Low Frequency Wave Measurements Onboard C/NOFS During the 2008-2009 Solar Minimum

- implications for lightning studies -

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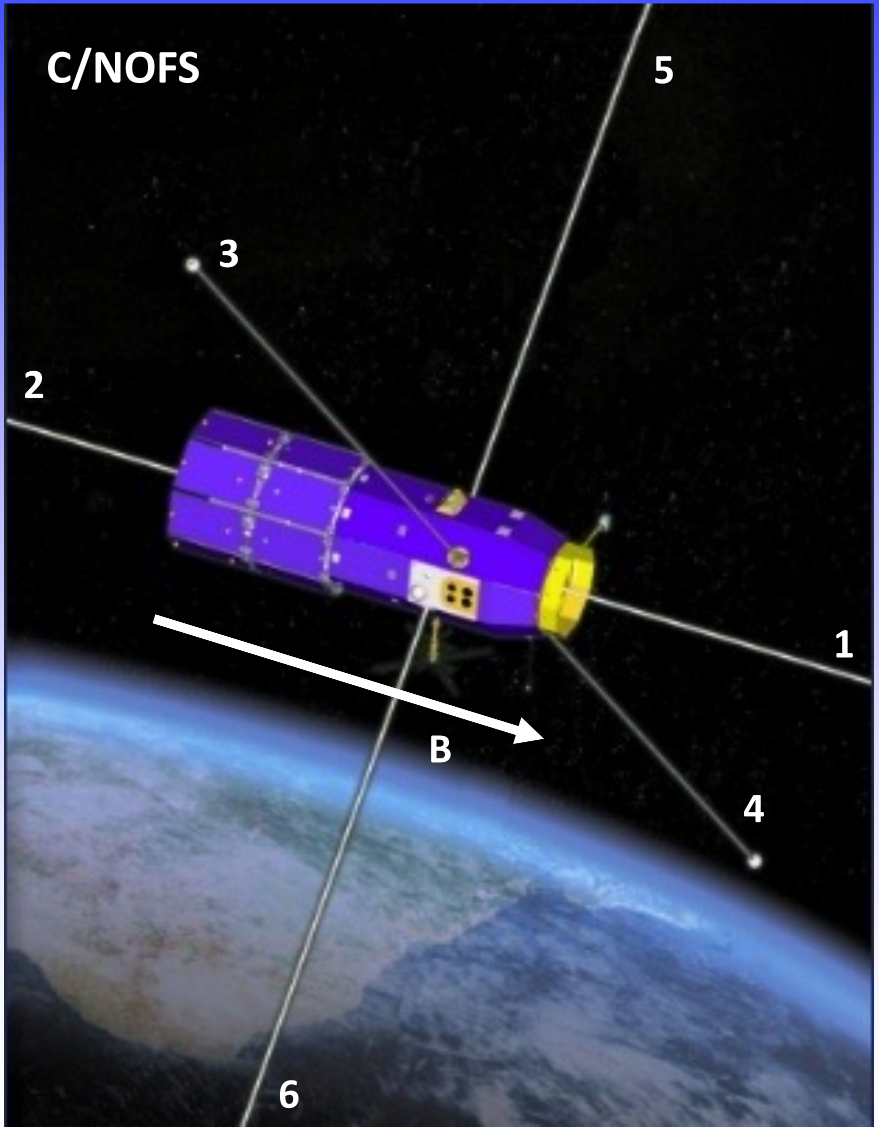
Outline

- **C/NOFS (Communications/Navigation Outage Forecasting System) satellite**
  - **VEFI measurements: sensitivity and operating modes**
- **Extremely Low Frequency (ELF) electric field measurements**
  - Schumann Resonance (SR)
  - Ionospheric Alfvén Resonator (IAR)
- **SR and IAR modeling - consequences for tropospheric-ionospheric coupling mechanisms**
- **Relevance for lightning studies**
  - Correlation between Communications/Navigation Outage Forecasting System (C/NOFS) satellite and ground based measurements
- **Summary**

Vector Electric Field Instrument (VEFI)



VEFI – includes 3 electric field dual probes to perform low frequency measurements

Boom size: 10 m
Dipole effective length: ~ 20 m
Sampling: 512 s^{-1}
Sensitivity: ~10 $nVm^{-1}Hz^{-1/2}$ (ELF range)
E12 is 'parallel' to B
E34, E56 are 'perpendicular' to B

Altitude: 400-850 km
Inclination: 13°
Orbit period: ~97 min

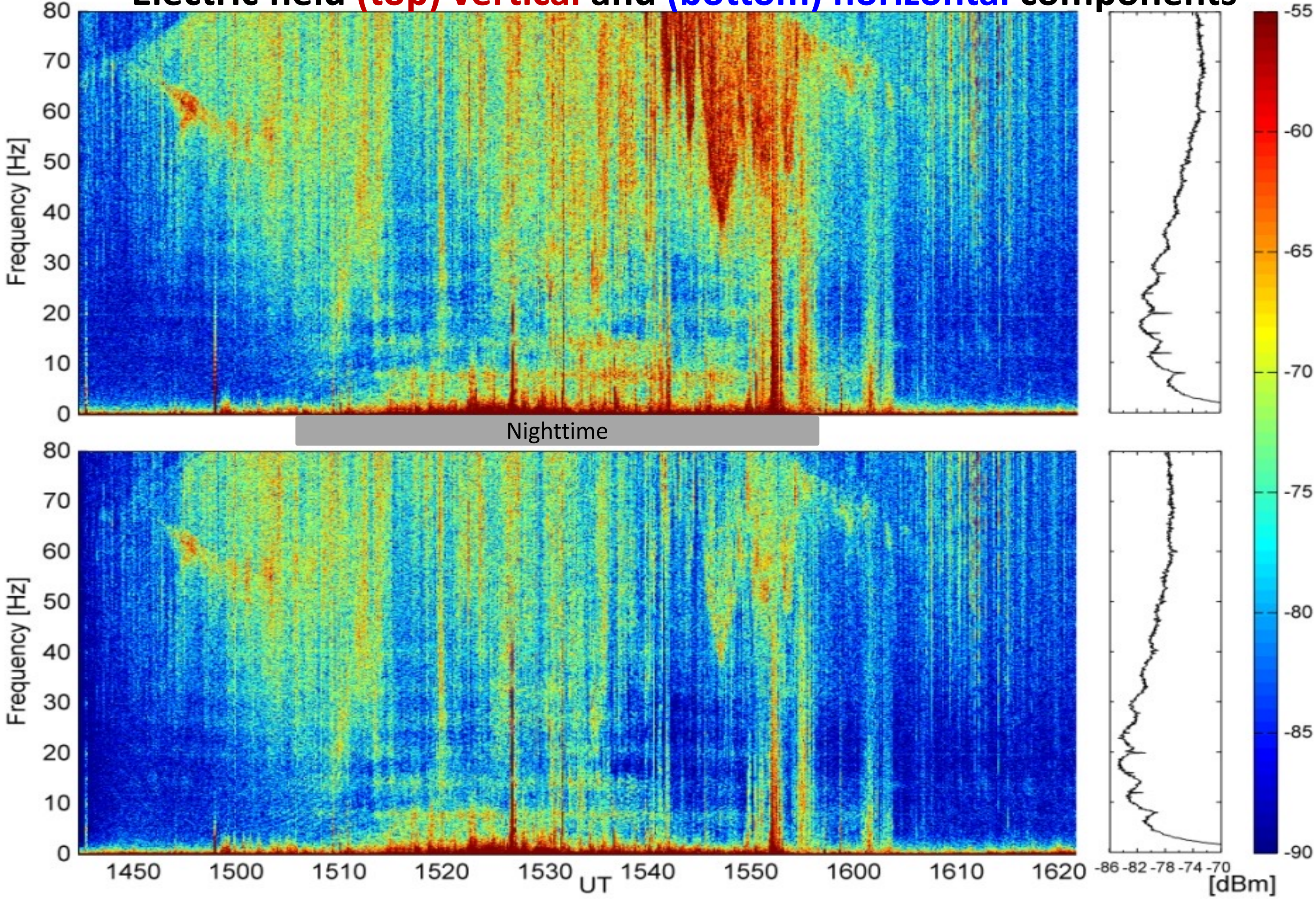
Concerning VEFI ELF measurements, only E34 and E56 waveforms are available in a regular basis

VEFI also includes two optical lightning detectors

Schumann Resonance Measurements

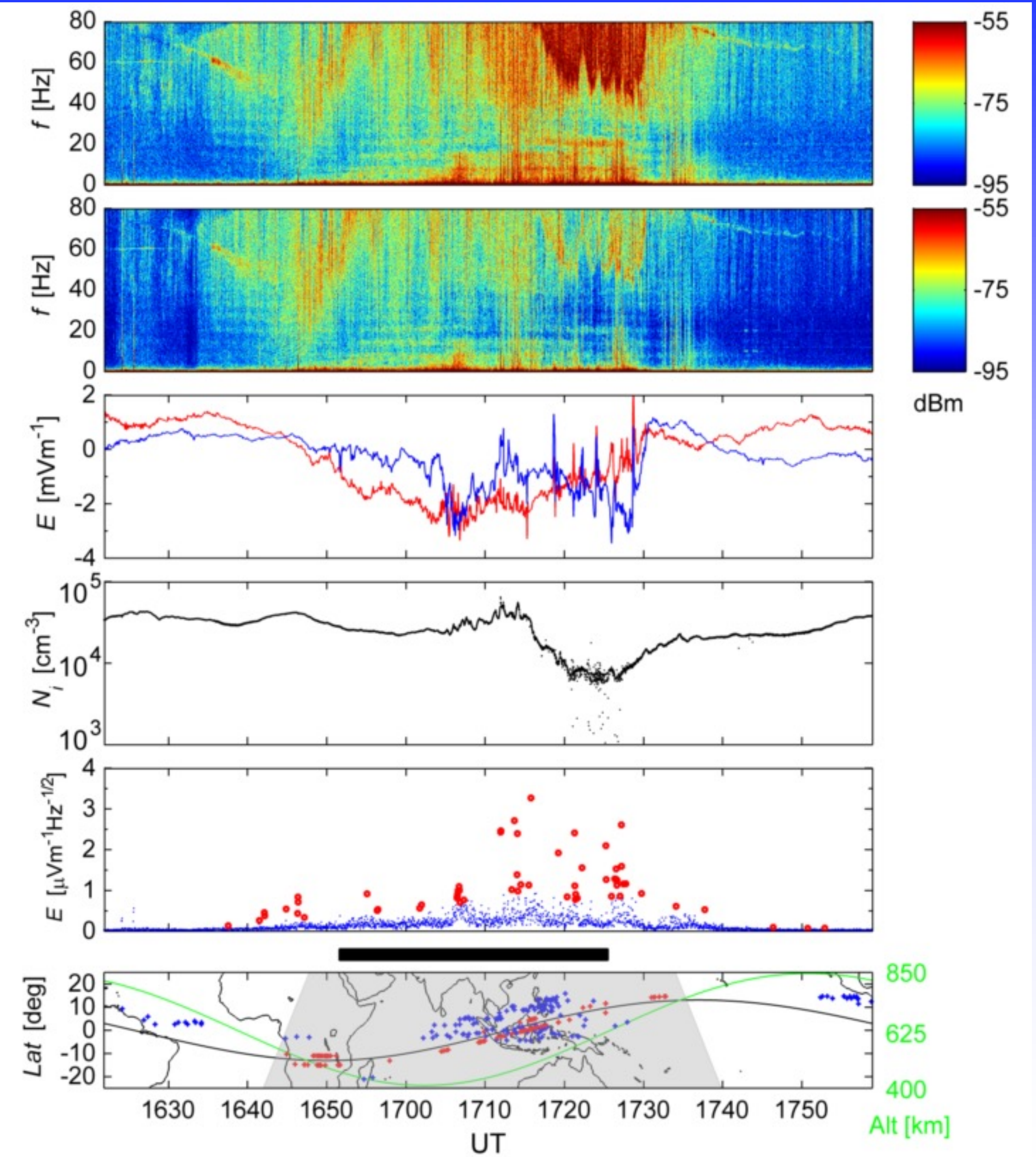
Orbit 666, 31 May 2008

Electric field (top) vertical and (bottom) horizontal components



Schumann Resonance – a Global Picture

Orbit 667, 31 May 2008



Meridional

Zonal

Meridional
Zonal

Ion density (IVM)

1st Schumann mode:
||E|| < mean+3σ
||E|| > mean+3σ

Lightning:
LD (C/NOFS)
WWLLN

Schumann Resonance – a Global Picture

• Models predicted that Schumann resonances should not be detected from space (the upper boundary of the cavity would be a perfect reflector at about ~100 km altitude);

• VEFI detected up to 10 peaks; the frequencies are corroborated by ground measurements;

• Leakage mechanism is still uncertain (waves are possibly propagating in the ordinary or extraordinary mode, i.e., wave vector perpendicular to the geomagnetic field);

• Peaks are visible during nighttime and preferentially at low altitude;

• Q-factor is ~5 in line with values reported on the ground;

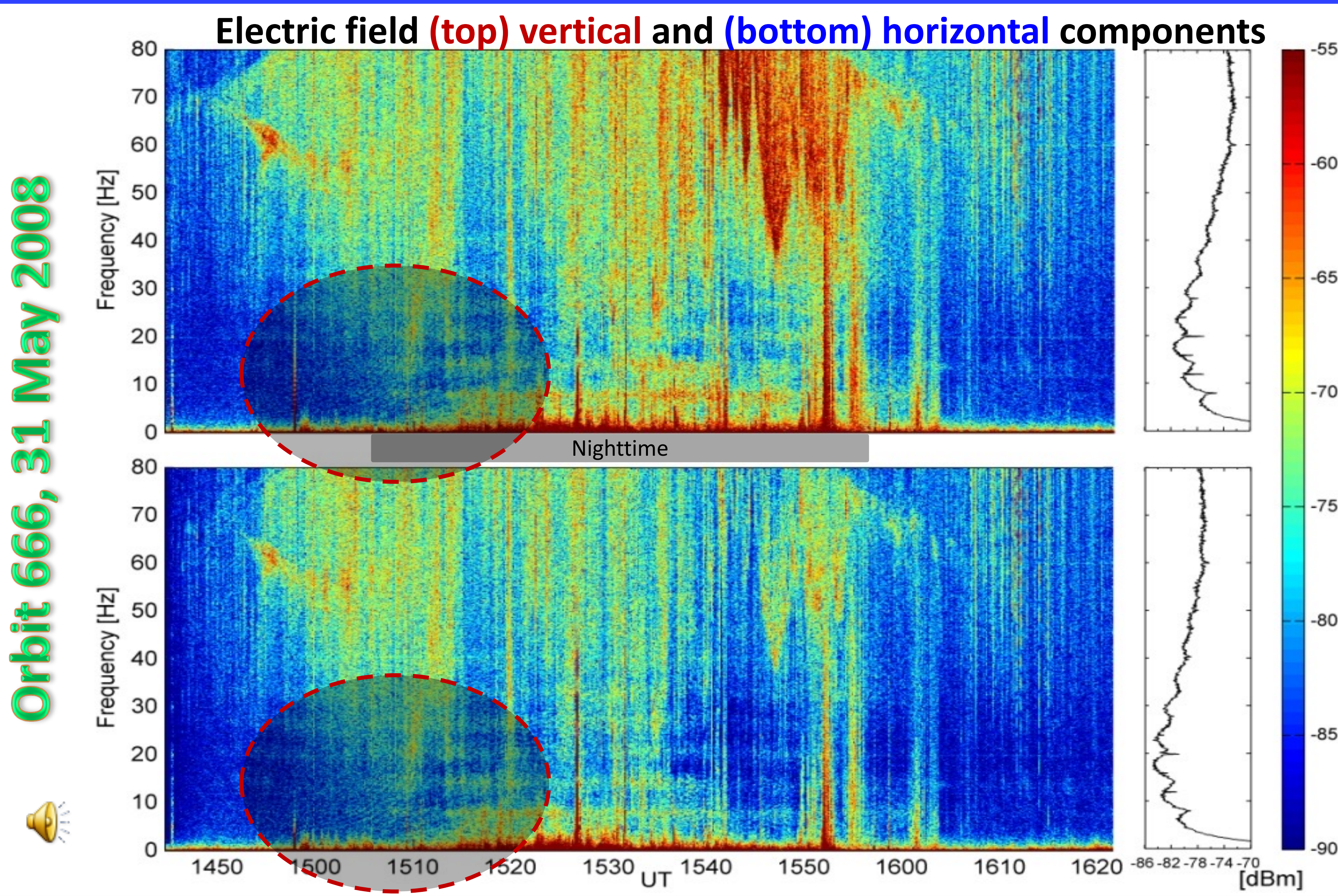
• This result has major implications for planetary science studies (Schumann resonances may be used to constrain the parameterization of the solar system);

• **The Schumann resonance amplitude seems correlated to lightning activity, corroborating ground measurements known as 'Q-burst enhancements' (strong thunderstorm activity);**

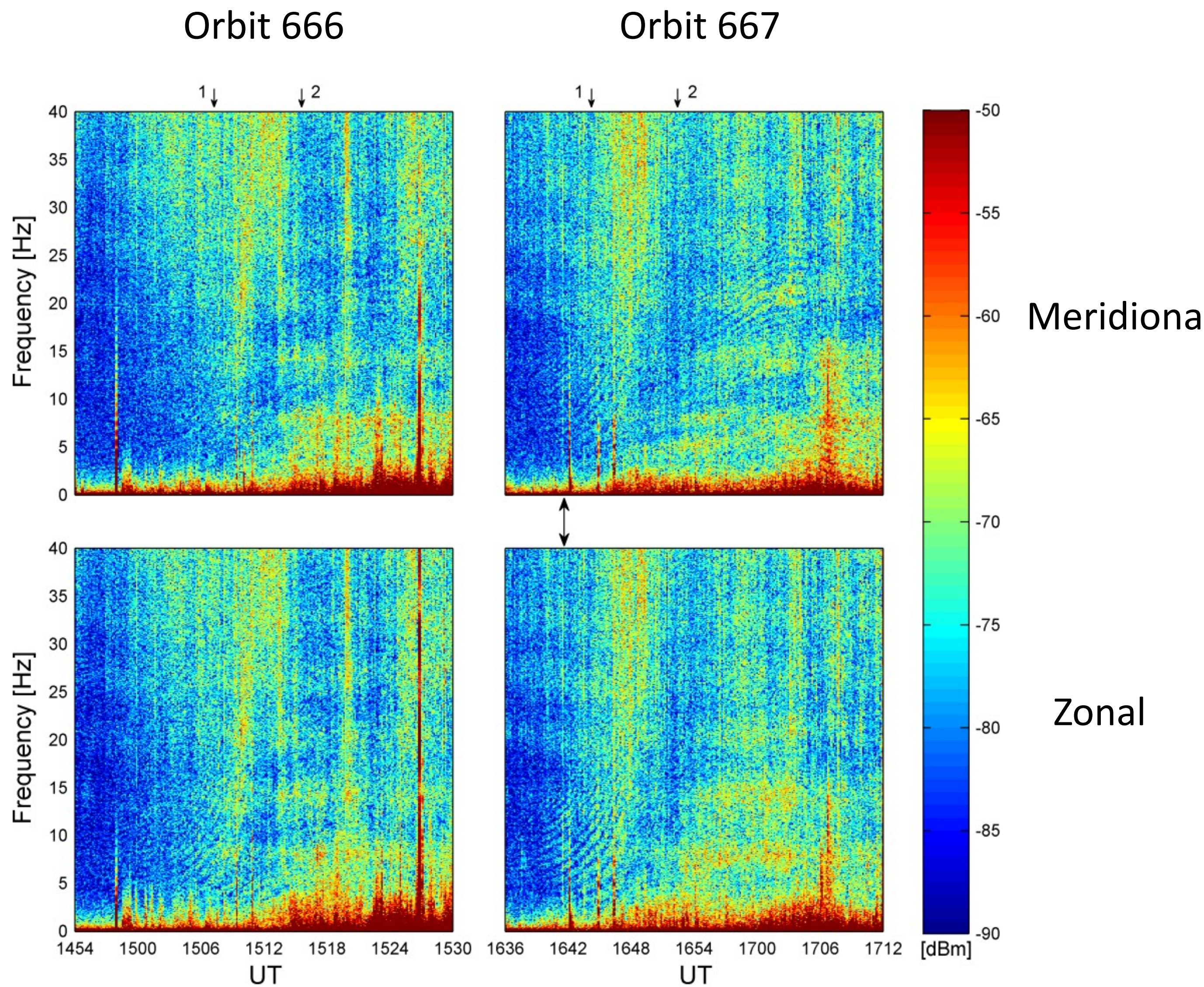
• **Ground based measurements of Schumann resonance transients have been connected to sprites (boccippio et al., 1995).**

Lightning activity can be inferred from orbit with optical sensors and also ELF electric field measurements

C/NOFS ELF 'Fingerprint'



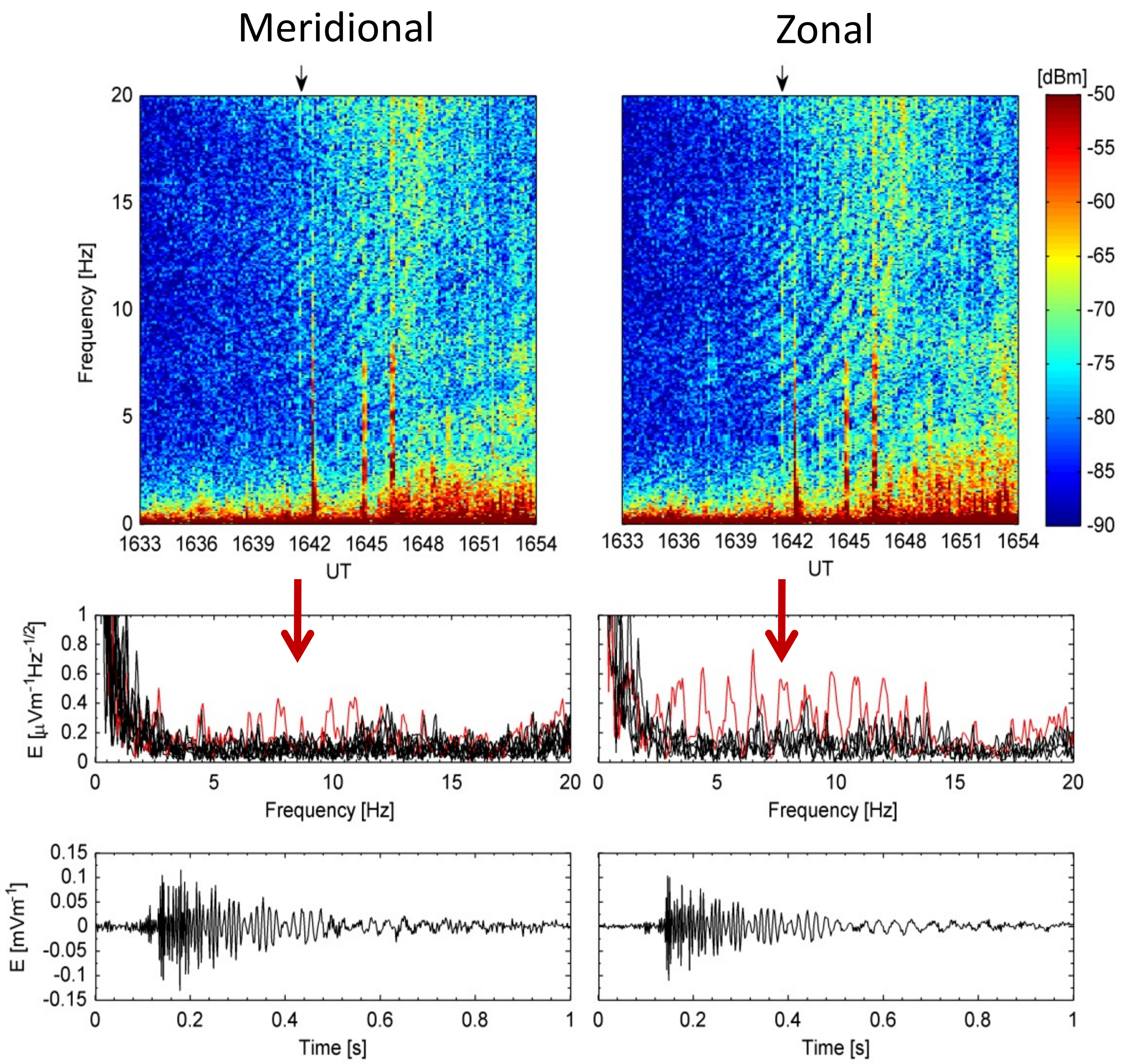
C/NOFS ELF 'Fingerprint'



1 – Sunset
2 – Satellite eclipse

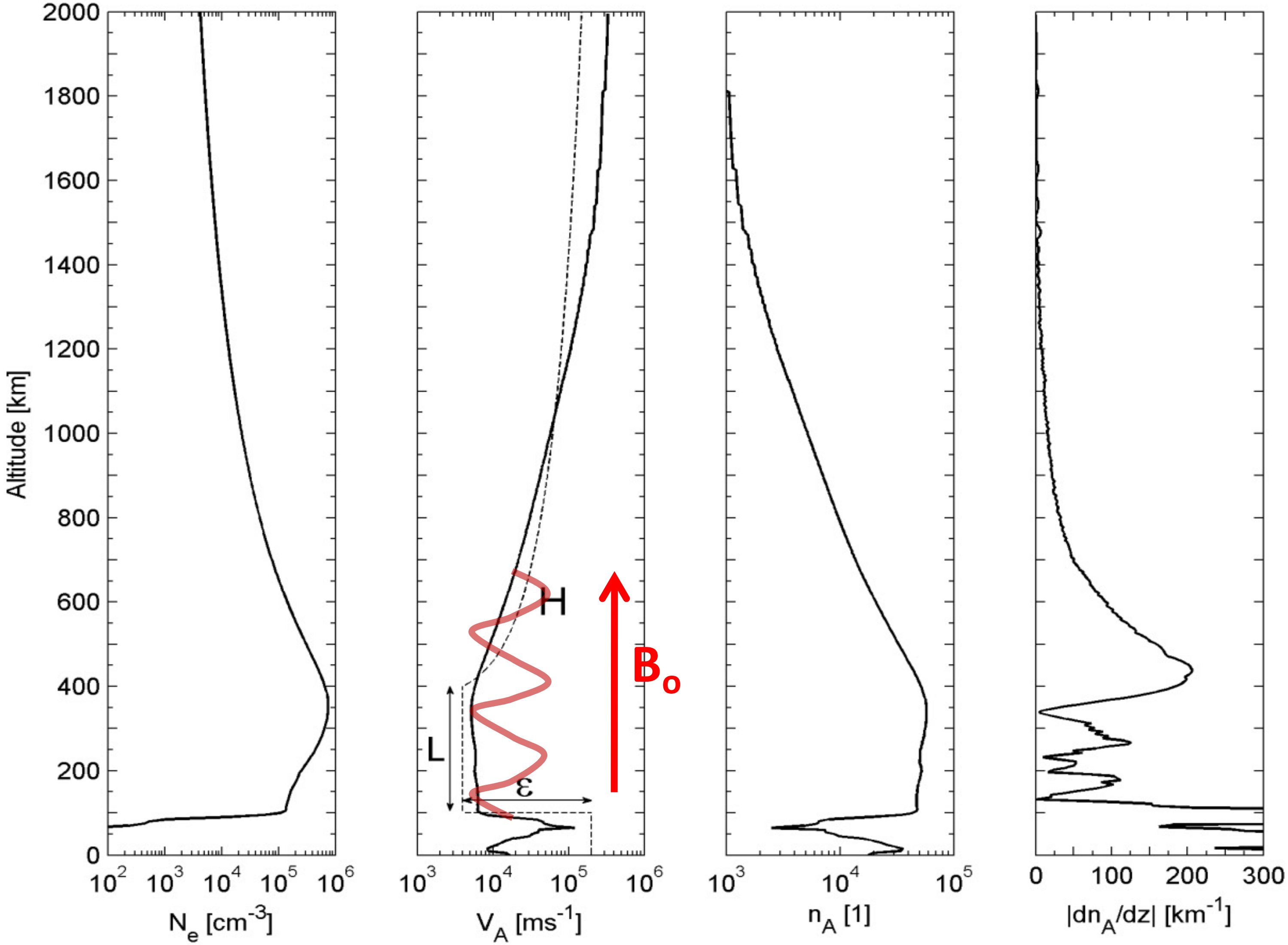
C/NOFS ELF 'Fingerprint'

Orbit 667, 31 May 2008

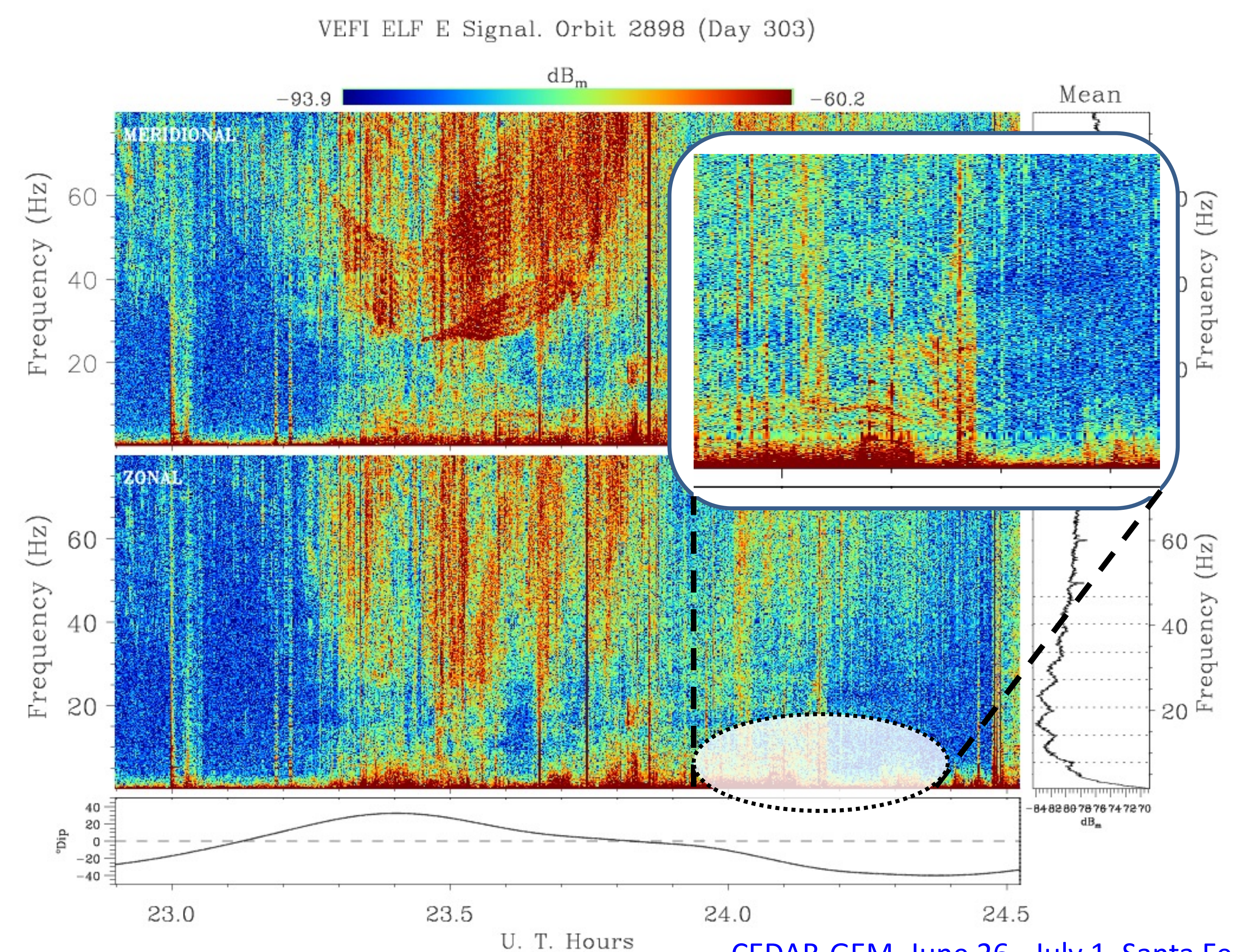


The Ionospheric Alfvén Resonator (IAR)

Typical low latitude profiles



C/NOFS ELF 'Fingerprint'



C/NOFS ELF 'Fingerprint' - Facts

Signature of the Ionospheric Alfvén Resonator

- Frequency range: 0.1-30 Hz
- Up to 20 peaks are seen
- Q-factor is ~15
- Δf ~ 0.5-2.5 Hz
- Amplitude is stronger in the zonal/horizontal component
- Signature seen during nighttime and close to the terminator
- Δf gradient is usually steeper close to the terminator
- Seen preferentially at low altitude
- Seen off the magnetic equator only
- Often seen in consecutive orbits
- Seen in different seasons

Implications for lightning studies:

A narrow event in orbit 667 matches the background Δf and shows Q~30; amplitude sudden variation occurs at ~15 Hz

IAR Characterization: Ongoing work

- ☑ Frequency
- ☑ Q-factor
- ☑ Electric field
- ☑ Diurnal variation
- ☑ Coupling (shear Alfvén + magnetosonic)
- ☑ Losses (Pedersen, Hall, transverse heterogeneity)
- ☑ Effect of altitude (position in the resonator)
- ☑ Effect of magnetic latitude (off the magnetic equator)

- ‽ Latitude
- ‽ *Electromagnetic source (lightning vs. Geomagnetic pulsations)*
- ‽ Effect of hiss
- ‽ Effect of terminator
- ‽ Real ionosphere + IRI modeling

- ☒ Wave vector
- ☒ Magnetic field
- ☒ Seasonal variation

Summary

- Lightning is possibly a major source to IAR excitation; if so, IAR signatures would provide additional means to investigate the impact of individual lightning strokes in the ionosphere;

- C/NOFS ELF measurements contribute to investigate lightning activity from space;

- Correlation between optical and ELF electric field is possible, contributing to lightning activity assessments at local and global scales;

- SR measurements of cavity leakage contribute to assessing global characteristics of lightning-thunderstorm distribution;

- SR measurements from orbit may be used to investigate transient luminous events and Q-bursts.

References (SR:IAR)

SR:

Prediction

Schumann (1952), On the free oscillations of a conducting sphere which is surrounded by an air layer and an ionosphere shell, *Z. Naturforsch.* ***A7***, 149–154 (in German)

First Observation on the ground

Balser and Wagner (1960), Observations of Earth-ionosphere cavity resonances, *Nature* **188**, 638–641

First Observation from space

Simões et al., submitted

Modeling

Sentman (1990), *J. Atmos. Terrest. Phys.* **52**, 35-46

Simões et al. (2007), *Planet. Space Sci.* **55**, 1978–1989, doi:10.1016/j.pss.2007.04.016

Simões et al. (2009), *Geophys. Res. Lett.* **36**, L14816, doi:10.1029/2009GL039286

Link to TLE's

Boccippio et al. (1995), Sprites, ELF transients, and positive ground strokes, *Science* **269**, 1088-1091

IAR:

Prediction

Polyakov (1976), On properties of an ionospheric Alfvén resonator, in symposium KAPG on Solar-Terrestrial physics, 72-73

First observation on the ground

Belyaev et al. (1990), The ionospheric Alfvén resonator, *J. Atmos. Terrest. Phys.* **52**, 781-788

First observation from space

In preparation

Modeling

Lysak (1999), *J. Geophy. Res.* **104**, 10017-10030

Link to lightning

TLE's - Sukhorukov and Stubbe (1997), *Geophys. Res. Lett.* **24**, 829-832 (1997)

Lightning - Surkov et al. (2006), *J. Geophys. Res.-Space* **111**, A01303, doi:10.1029/2005JA011320

Geomagnetic pulsations - Demekhov et al. (2000), *Geophys. Res. Lett.* **27**, 3805-3808

Acknowledgements

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Auxiliary Material

The Ionospheric Alfvén Resonator (IAR)

$\left(\frac{\partial}{\partial t}+\frac{\sigma_P}{\varepsilon}\right)Q=-V^2\frac{\partial J}{\partial z}\mp\frac{\sigma_H}{\varepsilon}M$		$\left(\frac{\partial}{\partial t}+\frac{\sigma_P}{\varepsilon}\right)M=-V^2\nabla^2 B_z\pm\frac{\sigma_H}{\varepsilon}Q$
$\frac{\partial}{\partial t}(1-\lambda^2\nabla_\perp^2)J=-\frac{\partial Q}{\partial z}+\eta_\parallel\nabla_\perp^2 \mathrm{J}$		$\frac{\partial B_z}{\partial t}=-M$
$\sigma_P=\sum_s\frac{N_s q_s^2}{m_s}\frac{\nu_s}{\nu_s^2+\Omega_s^2}$		$\sigma_H=-\sum_s\frac{N_s q_s^2}{m_s}\frac{\Omega_s}{\nu_s^2+\Omega_s^2}$
$V=\frac{c}{\sqrt{\varepsilon/\varepsilon_o}}$		$V_A=\frac{B_{oz}}{\sqrt{\mu_o\rho}}$
$\varepsilon\equiv\varepsilon_o\left(1+\sum_s\frac{\omega_{ps}^2}{\nu_s^2+\Omega_s^2}\right)=\varepsilon_o\left(1+\frac{c^2}{V_A^2}\sum_s\frac{m_s/M_{ave}}{1+\nu_s^2/\Omega_s^2}\right)$		
$Q=\nabla_\perp\cdot E_\perp$		$M=(\nabla_\perp\times E_\perp)\cdot\hat{z}$
$J=(\nabla_\perp\times B_\perp)\cdot\hat{z}$		$B_o=\mp B_{oz}\hat{z}$
$\lambda=\frac{c}{\omega_{pe}}$	$\sigma_\parallel=\frac{N_e q_e^2}{m_e\nu_e}$	$\eta_\parallel=\nu_e\lambda^2=\frac{1}{\mu_o\sigma_\parallel}$

Lysak (1999)

The Ionospheric Alfvén Resonator (IAR)

$$\frac{\partial^2 Q}{\partial z^2} + \frac{\omega^2}{V^2} Q = 0$$

$$\frac{\partial^2 M}{\partial z^2} + \frac{\omega^2}{V^2} M = 0$$

The Ionospheric Alfvén Resonator (IAR)

$$\frac{\partial^2 Q}{\partial z^2} + \frac{\omega^2}{V^2} Q = 0$$

$$\frac{\partial^2 M}{\partial z^2} + \frac{\omega^2}{V^2} M = 0$$

$$\frac{\partial^2 Q}{\partial z^2} + \frac{i\omega}{V^2}\left(-i\omega + \frac{\sigma_P}{\varepsilon}\right) Q = 0$$

$$\frac{\partial^2 M}{\partial z^2} + \frac{i\omega}{V^2}\left(-i\omega + \frac{\sigma_P}{\varepsilon}\right) M = 0$$

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$$\frac{\partial^2 Q}{\partial z^2} + \frac{i\omega}{V^2}\left(-i\omega + \frac{\sigma_P}{\varepsilon}\right) Q = \mp \frac{i\omega}{V^2}\frac{\sigma_H}{\varepsilon} M$$

$$\frac{\partial^2 M}{\partial z^2} + \frac{i\omega}{V^2}\left(-i\omega + \frac{\sigma_P}{\varepsilon}\right) M = \pm \frac{i\omega}{V^2}\frac{\sigma_H}{\varepsilon} Q$$

The Ionospheric Alfvén Resonator (IAR)

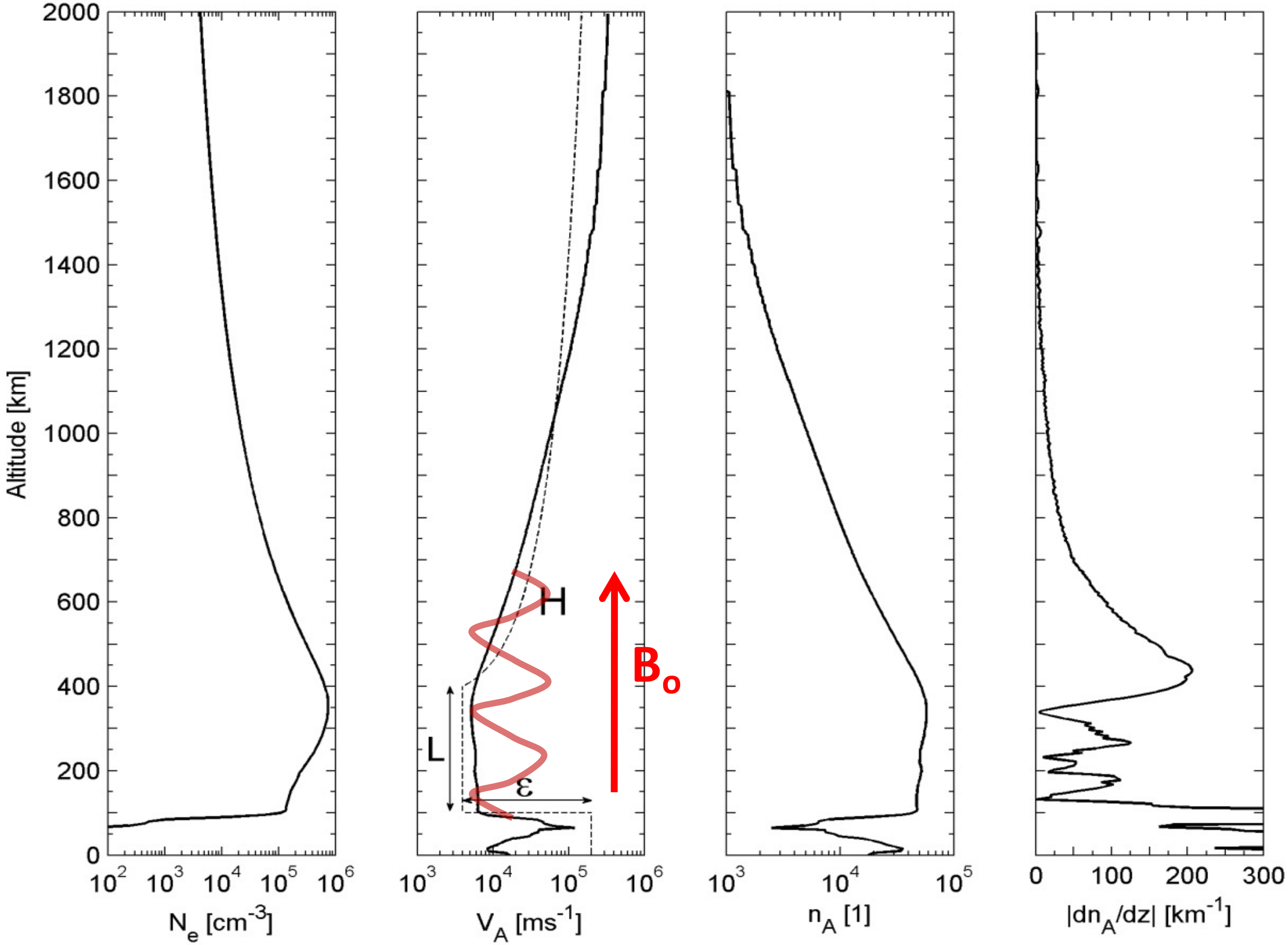
$$\frac{\partial^2 Q}{\partial z^2} - \frac{\left(1 - i\frac{\omega}{\nu}\right)\left(\alpha' - \frac{\alpha\sigma_\parallel'}{\sigma_\parallel}\right) + i\frac{\omega\alpha\nu'}{\nu^2}}{\mu_o\sigma_\parallel\beta}\frac{\partial Q}{\partial z} + \frac{\beta}{V^2}\left(-i\omega + \frac{\sigma_P}{\varepsilon}\right)Q = \mp\frac{\beta}{V^2}\frac{\sigma_H}{\varepsilon}M$$

$$\frac{\partial^2 M}{\partial z^2} + \frac{i\omega}{V^2}\left(-i\omega + \frac{\sigma_P}{\varepsilon}\right)M = \pm\frac{i\omega}{V^2}\frac{\sigma_H}{\varepsilon}Q$$

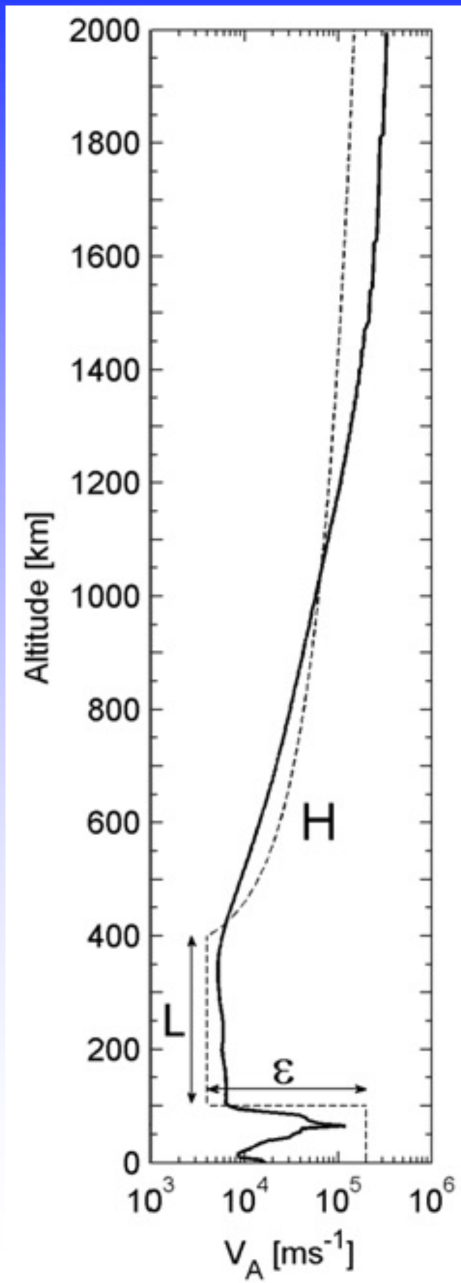
$$\beta = i\omega + \frac{\alpha}{\mu_o\sigma_\parallel}\left(1 - i\frac{\omega}{\nu}\right)$$

The Ionospheric Alfvén Resonator (IAR)

Typical low latitude profiles



The Ionospheric Alfvén Resonator (IAR)



Alfvén Velocity:

$$V_A = B/\sqrt{\mu_o \rho}$$

Alfvén Velocity Profile:

$$(V_A^2(z) = V^2{}_A^{min}/(\varepsilon^2 + e^{-z/H})$$

Resonator Eigenfrequencies:

$$f_n = V_A(n + 1/4)/2(L + H)$$

$$\Delta f = V_A/2(L + H)$$

Quality Factor:

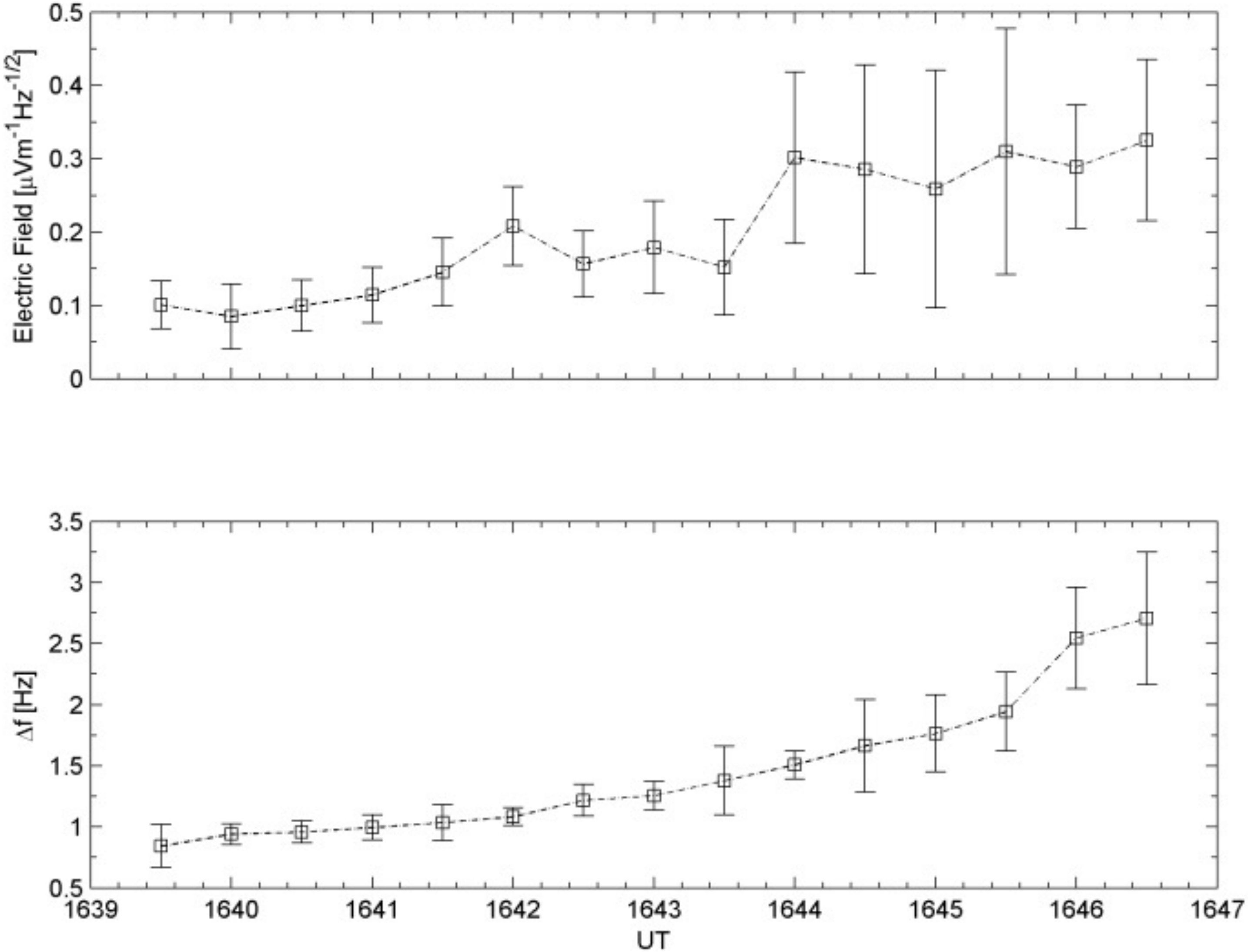
$$Q_n = (1 + L/H)/\pi\varepsilon$$

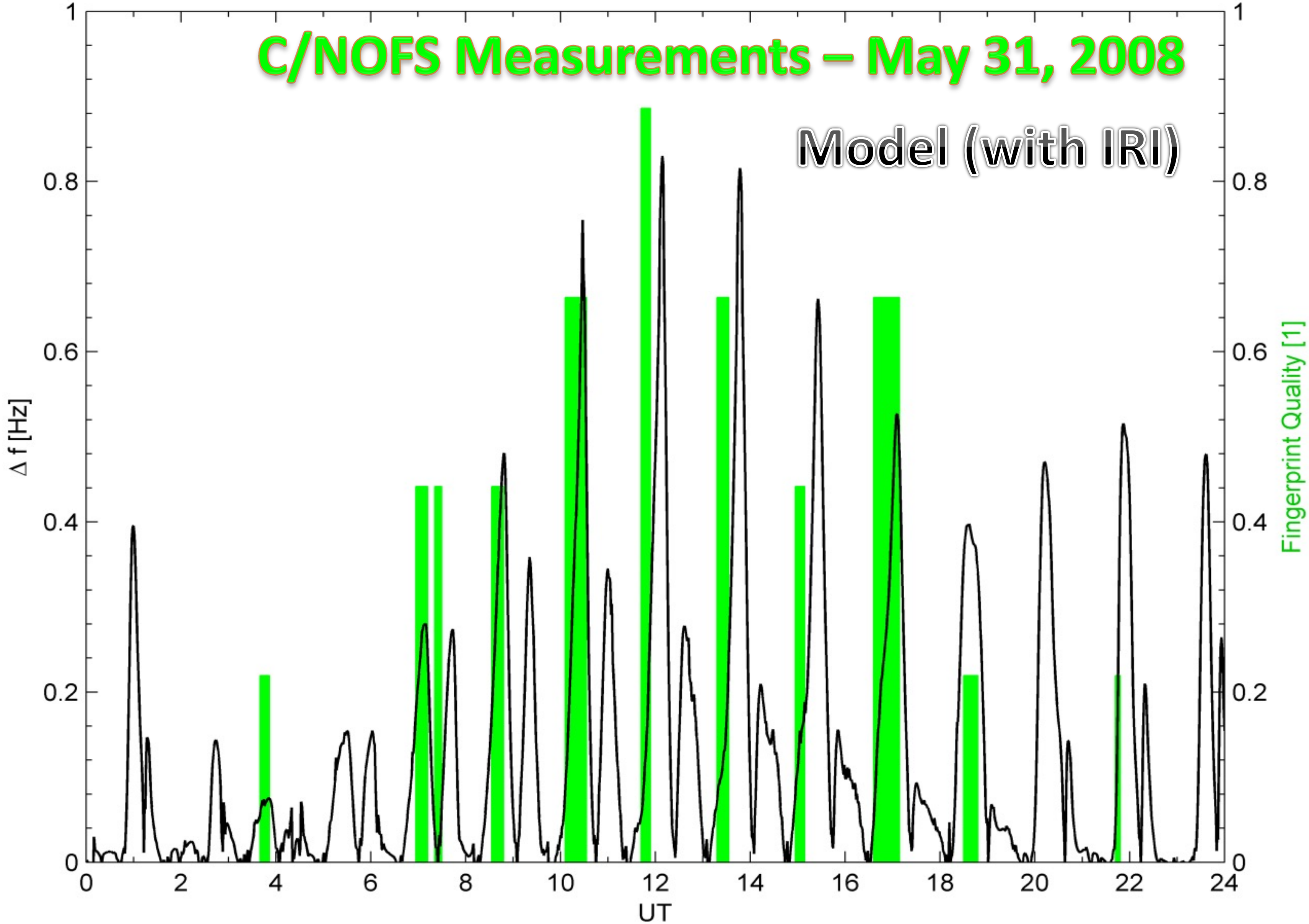
Upper Boundary Transparency Condition:

$$\pi\varepsilon\omega H/V_A < 1$$

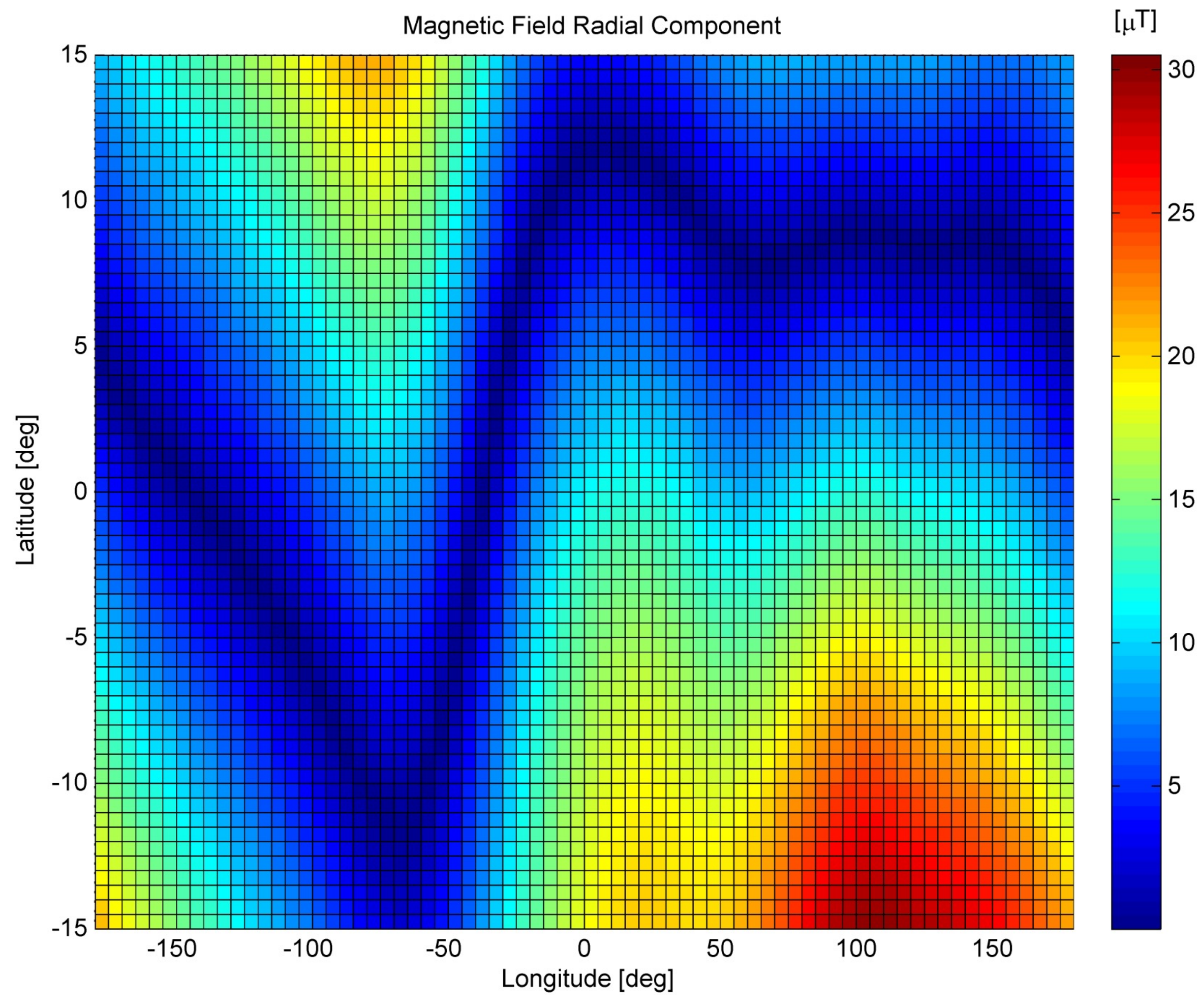
C/NOFS ELF 'Fingerprint'

Orbit 667, 31 May 2008

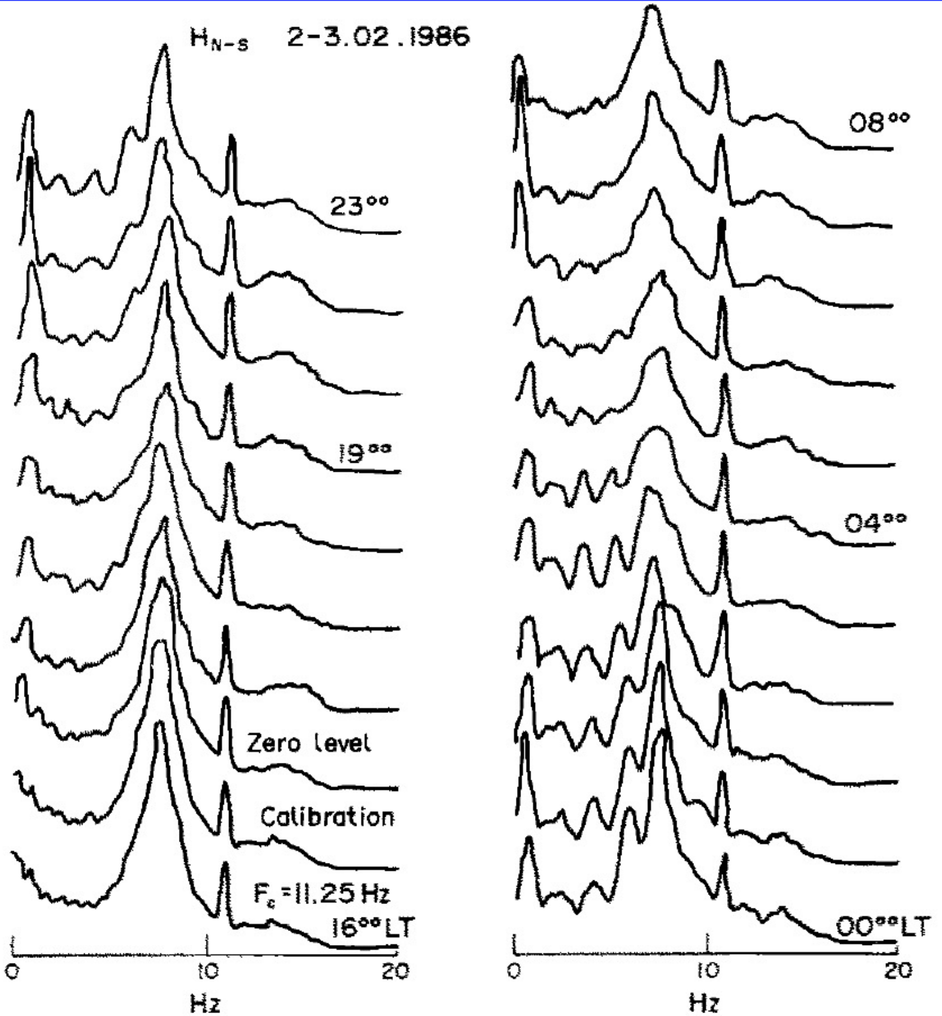



C/NOFS Measurements – May 31, 2008
Model (with IRI)
Δ f [Hz]
Fingerprint Quality [1]
UT
0
0.2
0.4
0.6
0.8
1
0
2
4
6
8
10
12
14
16
18
20
22
24

The Ionospheric Alfvén Resonator (IAR)

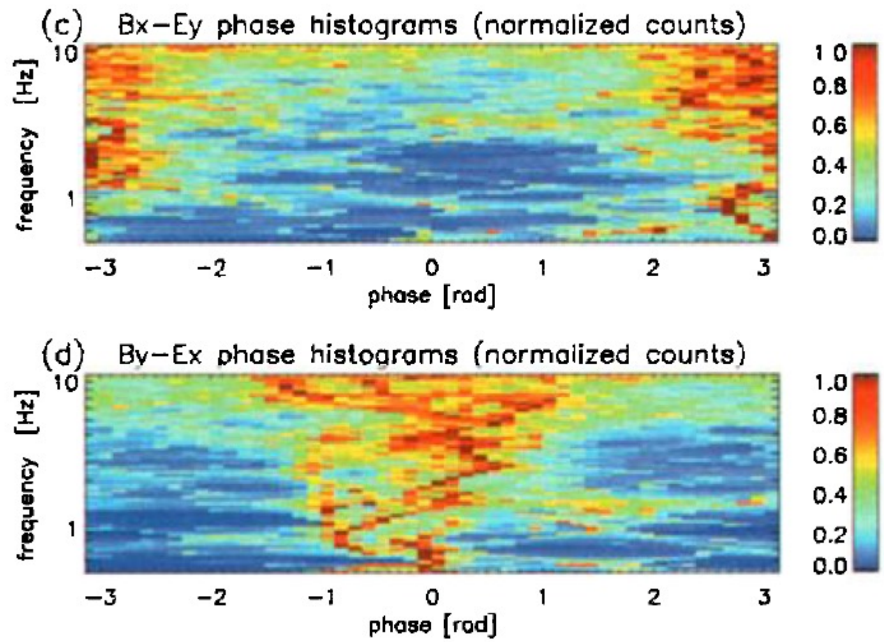


Ground- and Space-Based Observations



First ground observation

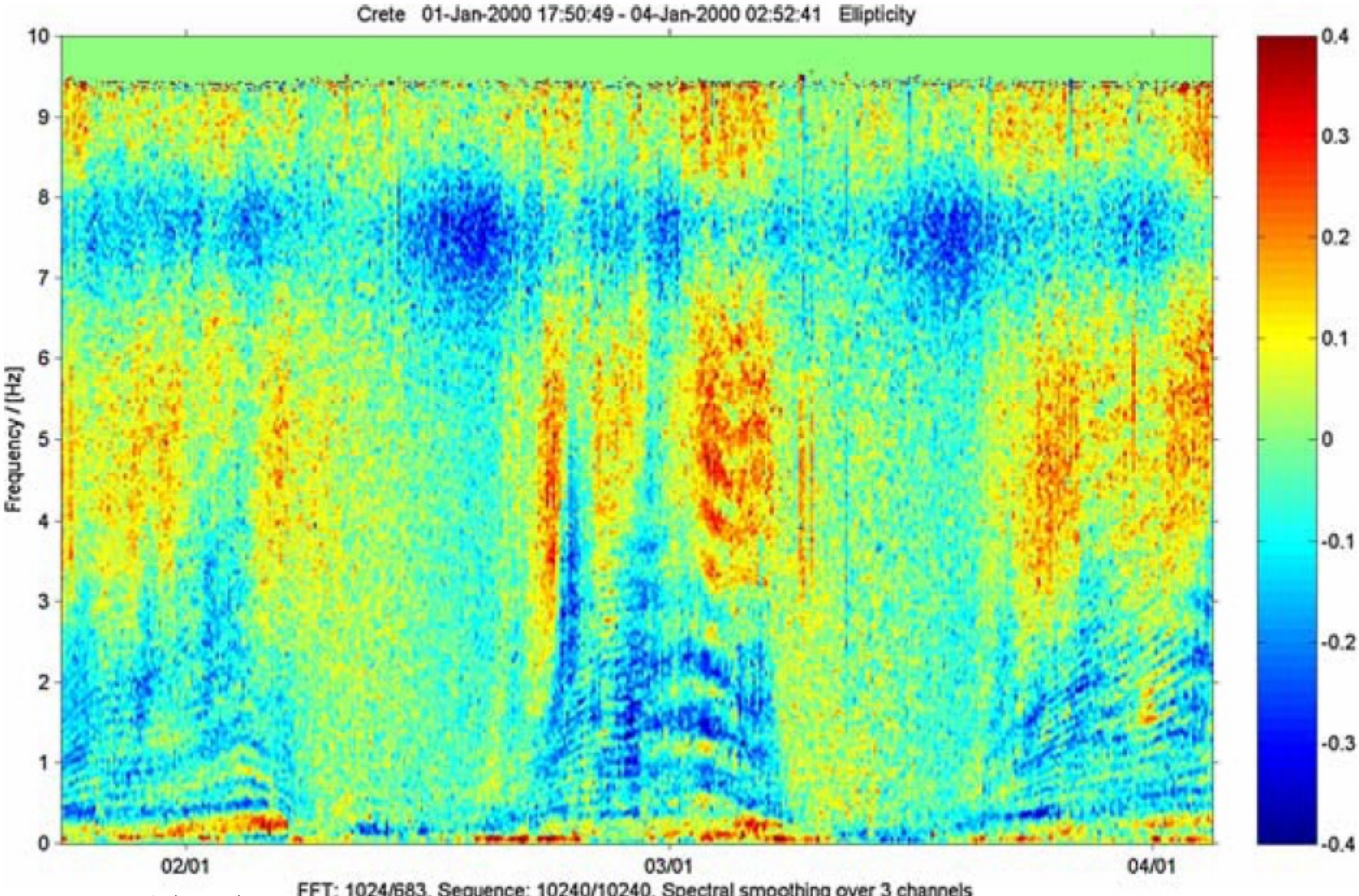
(mid latitude – Gorky, Ukraine) Belyaev et al. (1990)



First space observation

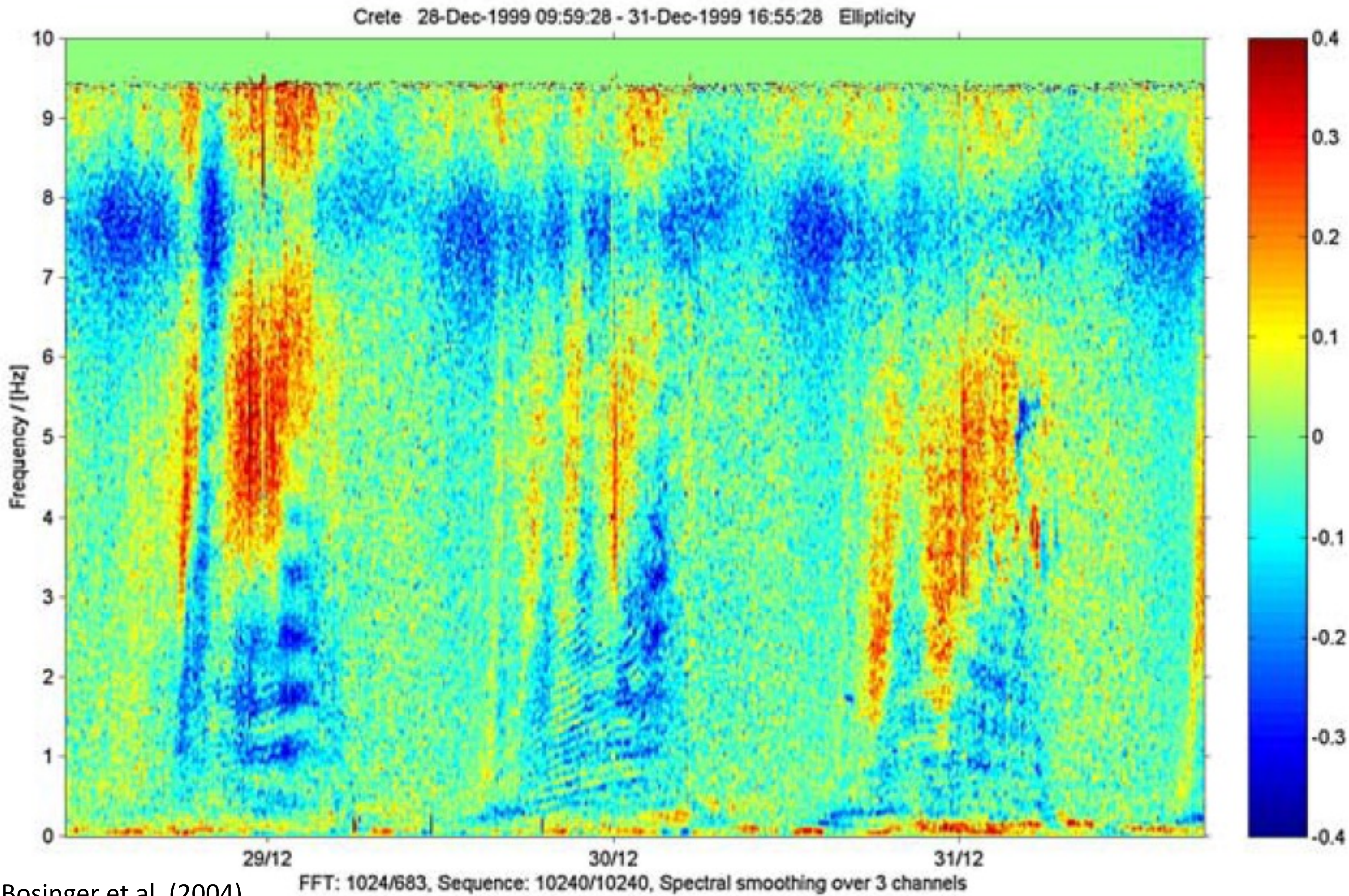
(high latitude – Freja satellite) Grzesiak (2000)

Ground- and Space-Based Observations



Bosinger et al. (2004)

Ground- and Space-Based Observations



Bosinger et al. (2004)

Summary

- C/NOFS unexpectedly detected Schumann resonance (SR) from space (up to 10 peaks are observed and confirmed by ground measurements)
- Previous models predicted that SR should remain confined to the Earth-ionosphere cavity (cavity leakage mechanism remains uncertain)
- Space-based SR measurements offer a new remote sensing technique for planetary science applications

- C/NOFS detected signatures of the Ionospheric Alfvén Resonator (IAR) - up to 20 lines are observed
- IAR shows peculiar variations with altitude, magnetic latitude, and local time
- IAR can be used for ionospheric monitoring, namely for checking the IRI model accuracy
- Investigating seasonal variations of IAR and SR is the next logical step

- **Simultaneous measurements of V12, V34, V56 at 512 S/s during a few days are recommended to constrain both the cavity leakage mechanism (SR) and propagation in the resonator (IAR)**

- **Yes, we can estimate TEC and put constraints on the ion density profile**