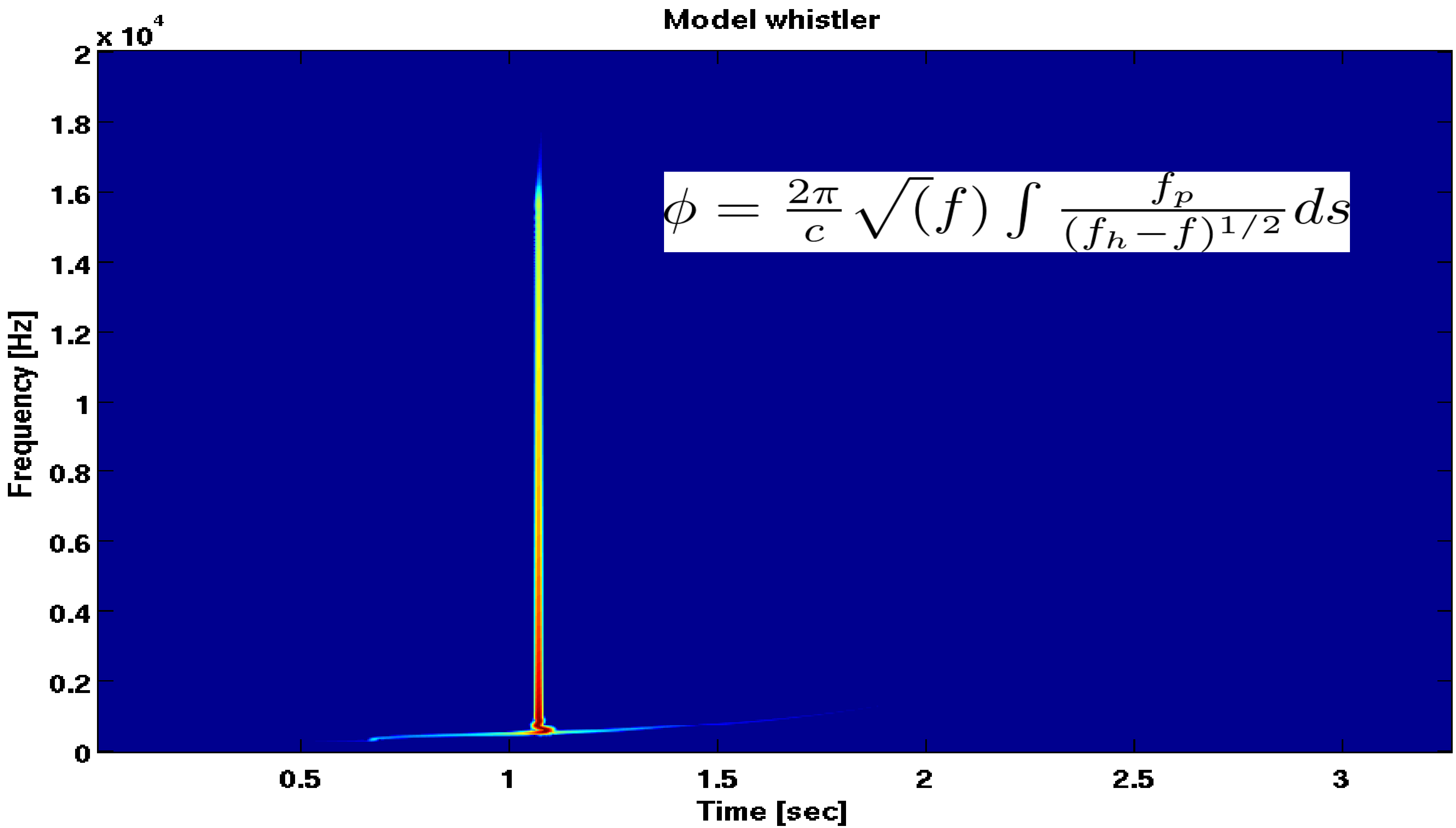

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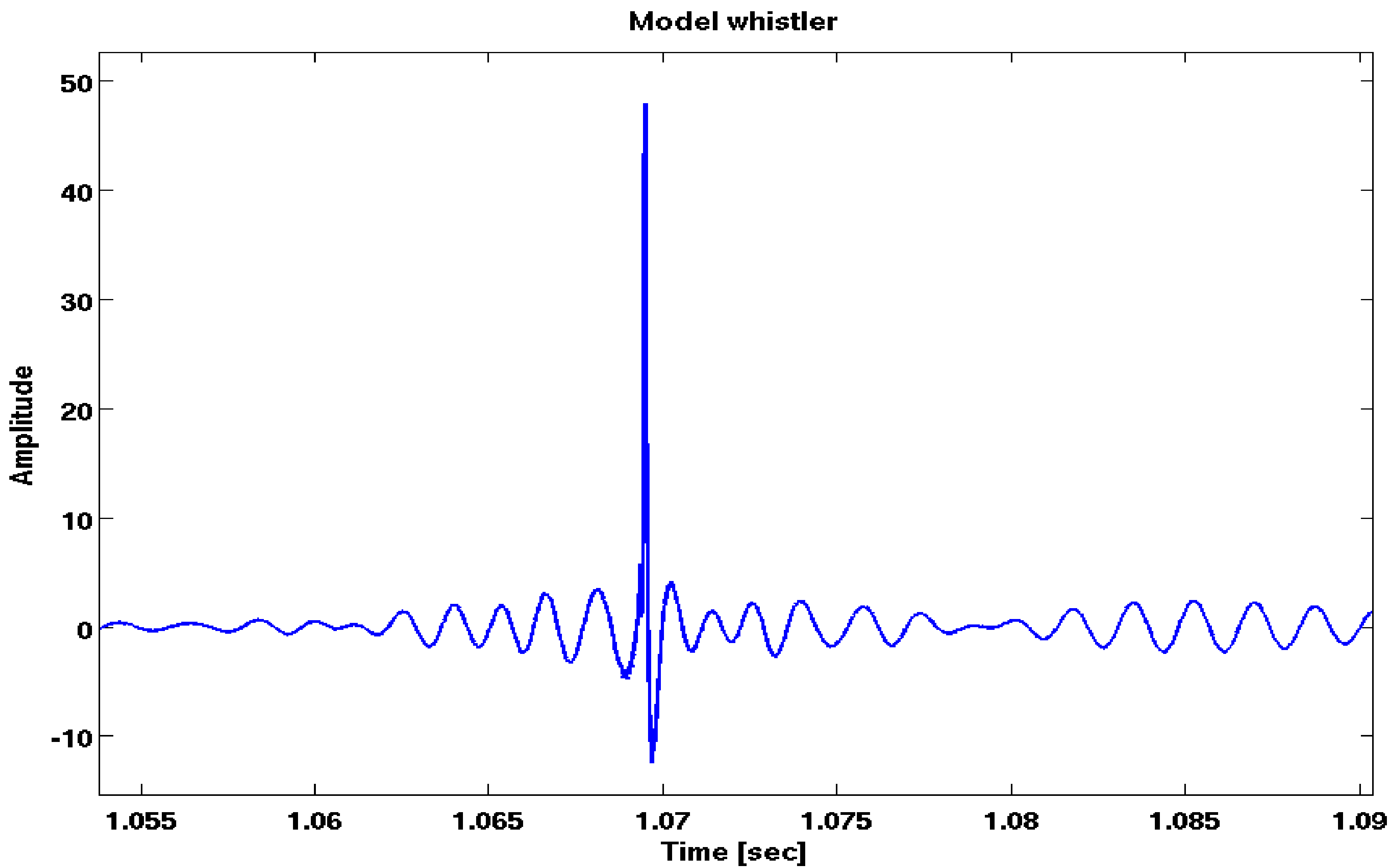

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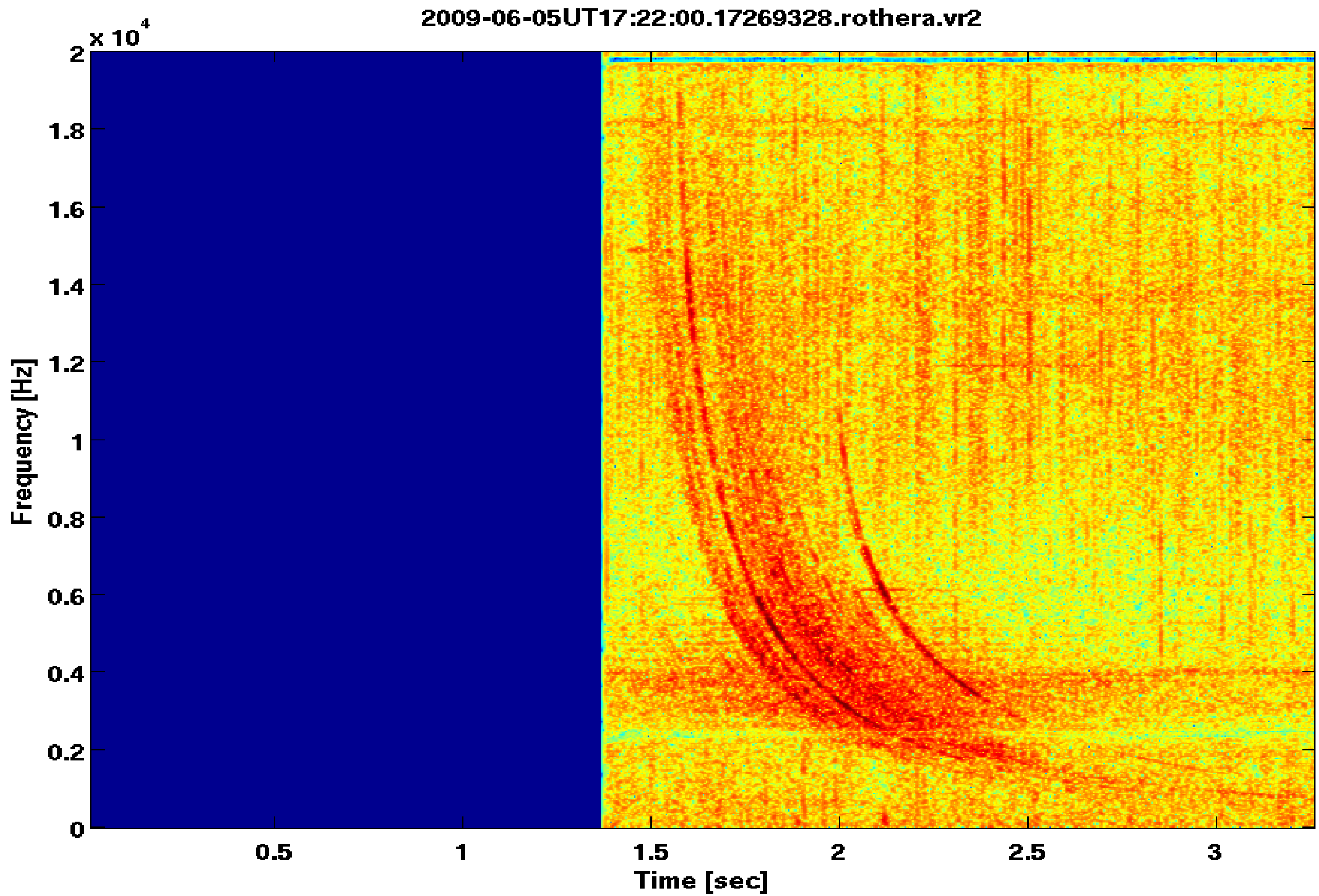

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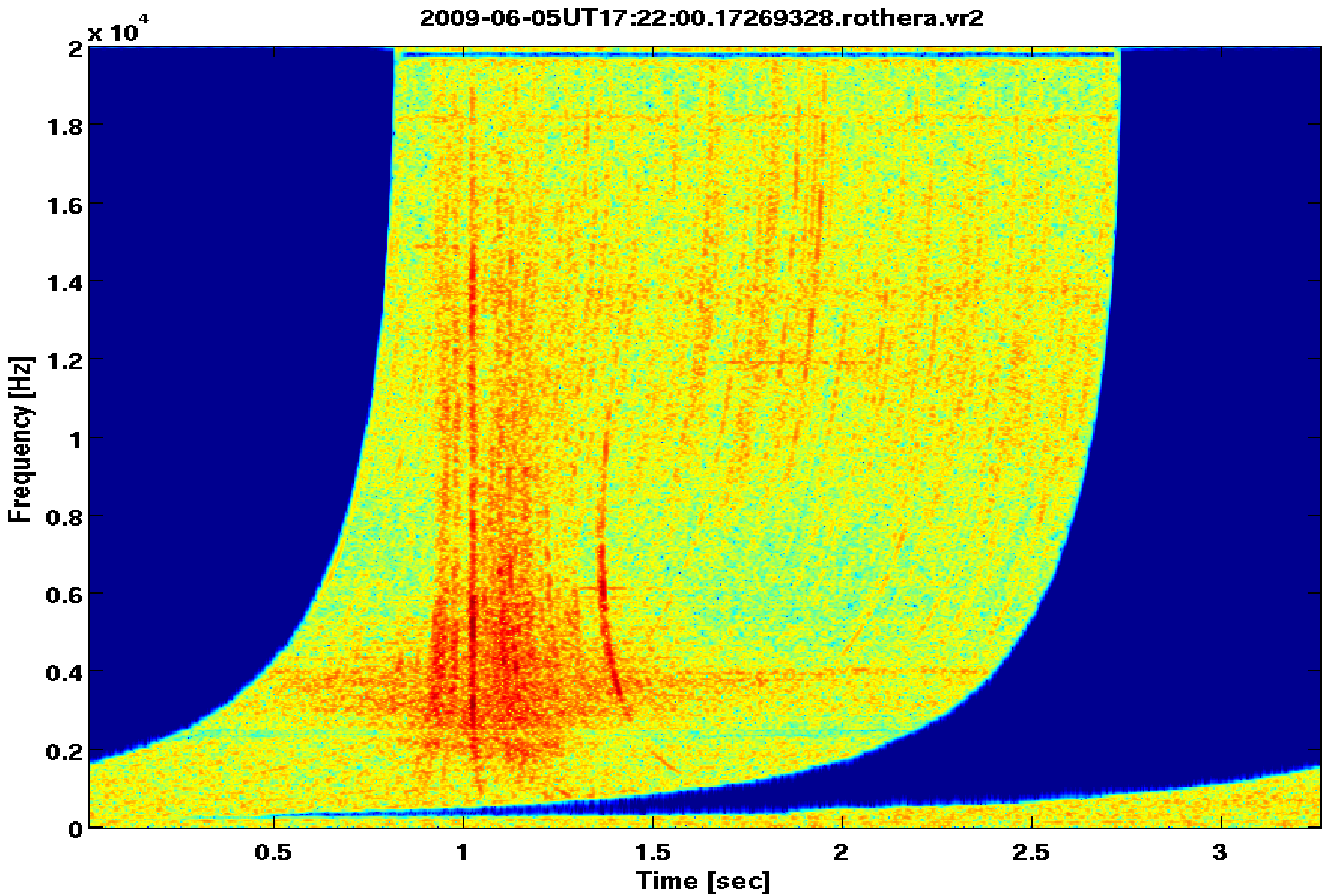

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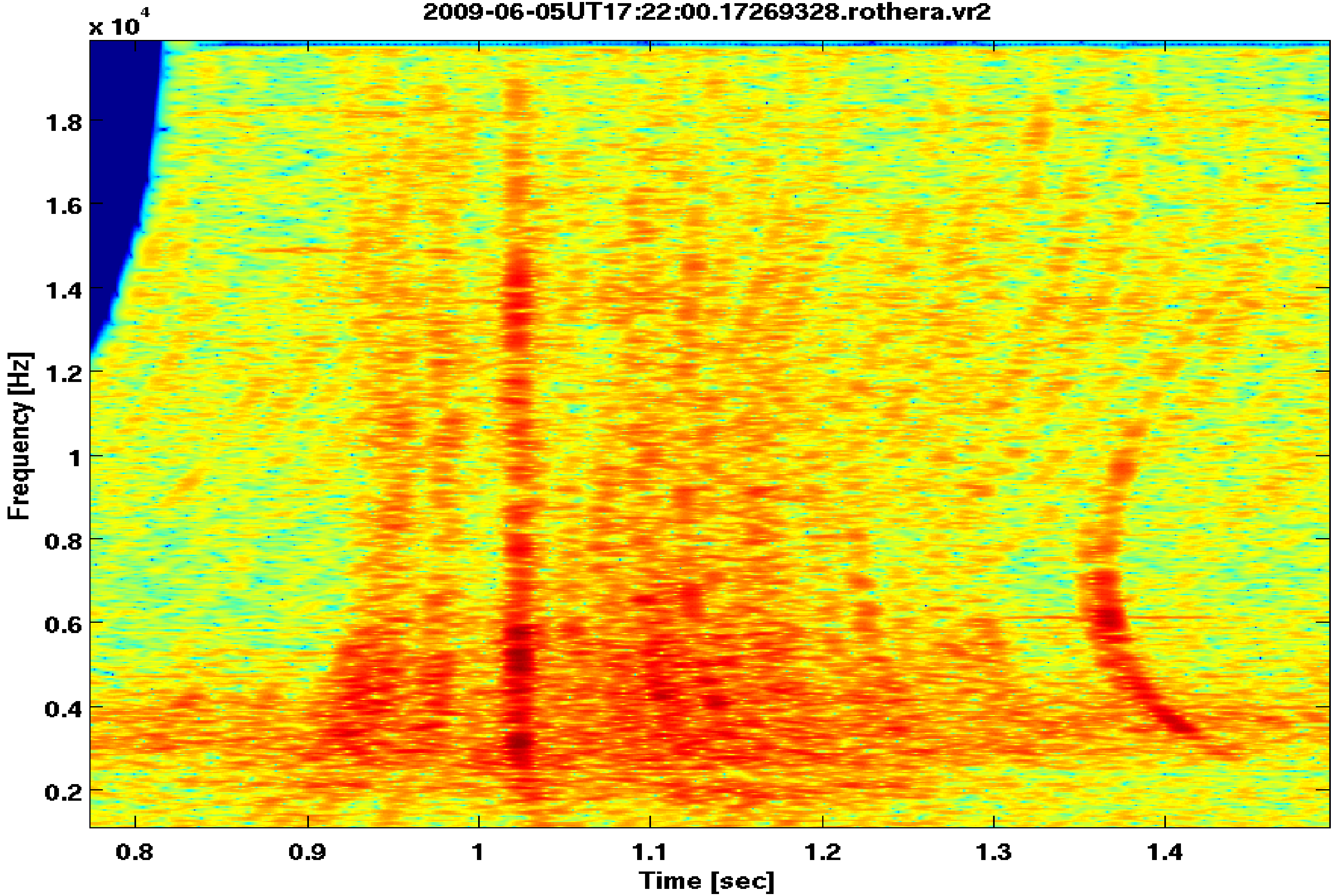

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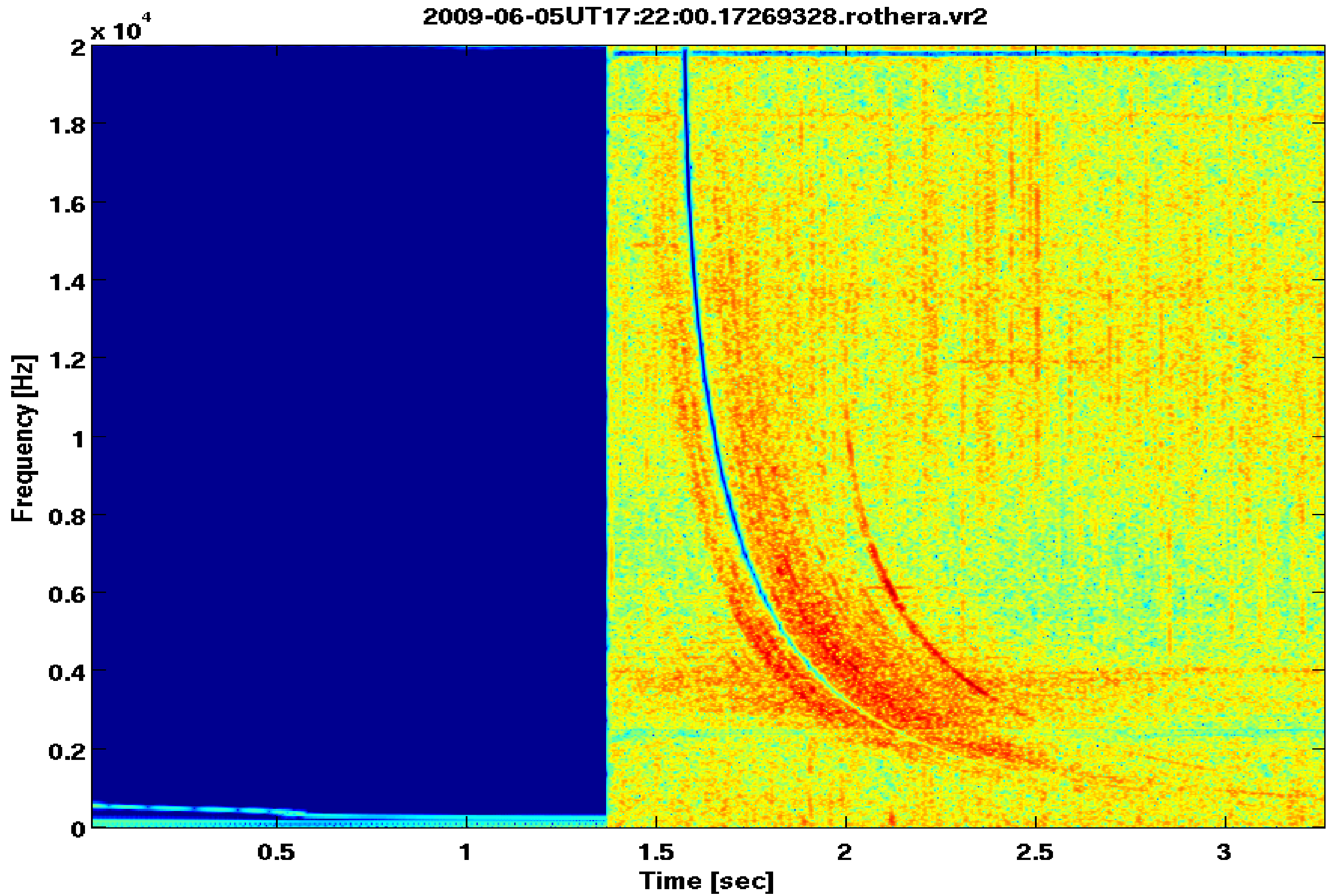

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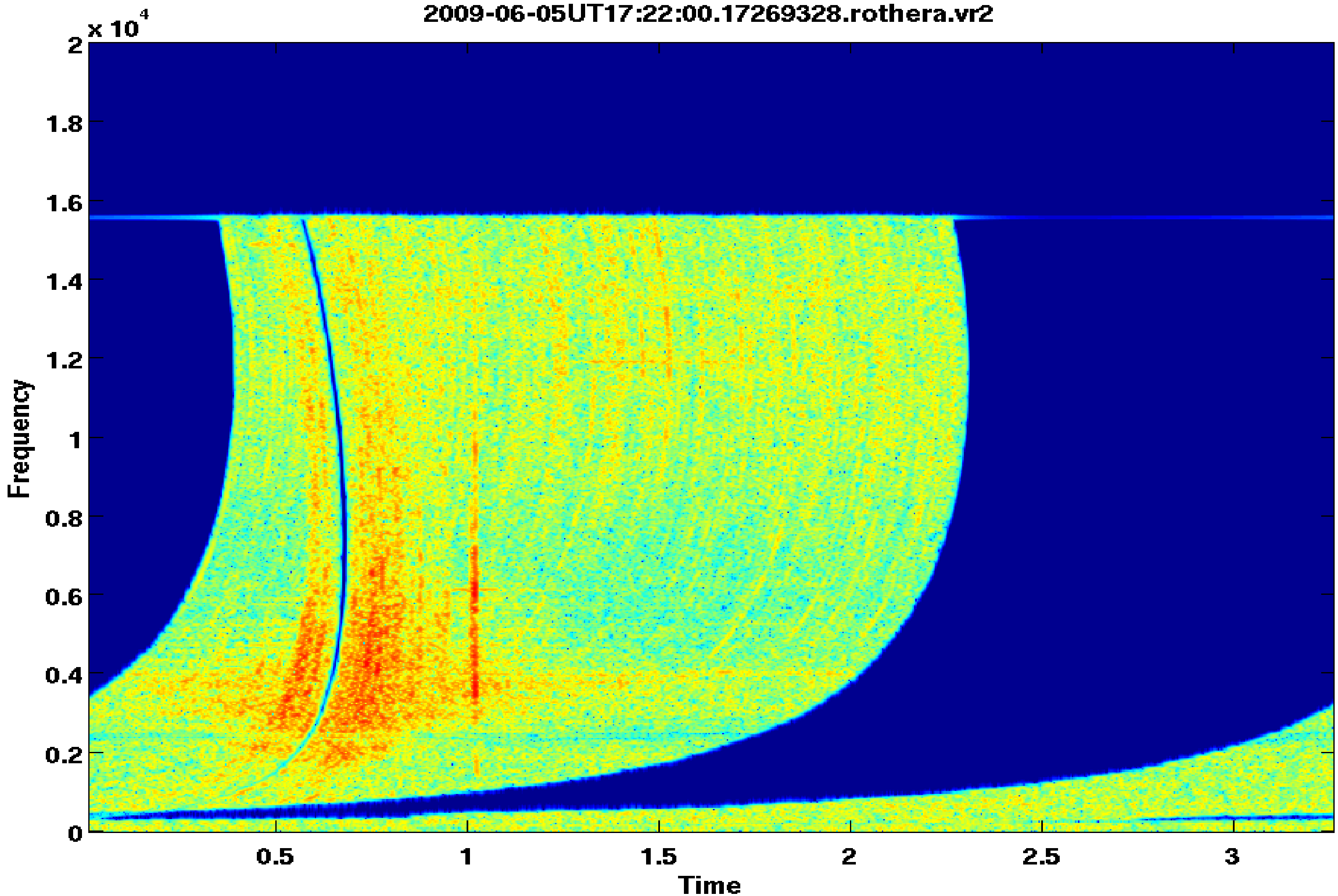

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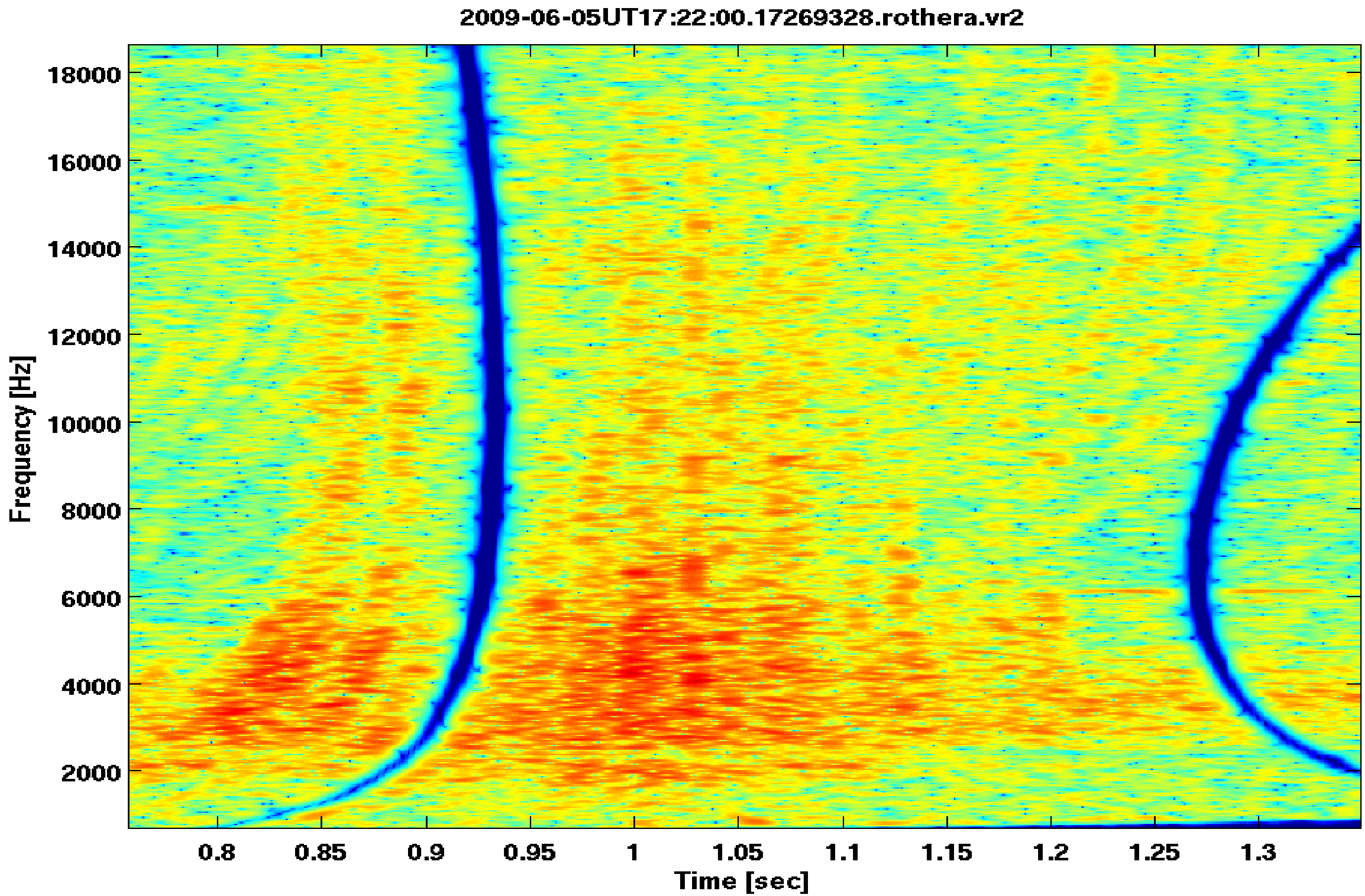

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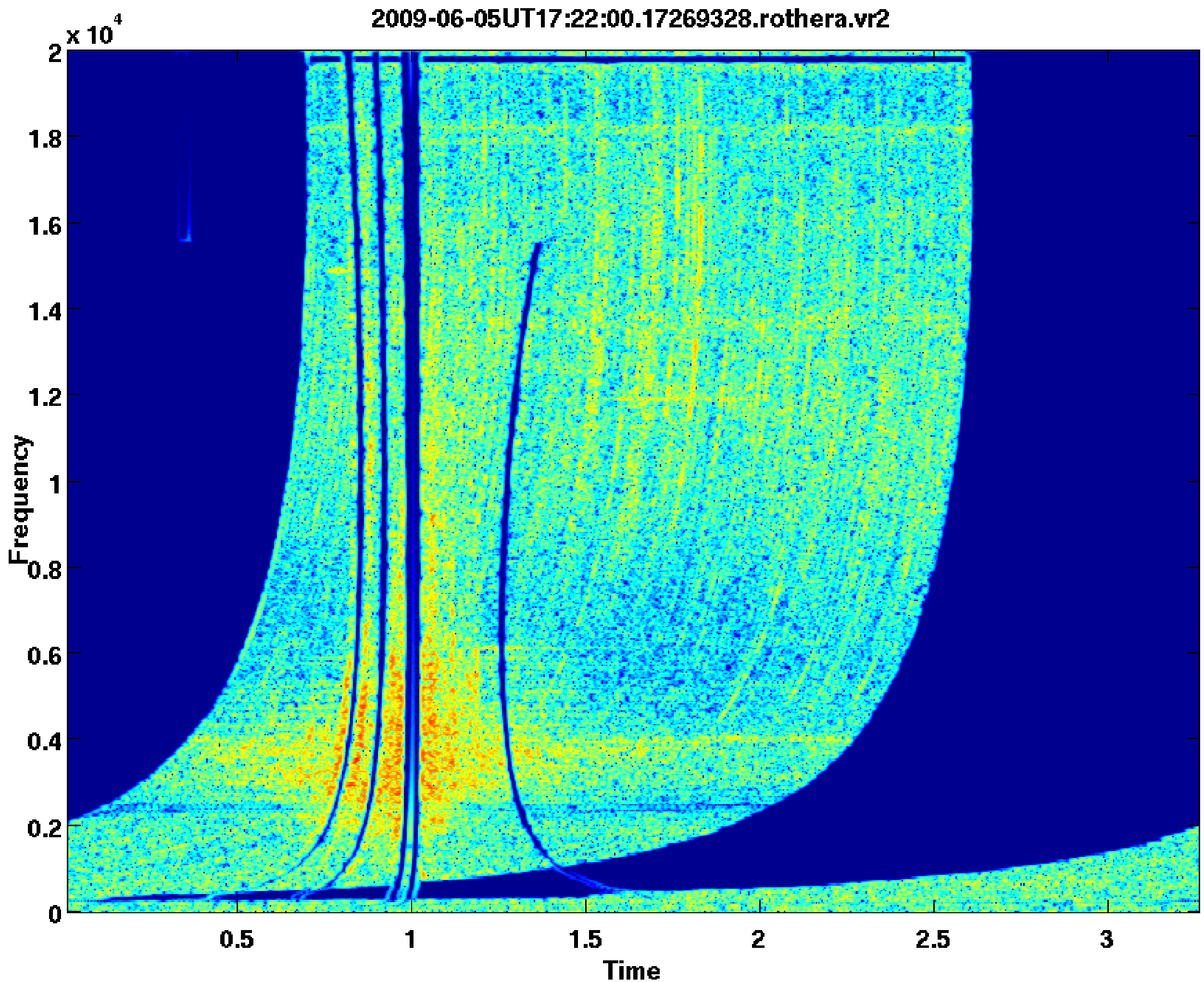

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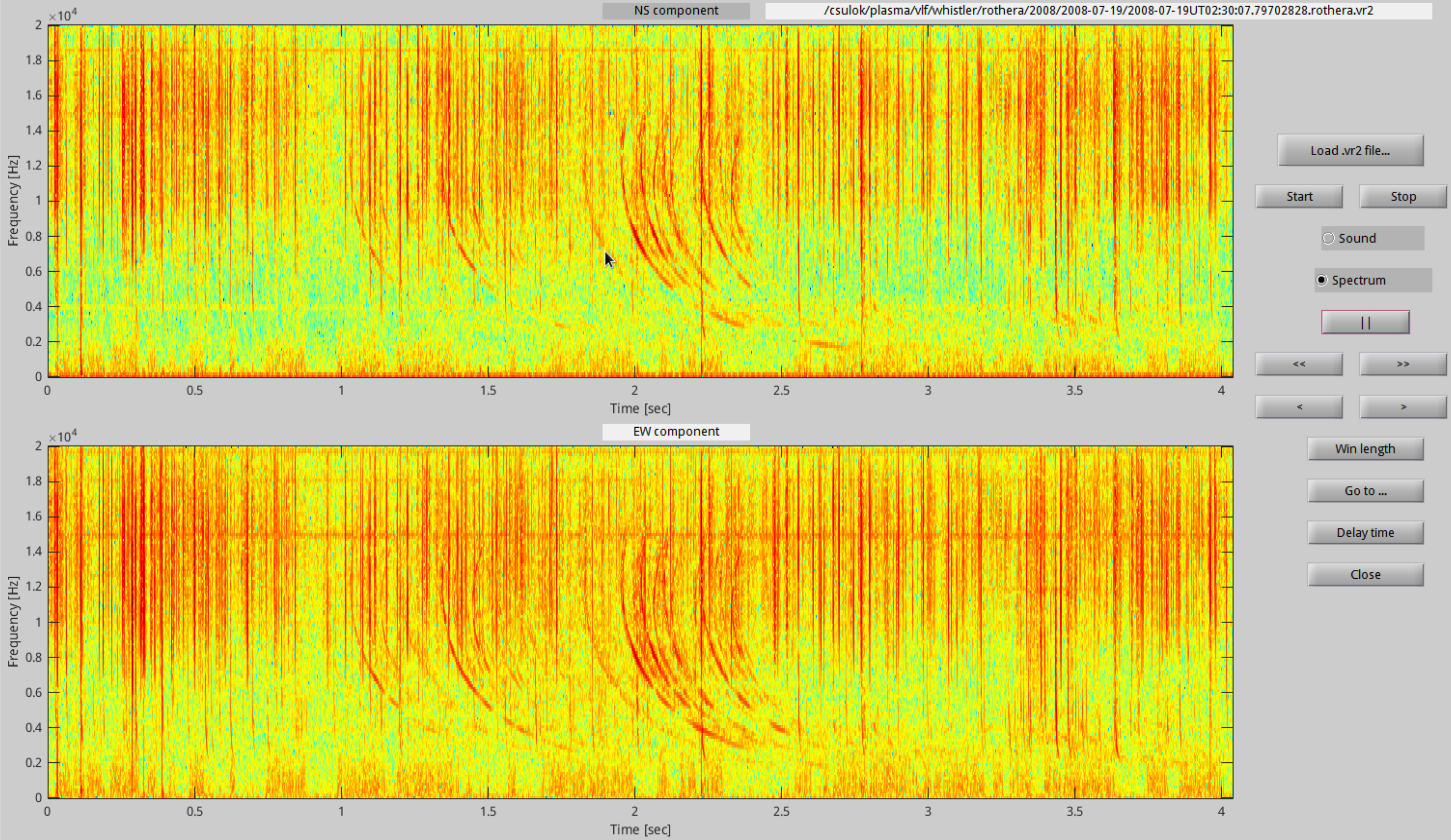

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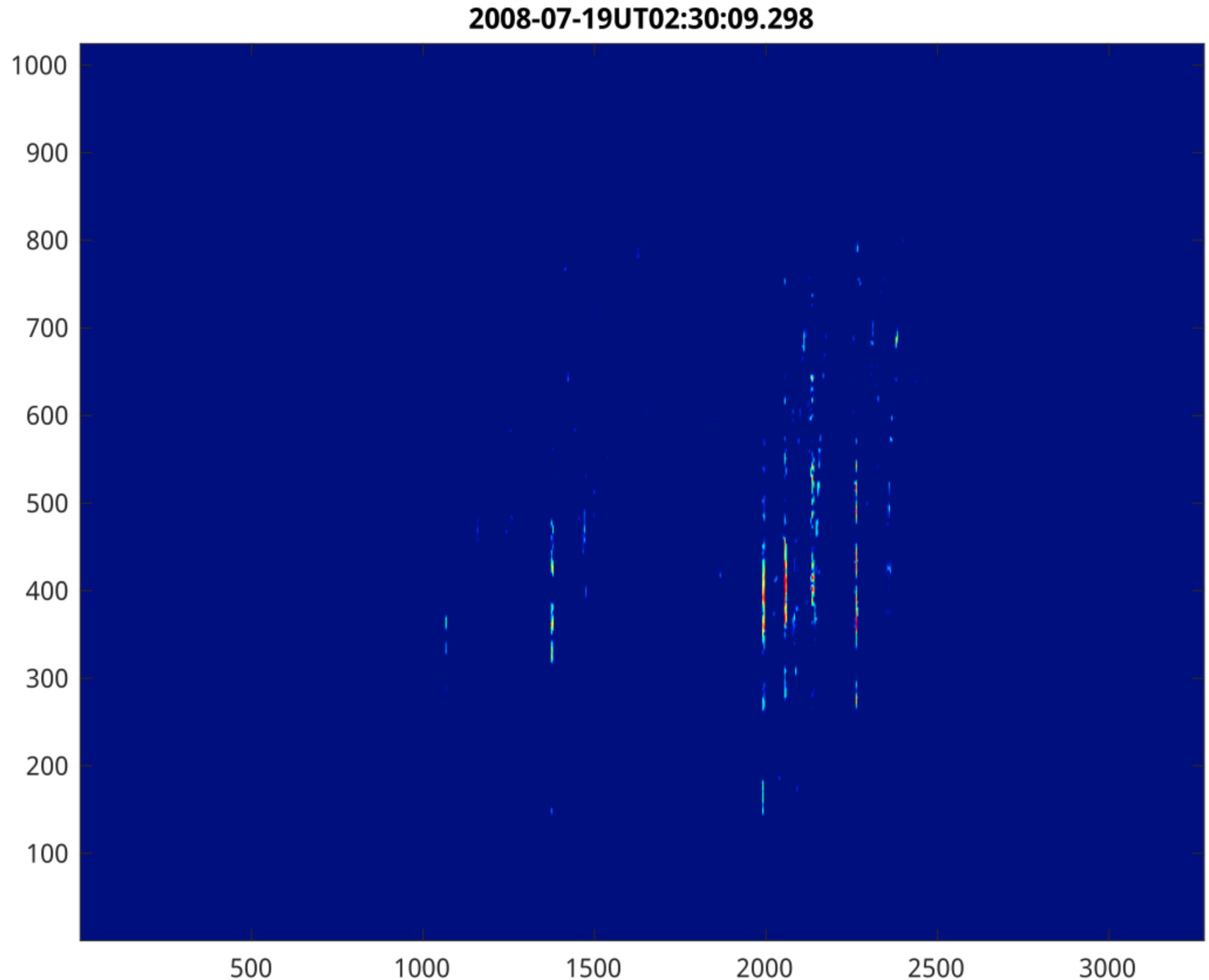
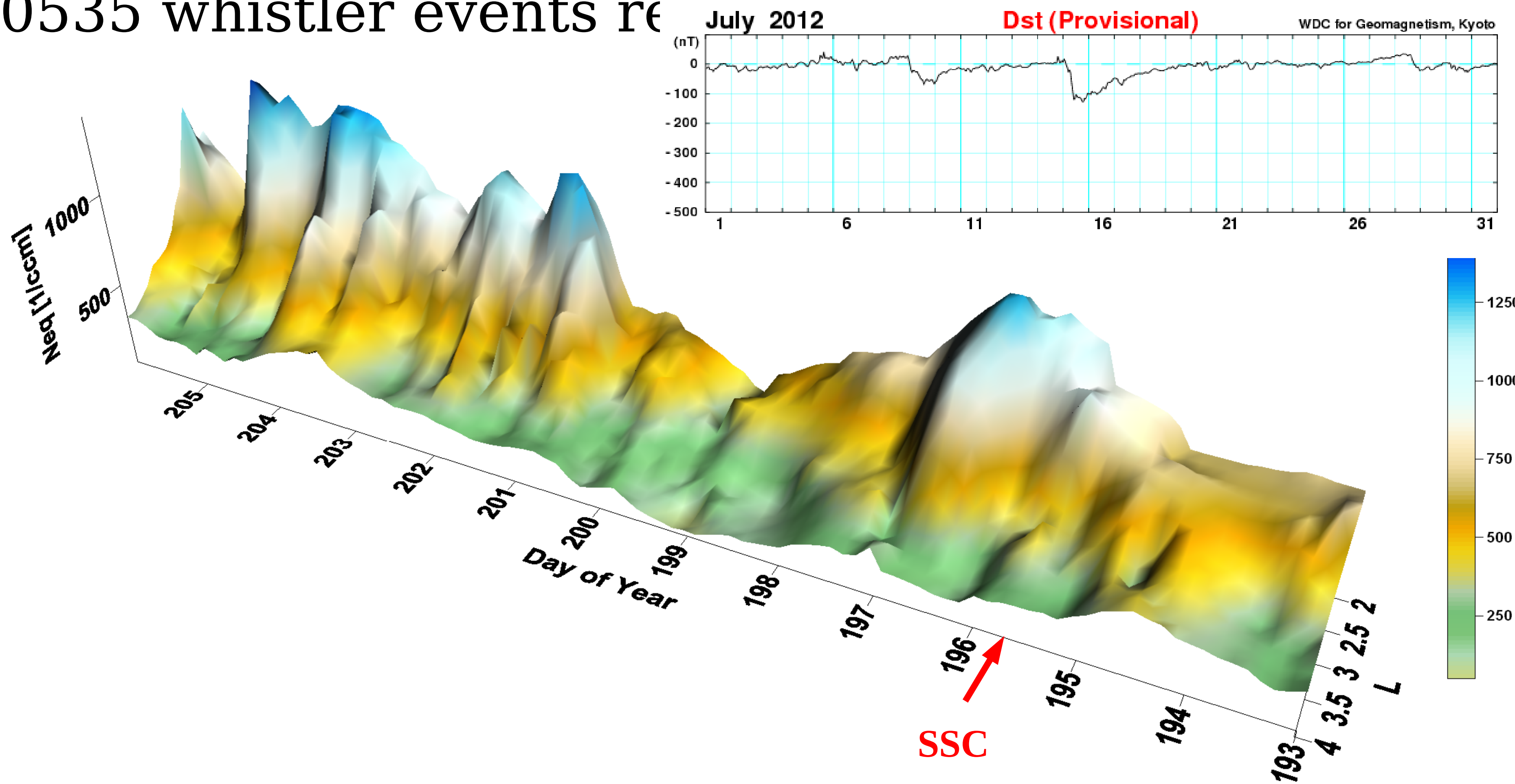


Large scale structure of the plasmasphere during space weather events

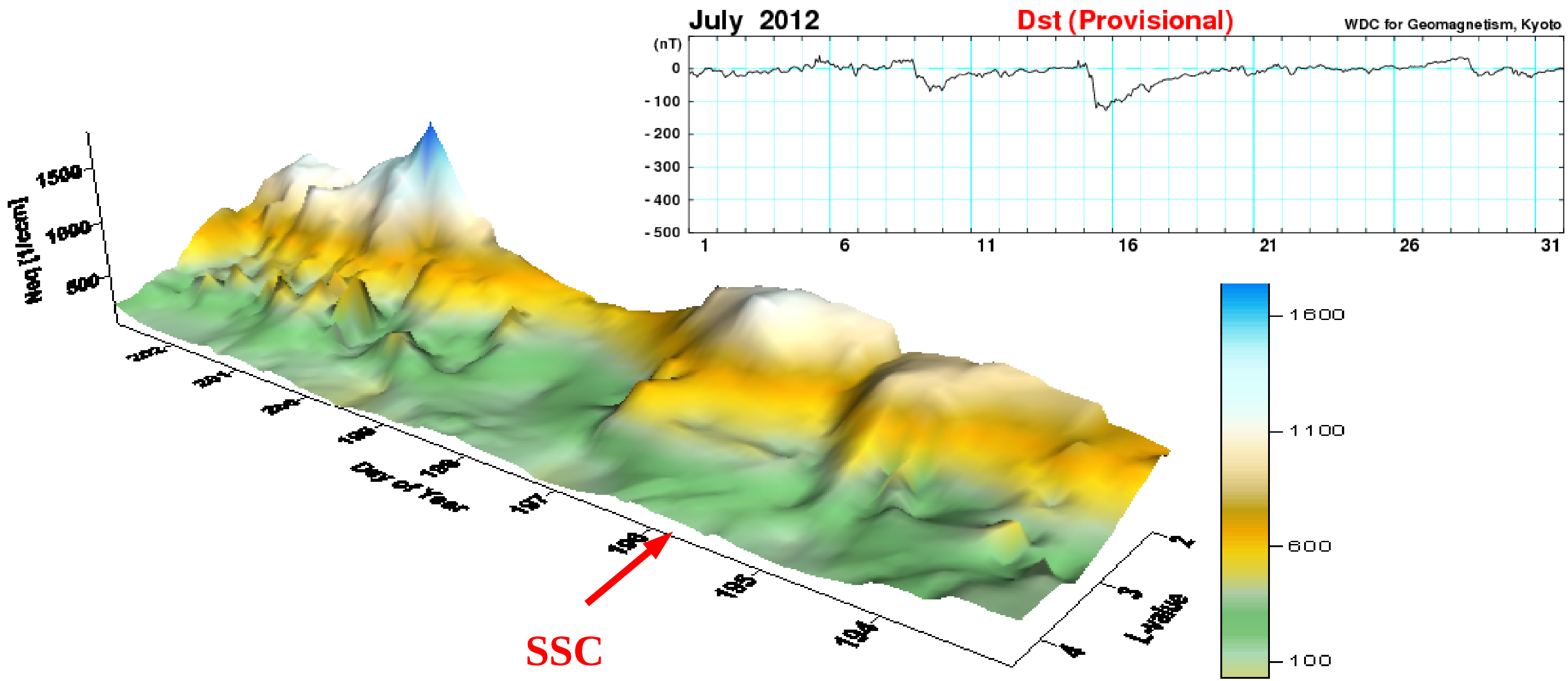
Magnetic Storm on 15 July 2012

10535 whistler events re … a)



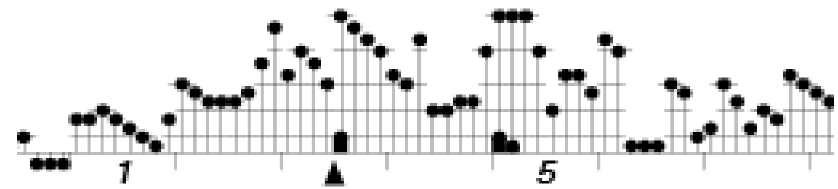
Magnetic Storm on 15 July 2012

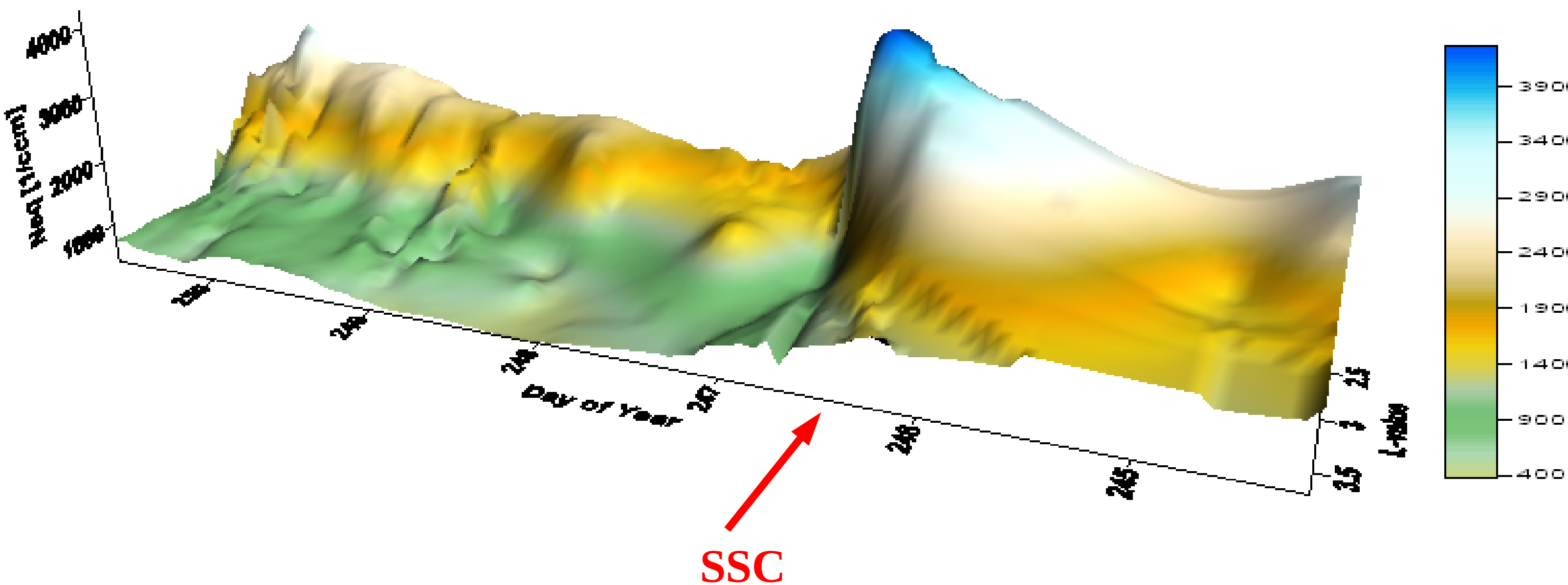
6866 whistler events recorded at Halley (Antarctica)



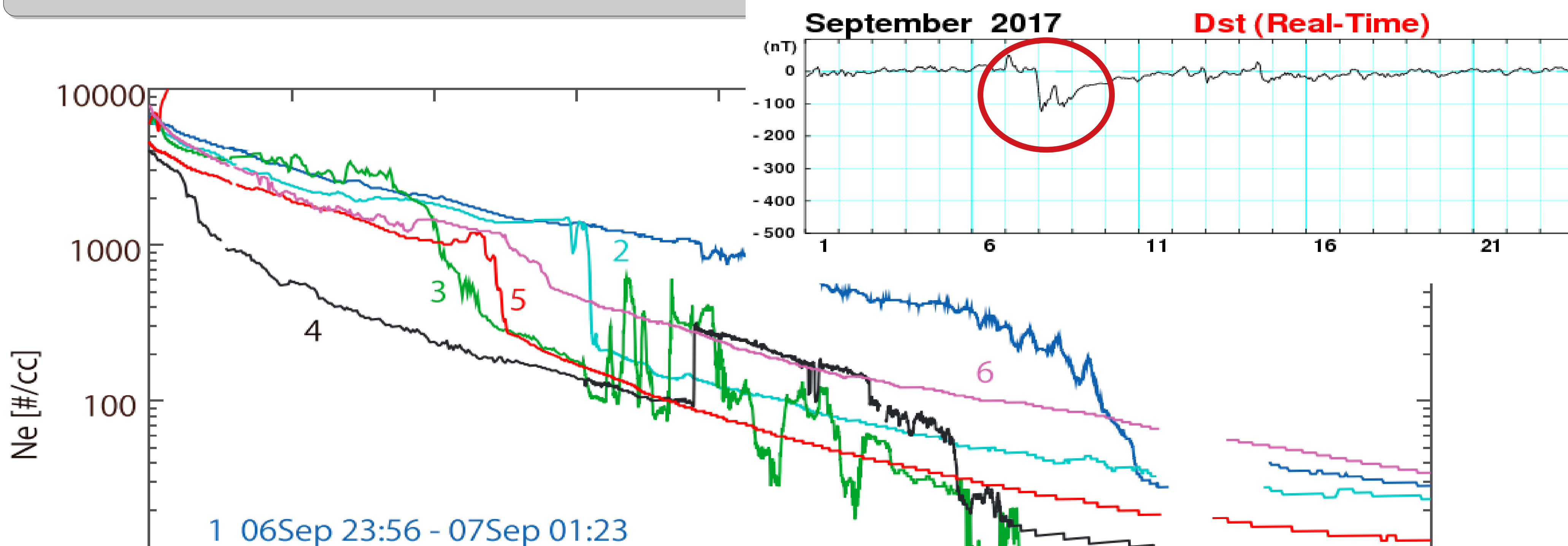
Magnetic Storm on 3 September 2012

1110 whistler events recorded at Karymshina (Kamchatka, Russia)





8-9 September 2017 – *large scale structure of plasmasphere*



phase starts. Surprisingly, almost the whole plasmasphere has been eroded and only a slightly dense area remains in the narrow region of $L \leq 1.7$. The decrease in density, which seems to correspond to the plasmapause, begins at $L = 1.6$ and ends at 1.7 around 13.2 MLT. The smooth shape of this black curve between $L = 1.7$ and 3.4 looks like the density profile of the saturated plasmasphere. However, we will note that the density level is very low. For example, Carpenter and Anderson

8-9 September 2017 – *large scale structure of plasmasphere*

Plasmasphere/plasmapause/plasmatrough and whistlers

- ***whistlers recorded on the ground are propagating in the plasmasphere in density ducts*** *(or at the plasmapause → knee whistlers)*

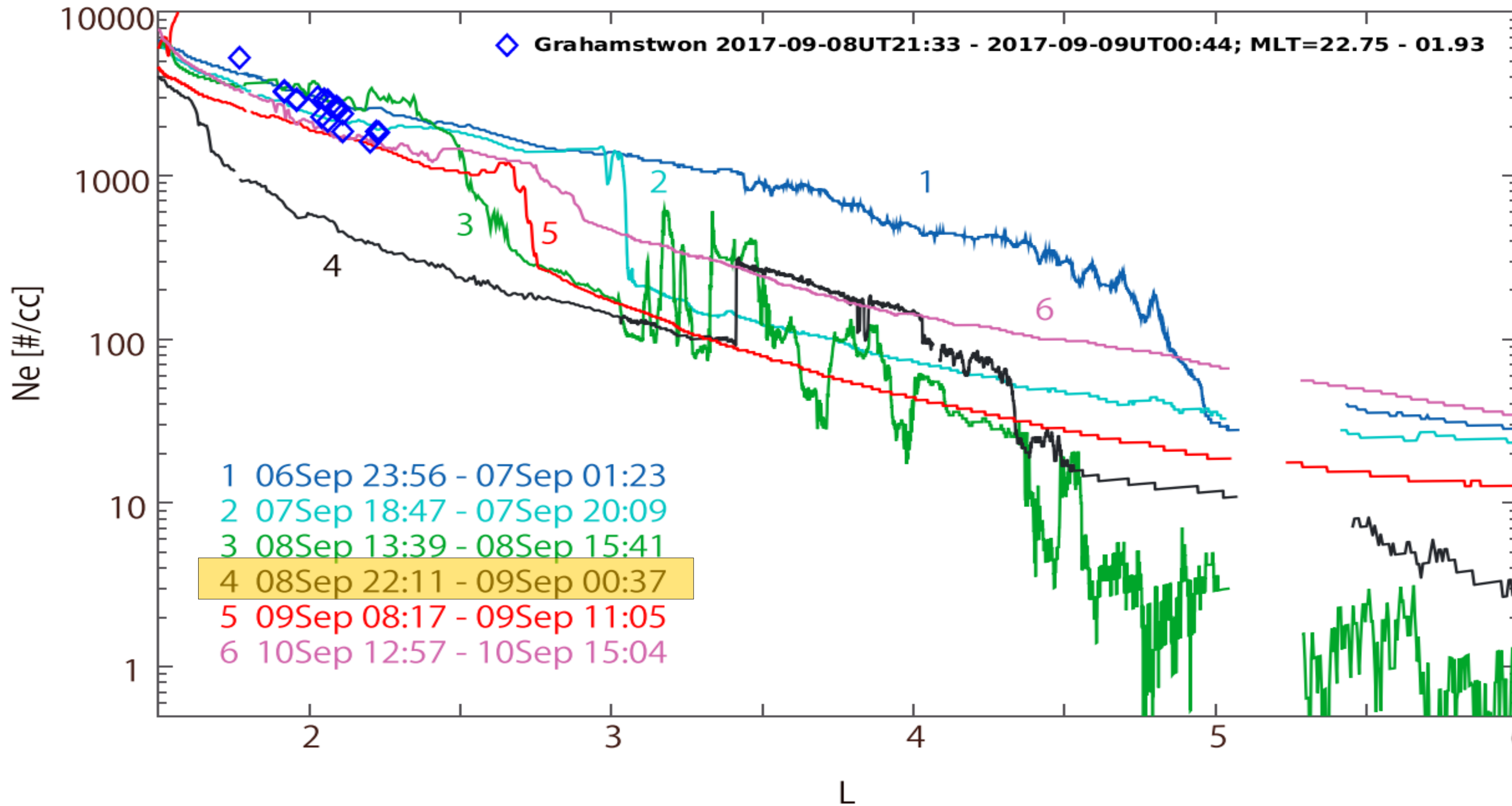
- **8811** whistlers were recorded at Rothera, Antarctica (**L=2.71**) between 21:00UT and 02:00UT on 8-9 September 2017

- **1258** whistlers were recorded at Grahamstown, South Africa (**L=1.81**)between 21:00UT and 02:00UT on 8-9 September 2017

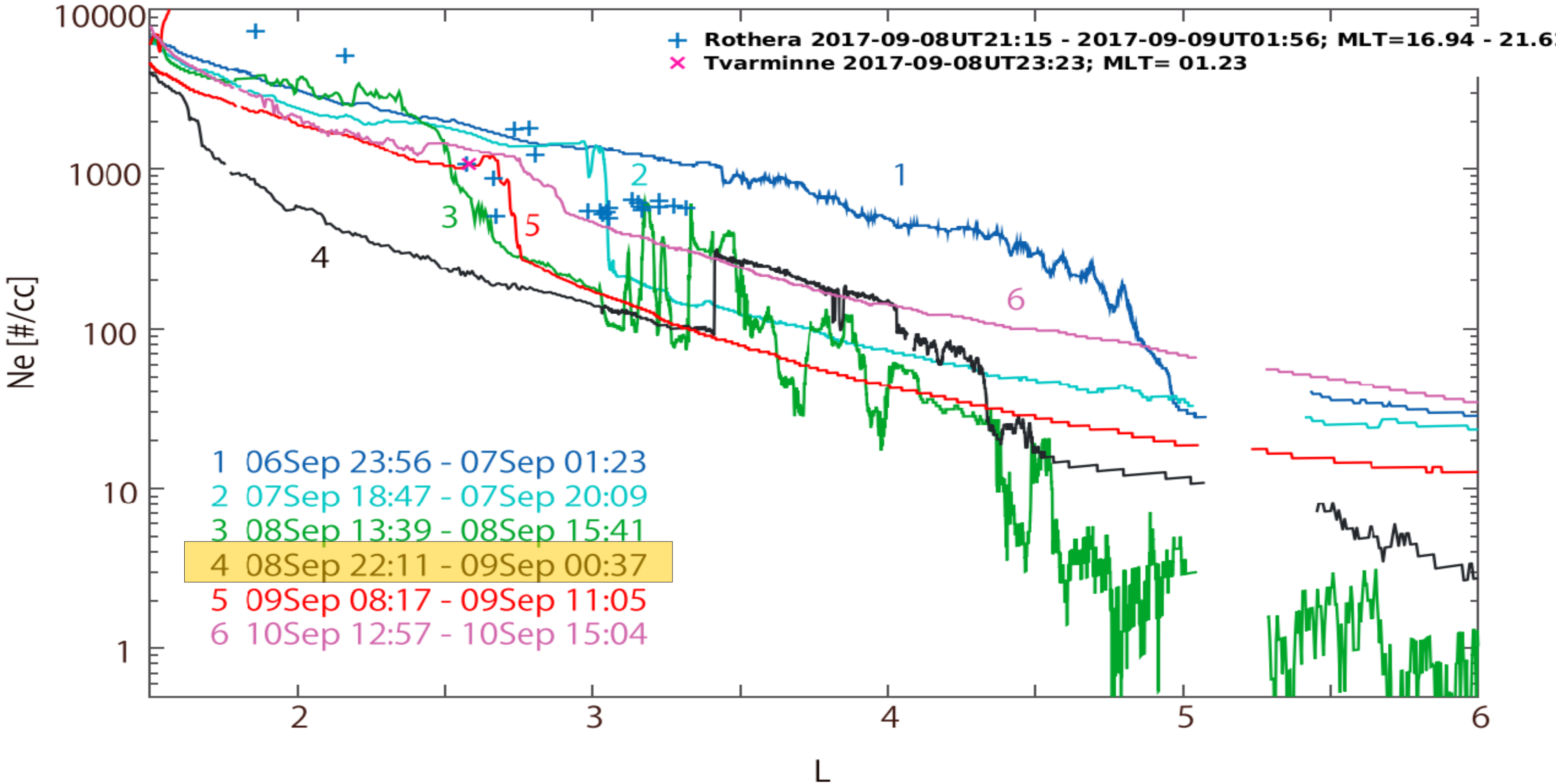
- **55** whistlers were recorded at Karymshina, Kamchatka (**L=2.13**)between 21:00UT and 02:00UT on 8-9 September 2017 *(it is on the Northern Hemisphere)*

These 3 receivers were surely inside the plasmasphere!

8-9 September 2017 – *large scale structure of plasmasphere*

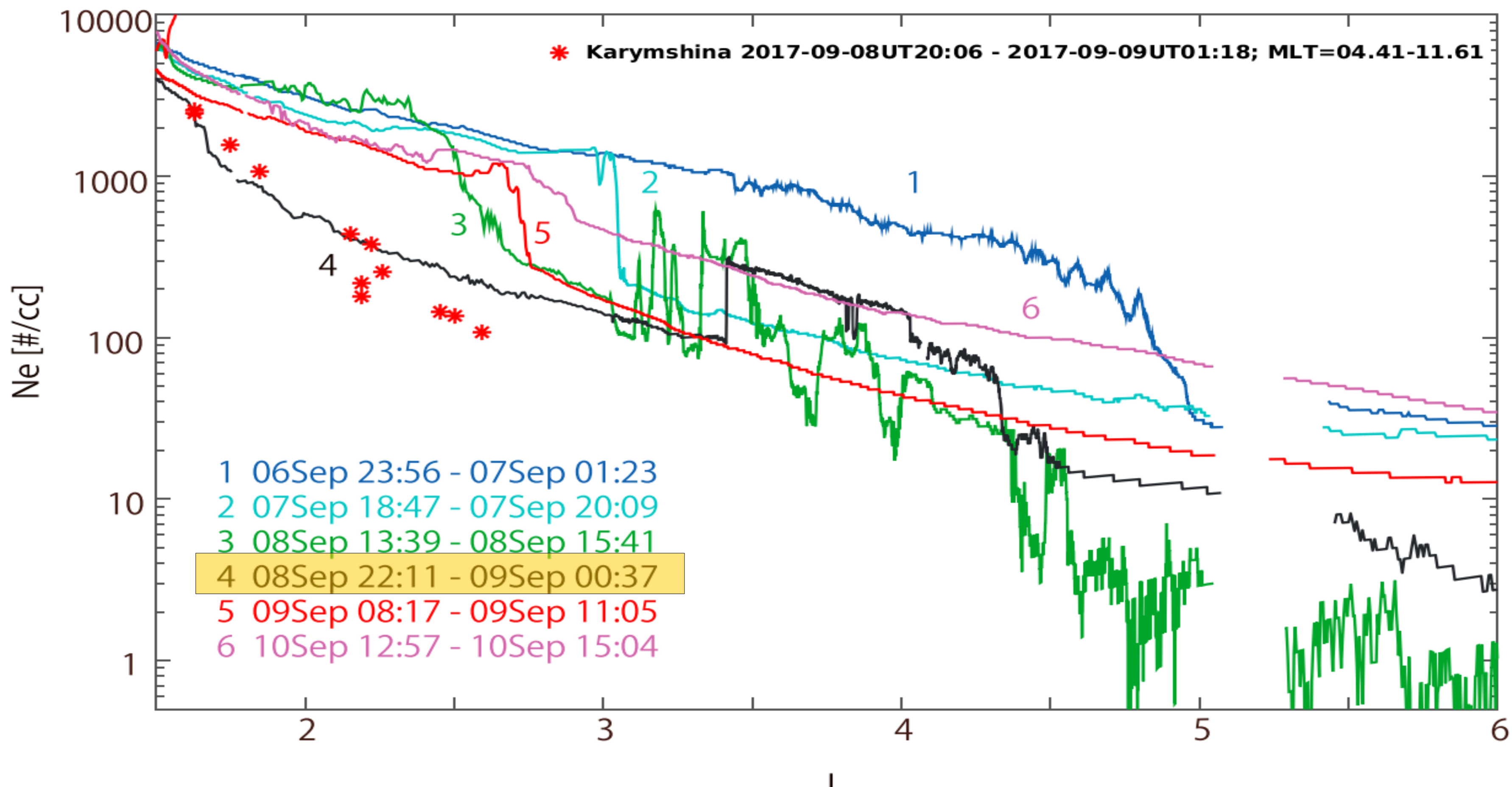


8-9 September 2017 – *large scale structure of plasmasphere*



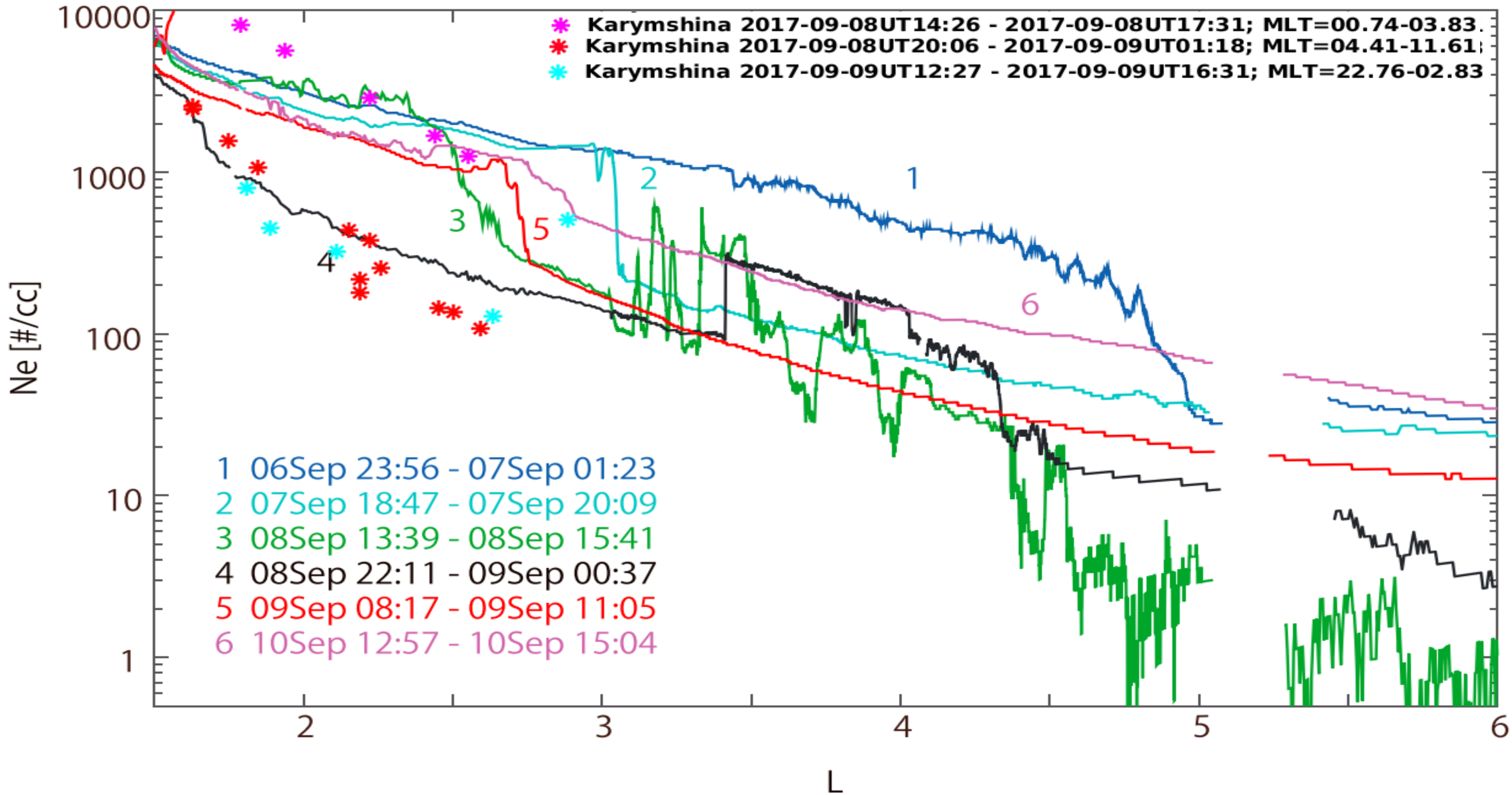
Is something wrong with ARASE density measurements?

8-9 September 2017 – *large scale structure of plasmasphere*

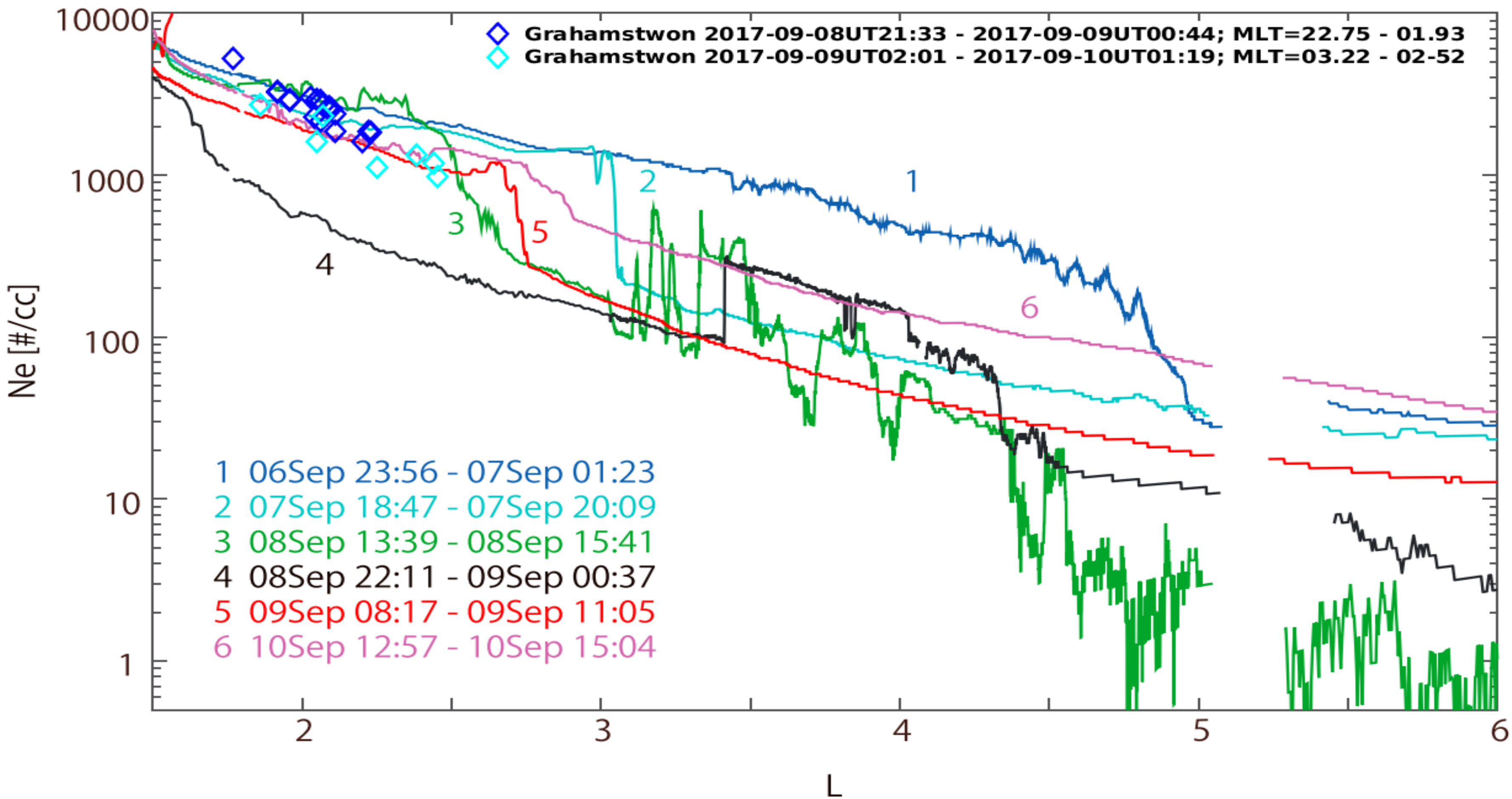


Is something wrong with ARASE density measurements? **NO!**

8-9 September 2017 – *large scale structure of plasmasphere*



8-9 September 2017 – *large scale structure of plasmasphere*



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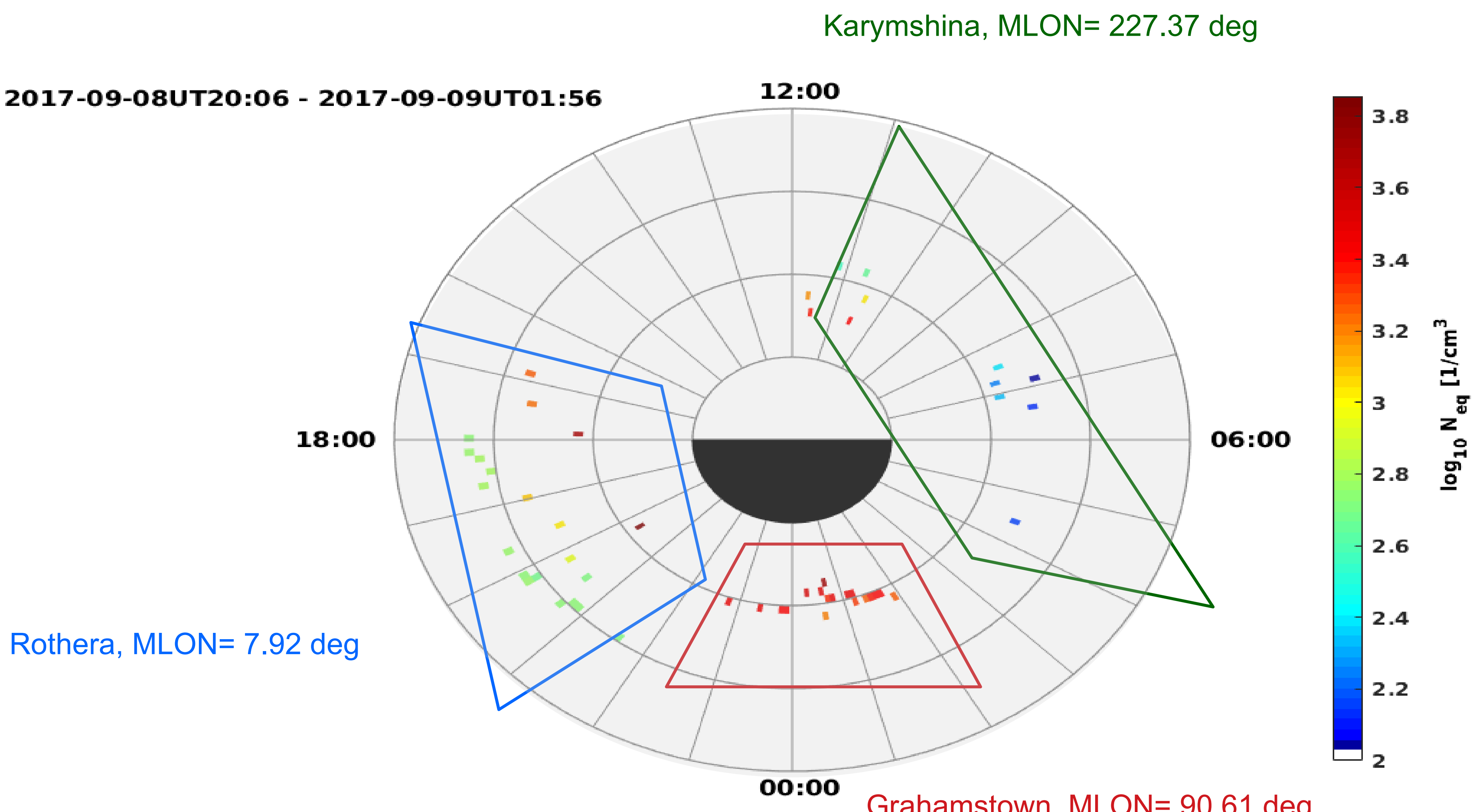

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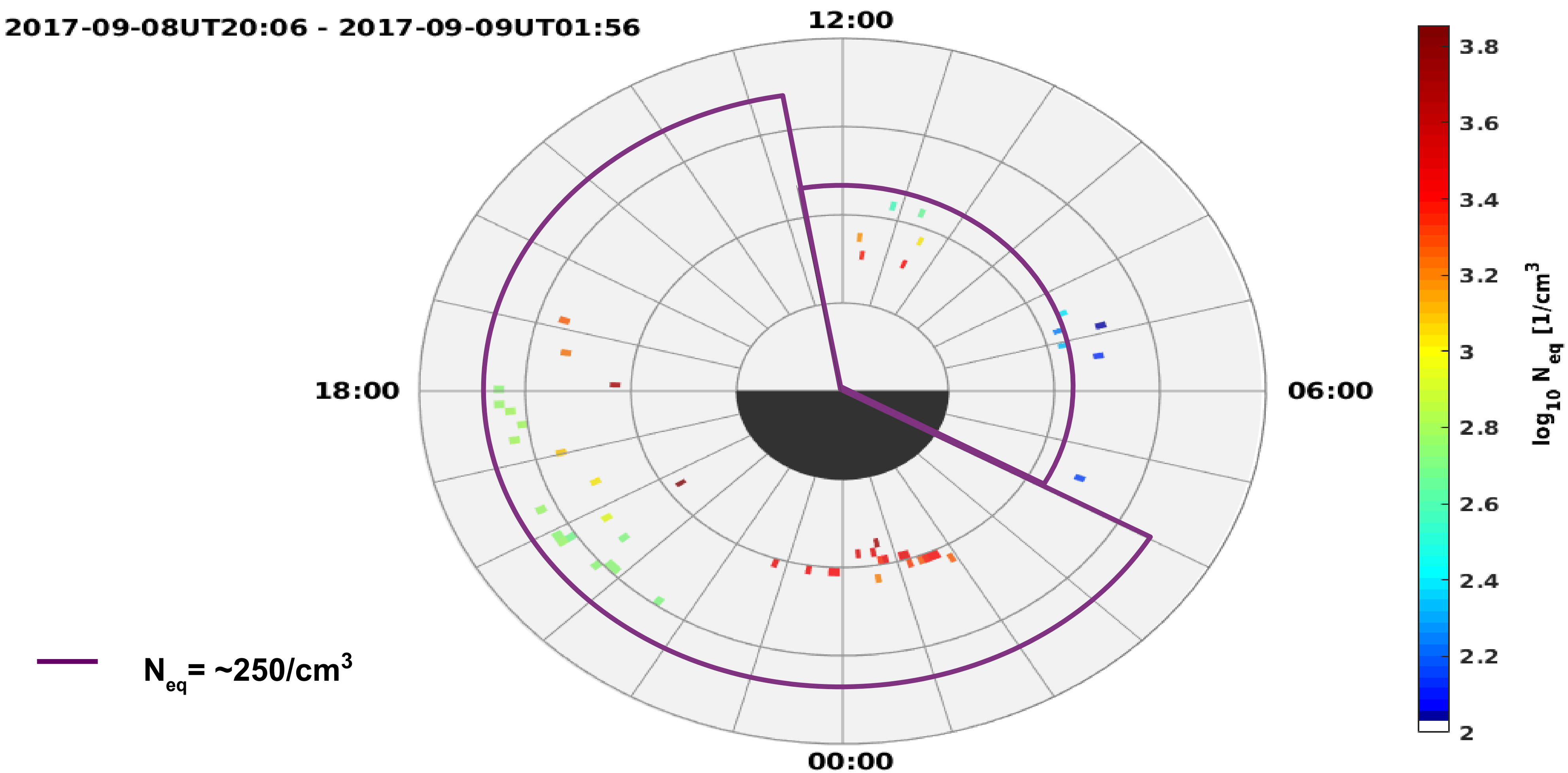
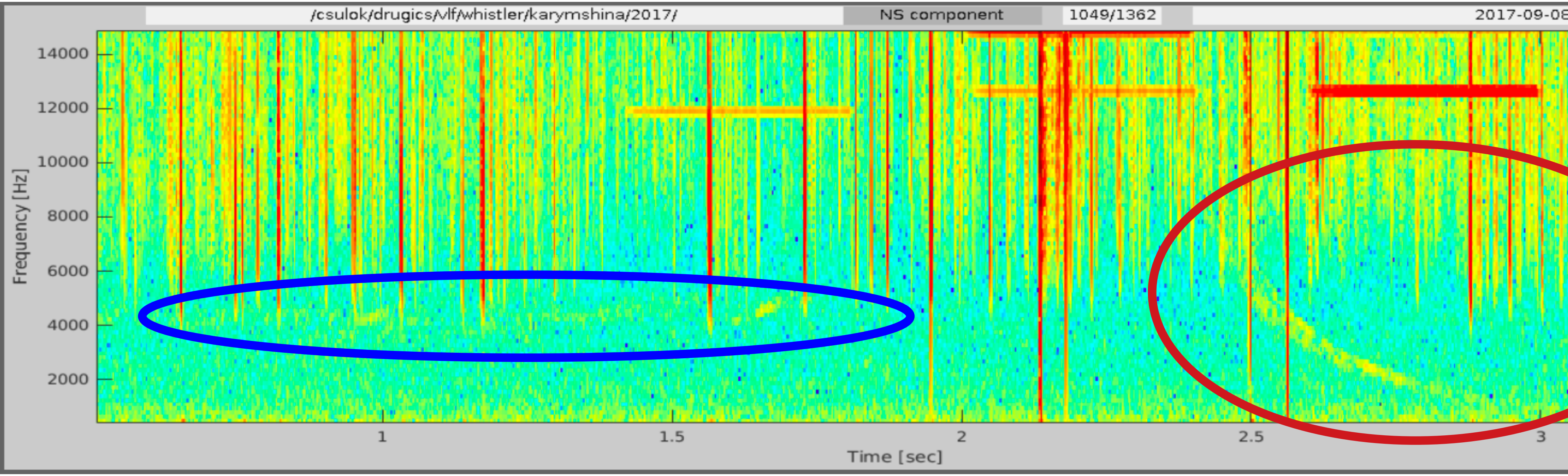


8-9 September 2017 – *large scale structure of plasmasphere* – ***plasmasphere or plasmatrough?***



Whistler and choruses were recorded simultaneously at Karymshina (Kamchatka) at 22:40UT on 8 September 2017

$L=2.13$; $L_{pp}=4.3$

Summary - What are the *whistlers* good for?

1. Infer plasmasphere densities

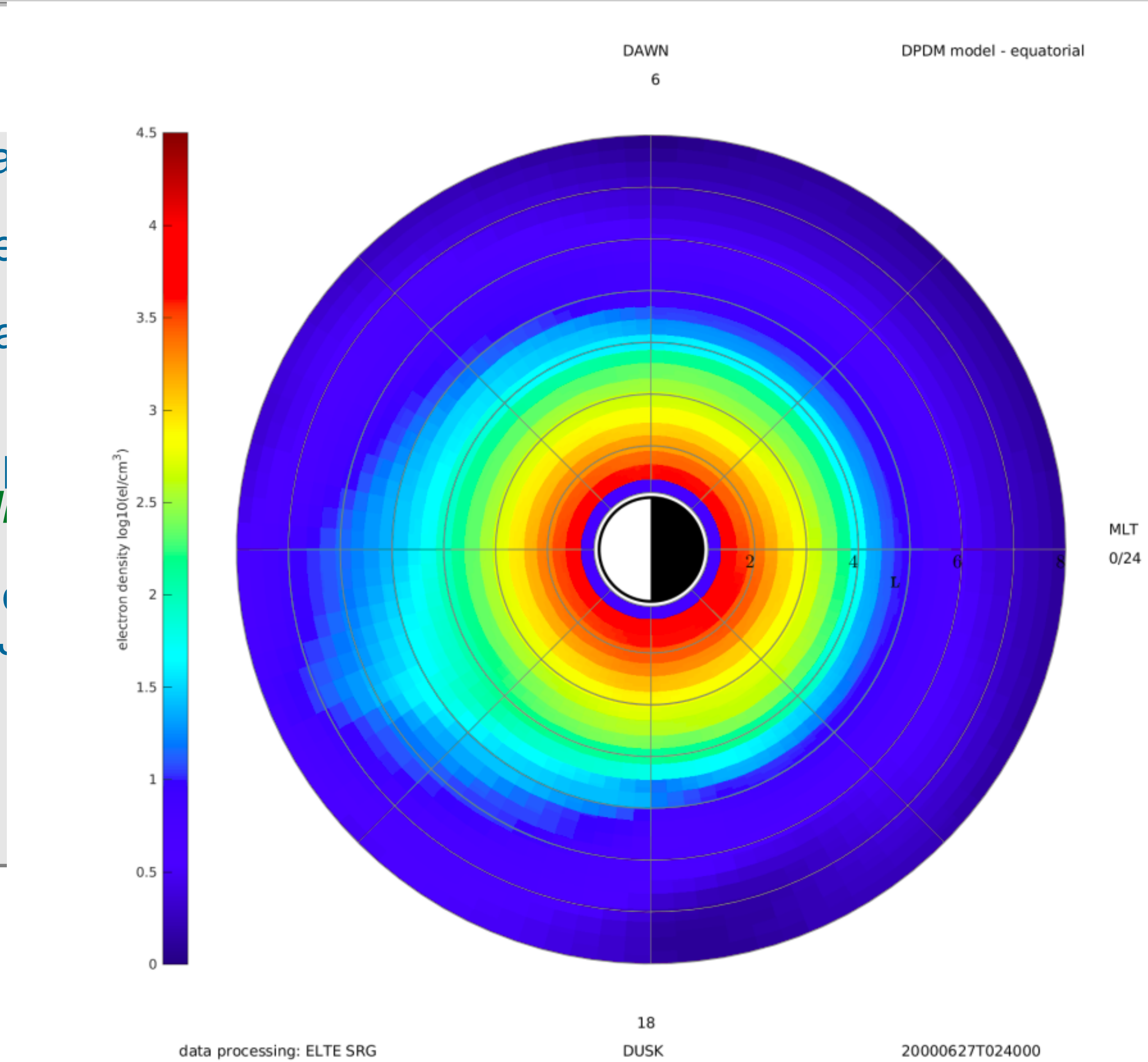
2. Estimate the lower limit of plasmapause

3. Input for Data Assimilative model of the plasmasphere (see Anders Jœrgensen's talk on Friday)

Summary - What are the *whistlers* good for?

1. Infer plasma
2. Estimate the
3. Input for Da… ærgensen's talk on Friday)
4. Use the amp… sured on the ground to derive ***d***

Forecasting … rizon Europe project starts at 1 J



Summary - What are the *whistlers* good for?

1. Inferring plasmasphere densities

2. Estimating the lower limit of plasmapause

3. Input for Data Assimilative model of the plasmasphere (see Anders Jœrgensen's talk on Friday)

4. Use the amplitudes of VLF waves (***whistlers, hisses, choruses***) measured on the ground to derive ***diffusion coefficients*** for Fokker-Planck equation:

   Forecasting of Actionable Radiation Belt Scenarios (**FARBES**): a EU Horizon Europe project starts at 1 January 2023

Summary - What are the *whistlers* good for?

Forecast in Space Weather modeling mostly ignore the fact everything is driven by the sun, that is basically unpredictable. Propagating observed solar dynamics to Earth is questionable, it depends on models whose boundary conditions we are incapable of constraining. We are limited to data at L1, giving a one hour lead time and neural net type forecasts of controlling parameters (e.g. Kp) that govern the physics of our best models.

Nowcasts are better: advanced data assimilation techniques with physics based models show great fidelity in reproducing the real radiation belt (RB) environment. Operational use of such Nowcasts is limited by lack of high quality real-time data beyond GEOS.

The FARBES project is different: it limits its ambition to simple, achievable prediction goals that are of utility to satellite operators, while avoiding the pitfalls of past projects. We hold that while it may be impossible to accurately predict the break of a space weather event, once an event has started we have the tools to predict subsequent behavior and to update our predictions during the event. While we may not be able to globally predict in detail the subsequent dynamic behavior, we can provide actionable forecasts for satellite operators on a few key event characteristics:

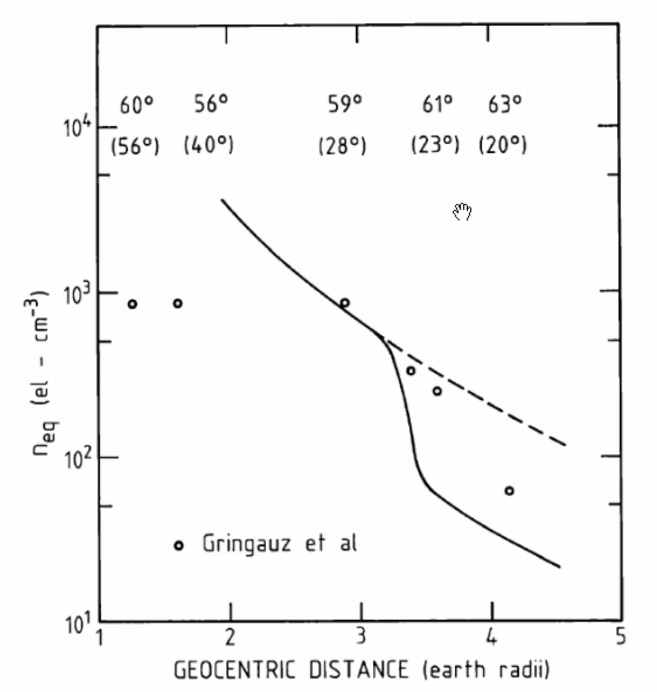
a. Time to most severe environment
b. Most severe Flux reached
c. Time to the end of event

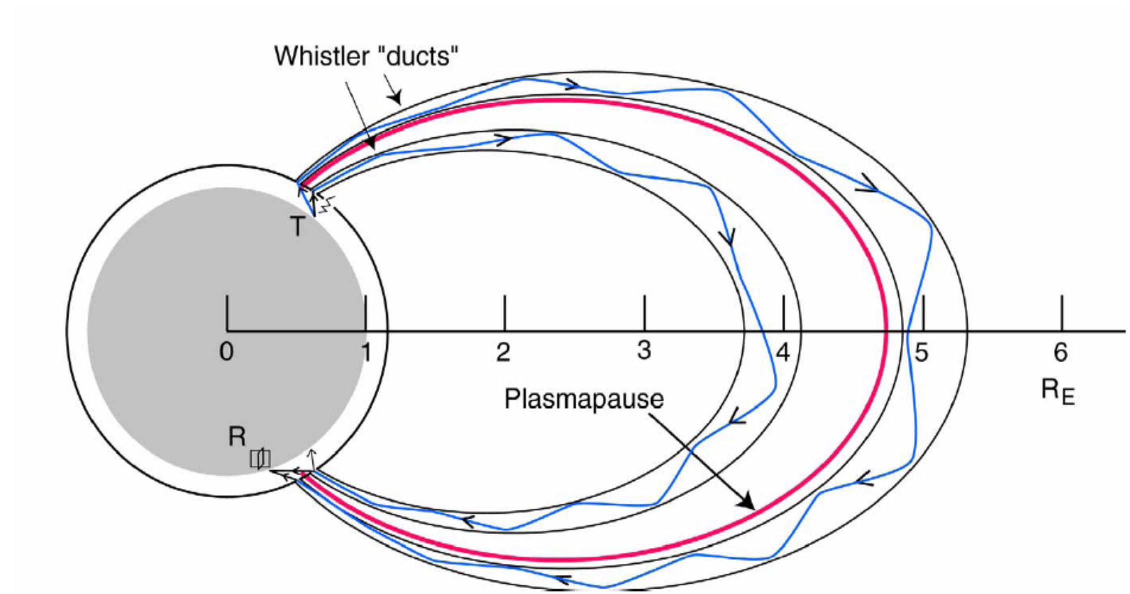
These characteristics were deemed most useful by spacecraft operator

Instead of conclusions – a checkpoint

Estimate, which one propagates faster (arrives earlier): a knee whistler or a nearby plasmaspheric whistler?

$$T_m(f) = \frac{1}{2c} \int_s \frac{f_p f_H}{f^{1/2}(f_H - f)^{3/2}} ds$$





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