ВОЗБУЖДЕНИЕ ИОНОСФЕРНОГО АЛЬВЕНОВСКОГО РЕЗОНАТОРА МАГНИТОСФЕРНЫМИ И АТМОСФЕРНЫМИ ИСТОЧНИКАМИ

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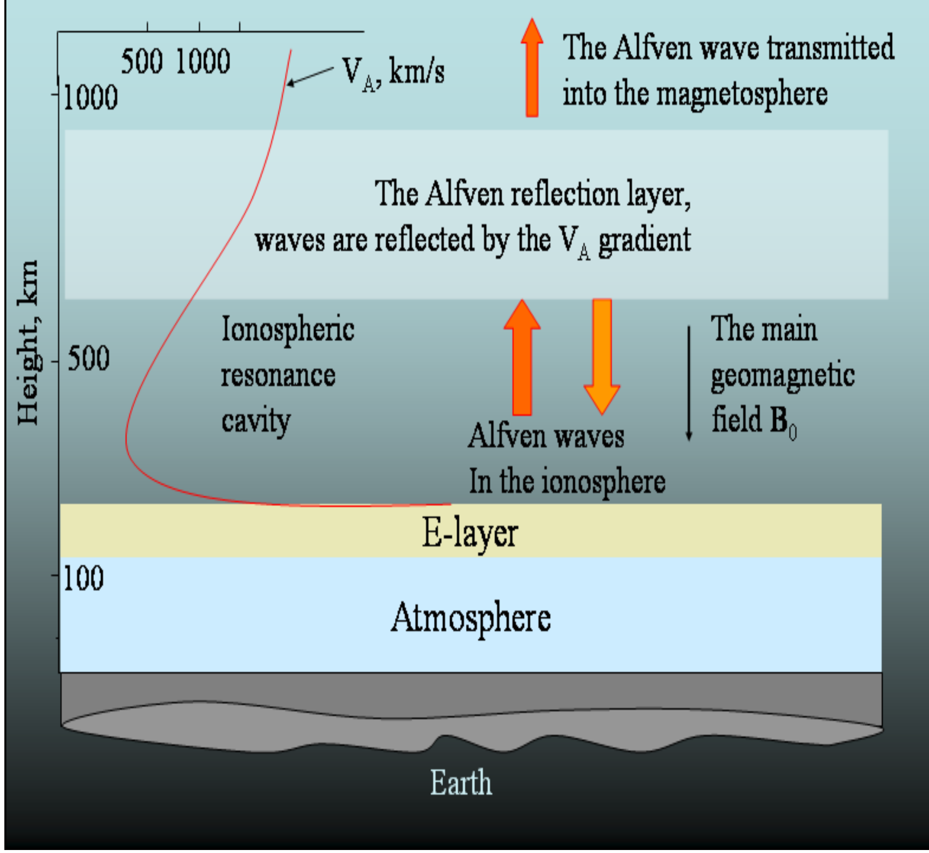
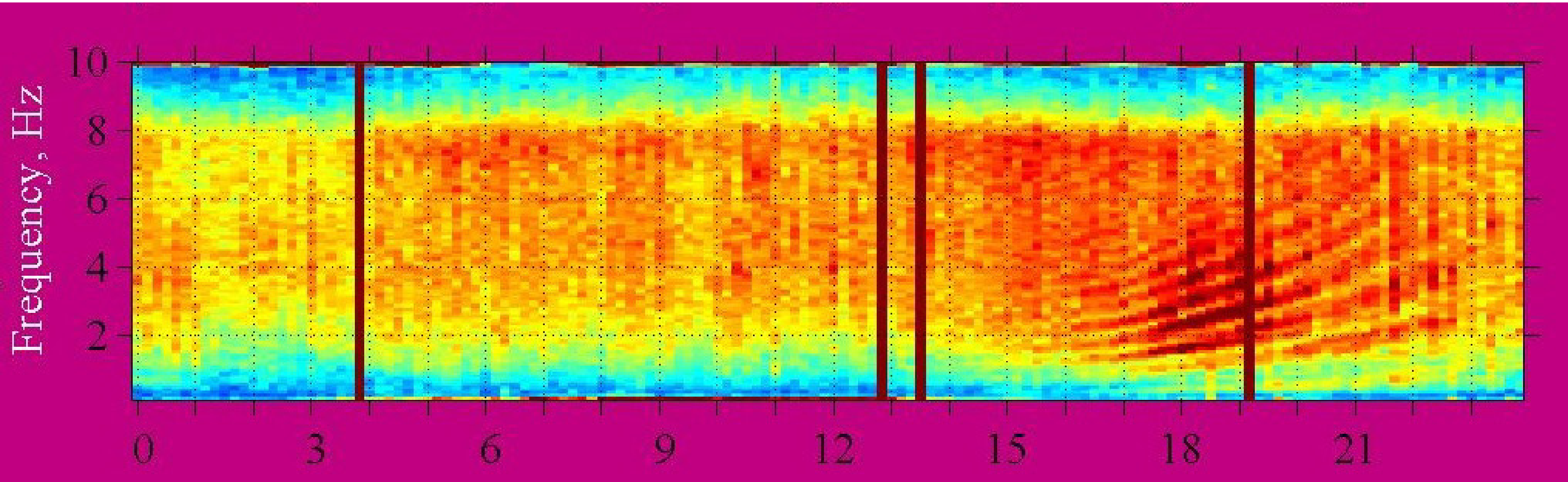
A peculiar feature of ULF geomagnetic variations is the occurrence of Spectral Resonant Structure (SRS), attributed to the Ionospheric Alfven Resonator (IAR). The IAR lower boundary coincides with *E*-layer, whereas the upper boundary is located at altitude of a few thousands of km due to a partial reflection of Alfven waves from a steep gradient of the $V_A(z)$ vertical profile above the *F*-layer.

This ionospheric cavity with minimum of $V_A(z)$ works as

- resonator for Alfven waves
- waveguide for the magnetosonic mode

IAR excitation mechanism: the world thunderstorm centers or regional thunderstorms?

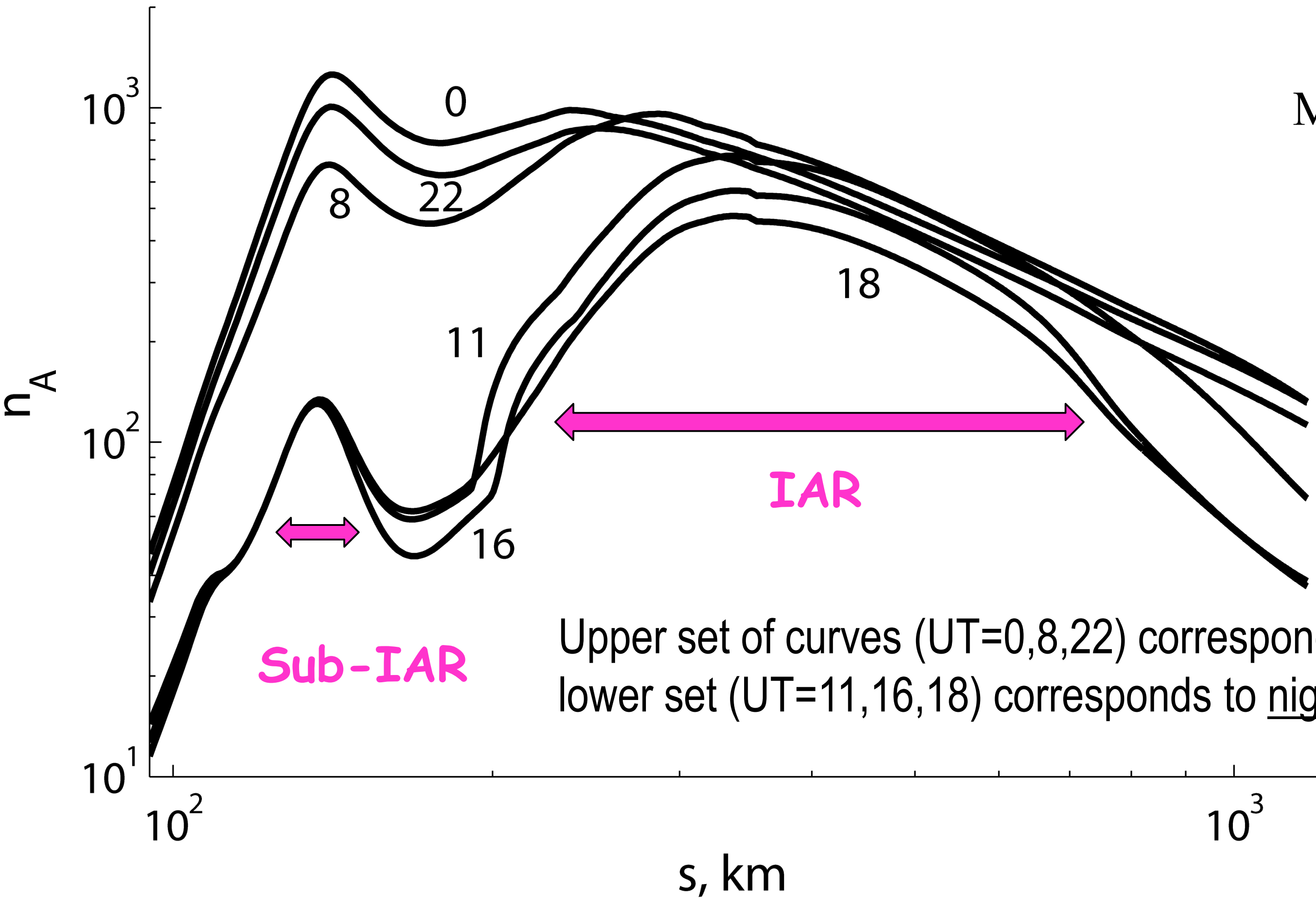




Profile of the Alfven refractive index in the mid-latitude ionosphere for various UT

Though the decrease rate of Ne with altitude is nearly the same at all UT, the gradient of $n_A(s)$ is steeper during night hours due to the contribution of heavy ions into the effective Alfven velocity.

During nighttime a valley is formed in $n_A(s)$ profile between F- and E-layers at z~120–200 km

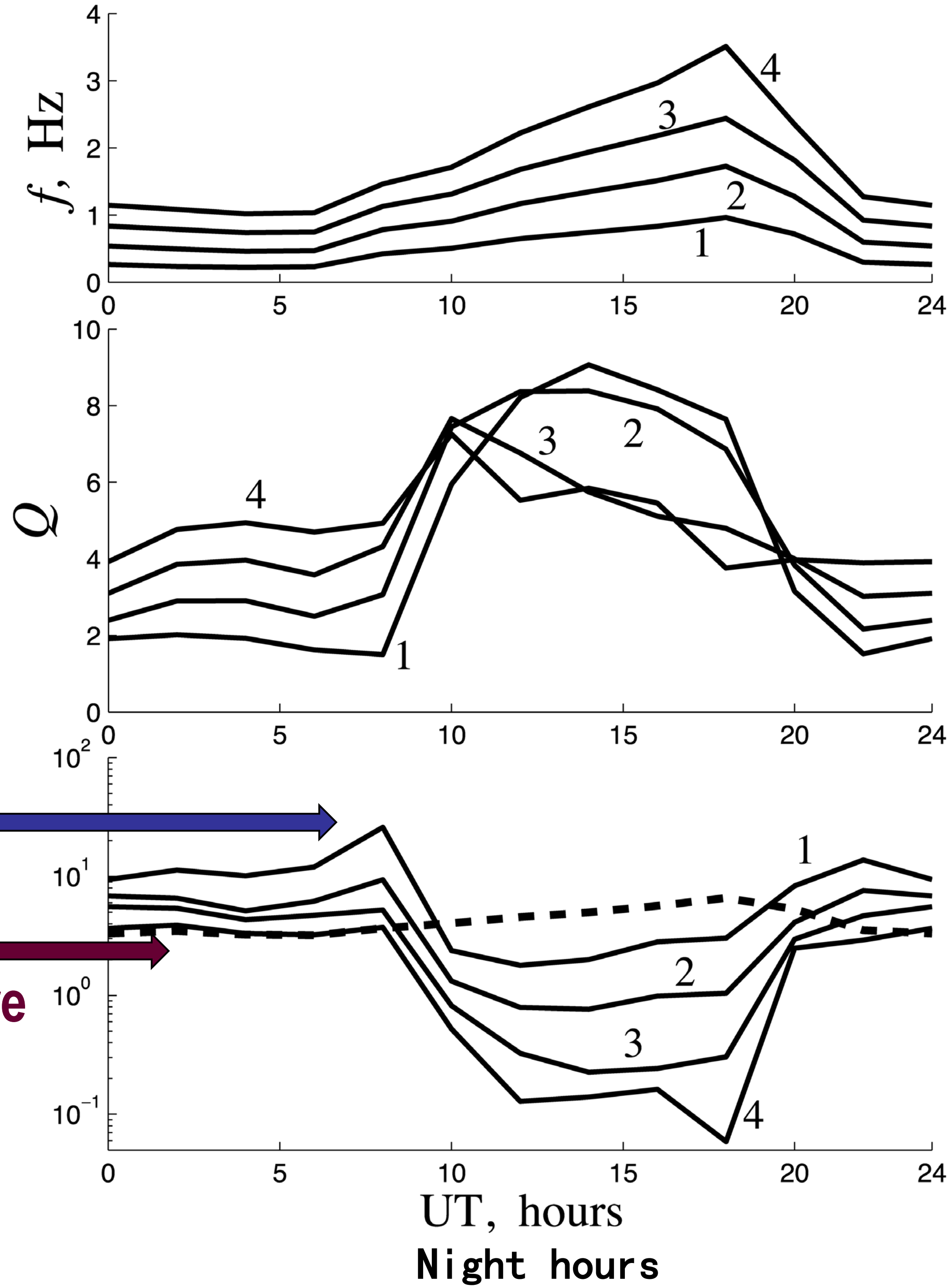


Upper set of curves (UT=0,8,22) correspond to <u>daytime</u> hours lower set (UT=11,16,18) corresponds to <u>nighttime</u>.

Diurnal variations of the eigenfrequencies & Q-factors for the IAR harmonics (n=1-4)

Height-integrated Joule dissipation and

energy flux into magnetosphere



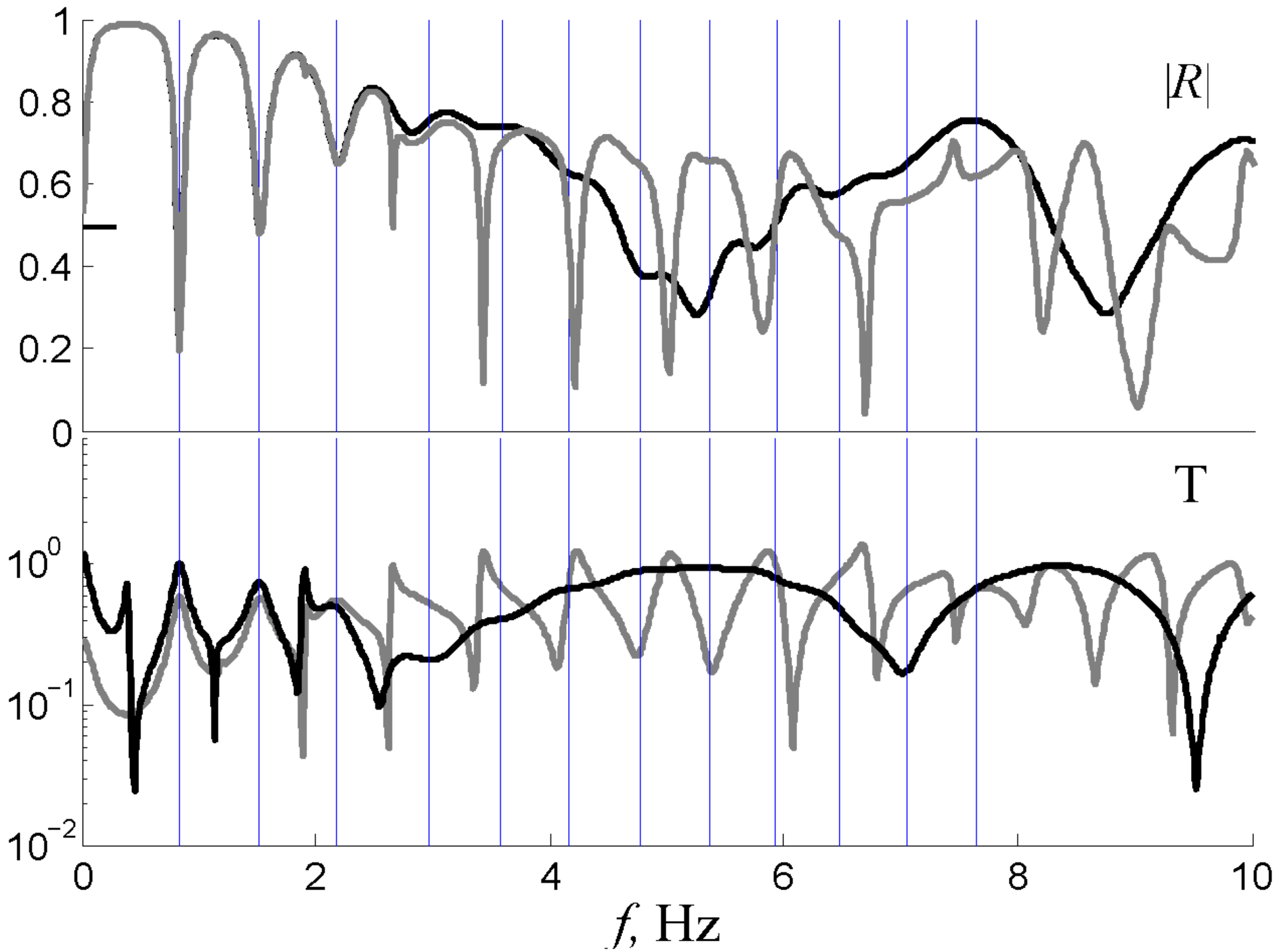
Frequency dependence of reflection R(f) & transmission T(f) coefficients

The occurrence of the IAR and FMS waveguide results in a strong frequency dependence:

- R(f) has minima at IAR eigenfrequencies;
- T(f) has maxima at the IAR eigenfrequencies with *f*<4Hz;

At *f*>3Hz: for *k*=10**{-2}1/km T(f) is oscillatory, whereas for *k*=10**{-3}1/km broadband “transmission window” appear at *f*~4-6 Hz.

Occurrence of "transparency windows“ results in the formation of narrow-band emissions on the ground



IAR signatures in the upper ionosphere?

Continuous IAR multi-band emission on the ground due to cumulative effect of many regional thunderstorms is a regular nighttime phenomenon.

Rather surprisingly, while there are so many ground observations of IAR, there are practically no reports on space IAR observations. Even E-field measurements onboard C/NOFS satellite did not reveal typical long-lasting multi-band spectral IAR signatures???

According to calculations (*Plyasov et al.,* 2012) spectral Alfven amplitudes excited in the nighttime ionosphere (z=400 km) by isolated electric discharge at R=10^3 km with typical parameters ($M_\omega = Id/\omega \sim 10$ Am/s^{-1}) at f=0.5 Hz can reach $E^{(max)} \sim 0.05$ (μV/m)/Hz. Sufficient to be detected by C/NOFS E-field sensor!?

Change of paradigm is necessary?

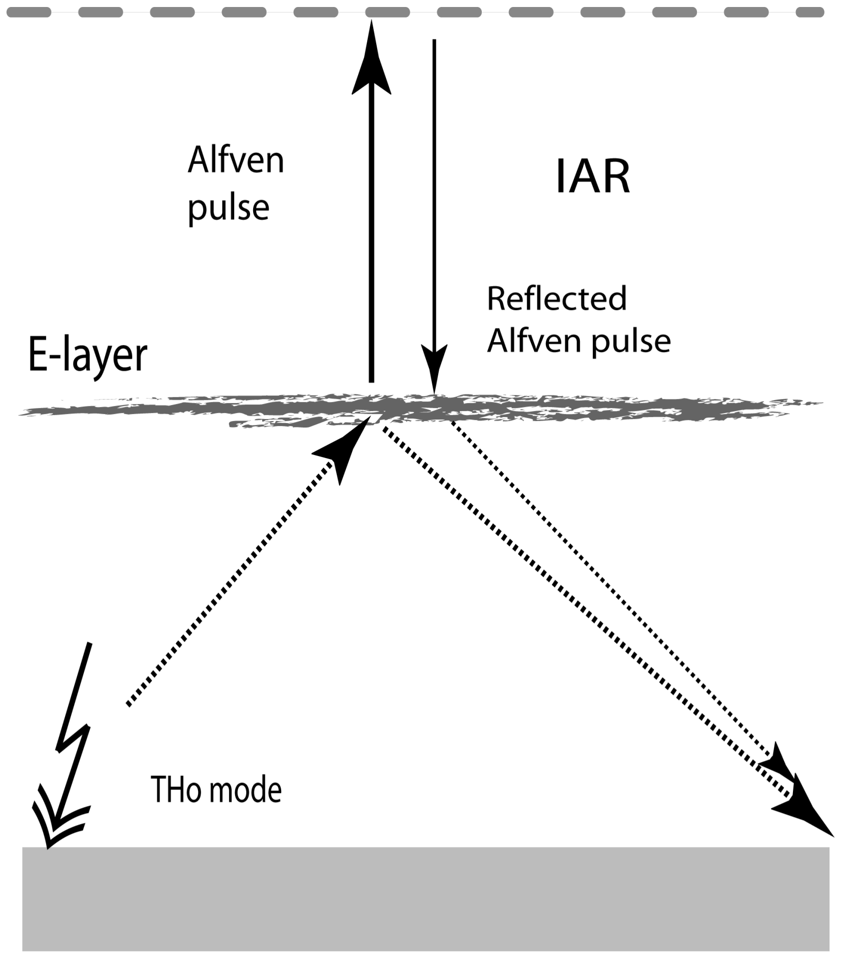
Theoretical scheme of the IAR excitation by a lightning discharge

The multi-frequency spectral structure can be formed due to a sequence of paired pulses. The main impulse is produced by a lightning discharge, whereas echo-pulse is caused by the reflection of the Alfven pulse from the upper IAR boundary.

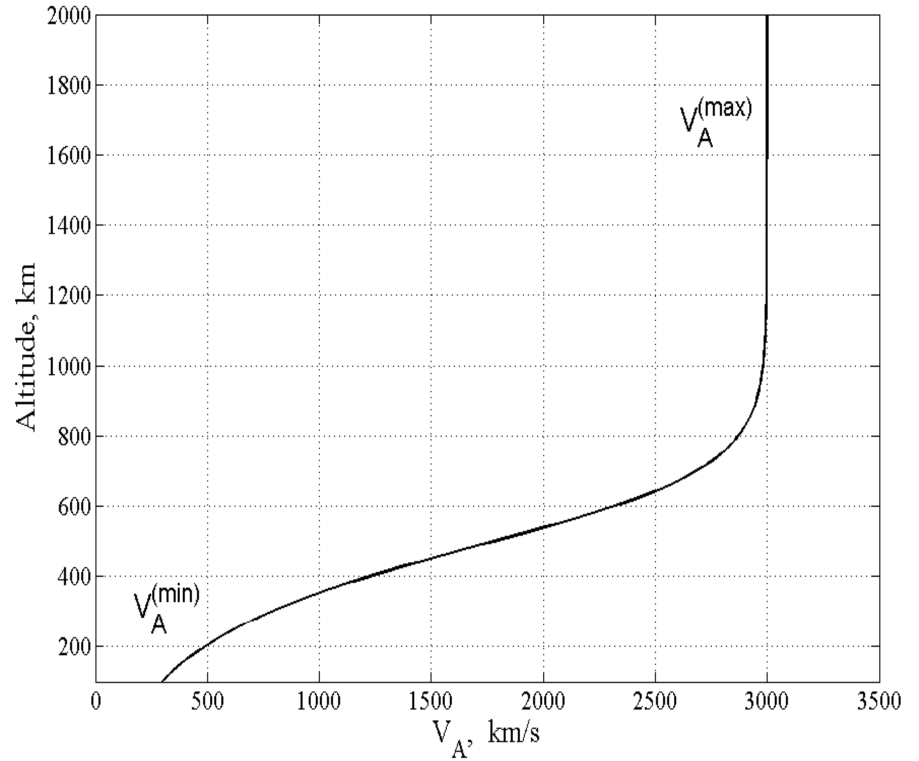
Lightning discharge excites an initial TM-mode pulse in the atmosphere. Besides that, TE-mode is excited due to mode coupling in the anisotropic lower ionosphere. An initial pulse propagates in the waveguide ionosphere-ground and instantly reach an observation site.

Meanwhile, TE pulse partially penetrates into the ionosphere, travels upward as Alfven pulse, reflects from the upper IAR boundary, and returns back to the ground as an echo-pulse in the TE mode.

Delay between echo & main pulses is about Alfven propagation time up & down in the ionosphere (IAR fundamental period). Observed spectra is to be multi-band structure with frequency gap $\Delta f = 1/\tau_A$



Modeling impulsive excitation of the IAR



We use the popular IAR model, where the dependence of Alfven velocity on coordinate along a field line *z* is

$$V_A^2(z) = [V_A^{\min}]^2[\varepsilon^2 + \exp(-z/H)]^{-1}$$

Propagation of Alfven pulse is described by the wave equation

$$\partial_z^2 E - V_A^{-2}(z)\partial_t^2 E = \mu c^{-1}\partial_t j_d$$

Alfven wave excitation by a point impulsive source with intensity *q* located at altitude $z=0$: $j_d = q\delta(z)\delta(t)$

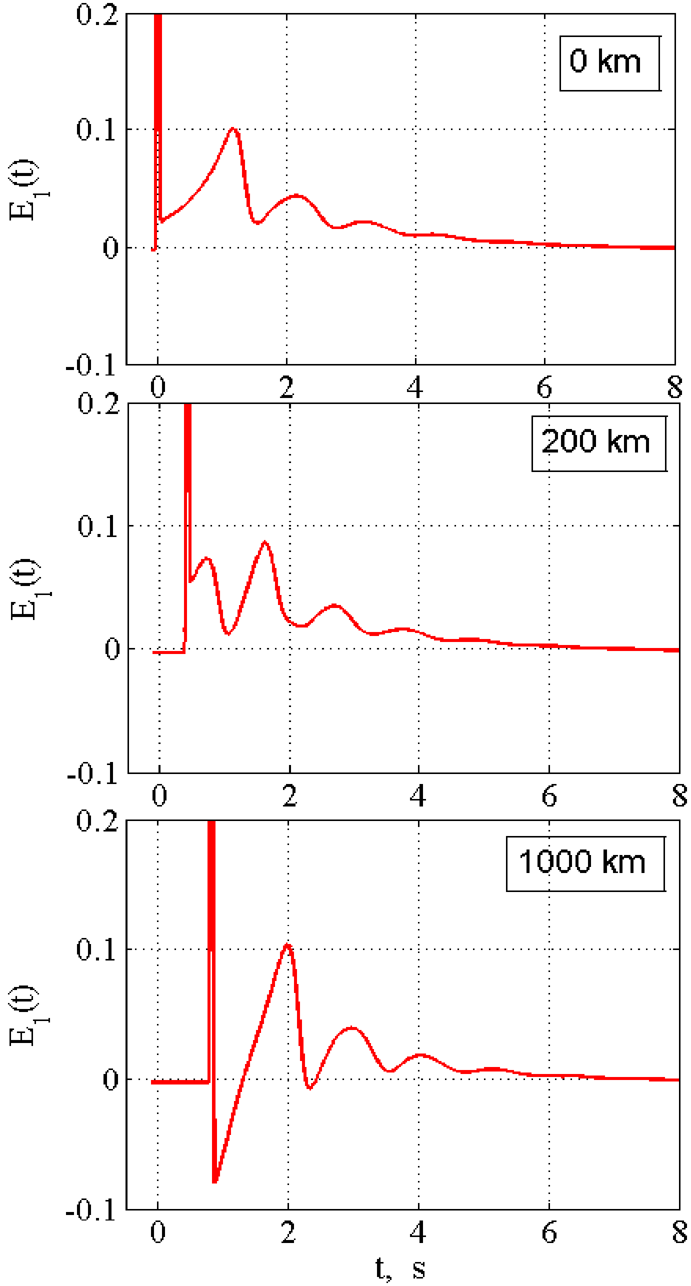
$$E(s) = \hat{L}[E(t)]$$

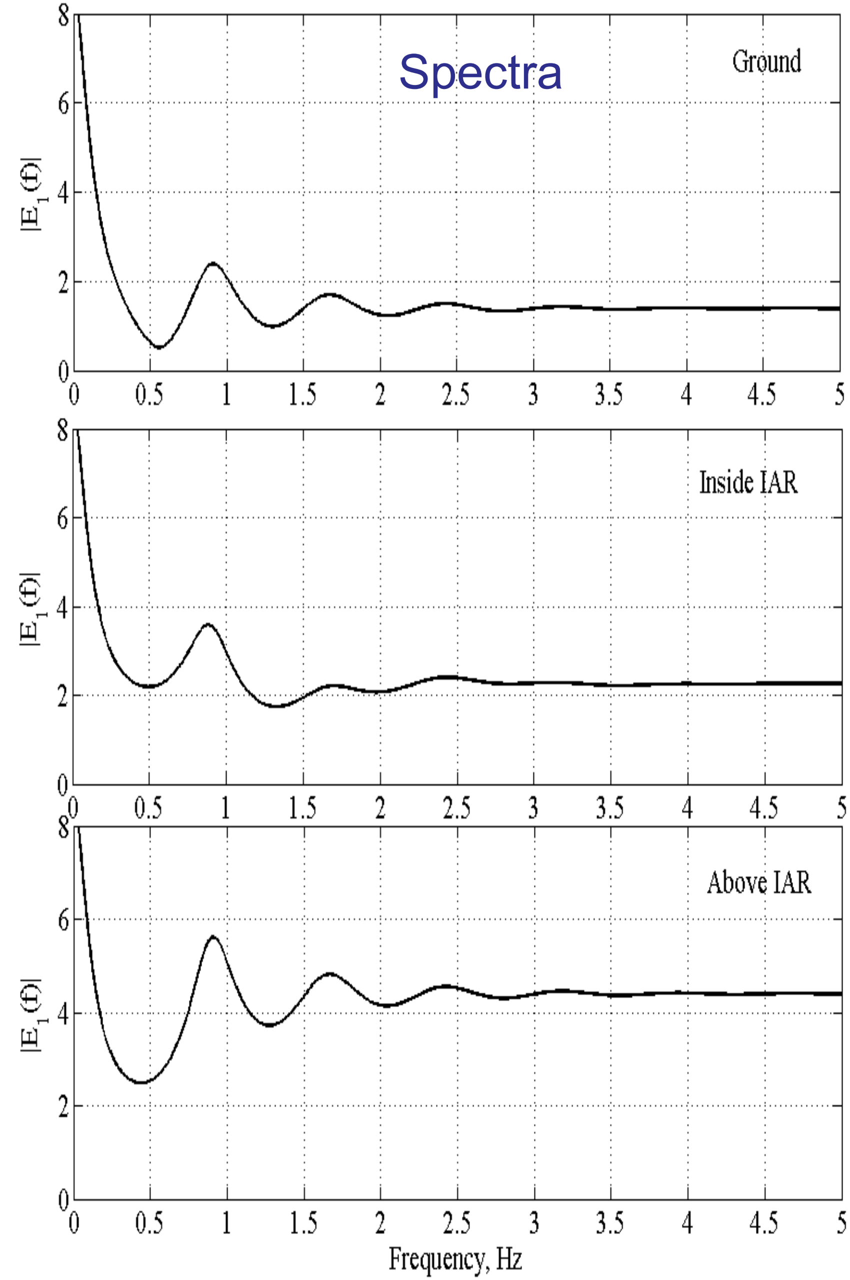
After tedious calculations, expression describing the spatial-time evolution of the wave E-field is obtained via the inverse Laplace transform

Obtained expression was numerically calculated for selected *z*

Finally, for a resulting *E(t)* the Fourier spectrum *E*(*f*) has been estimated.

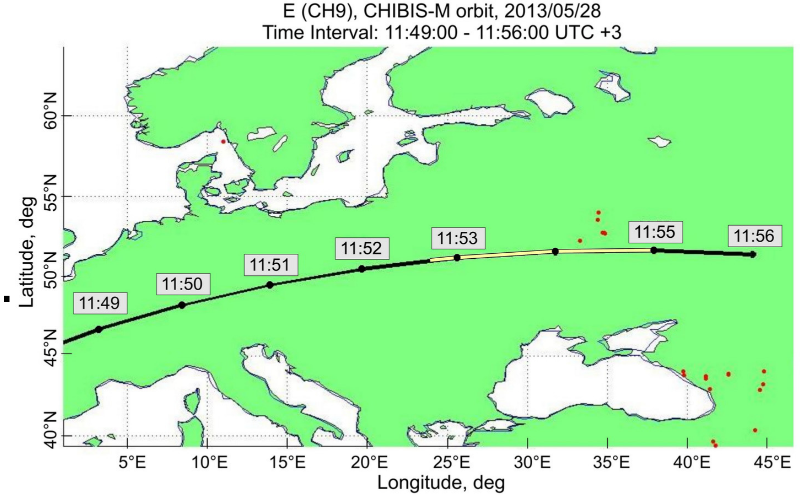
Modeling of space-time evolution of Alfvenic pulse launched from bottom of ionosphere

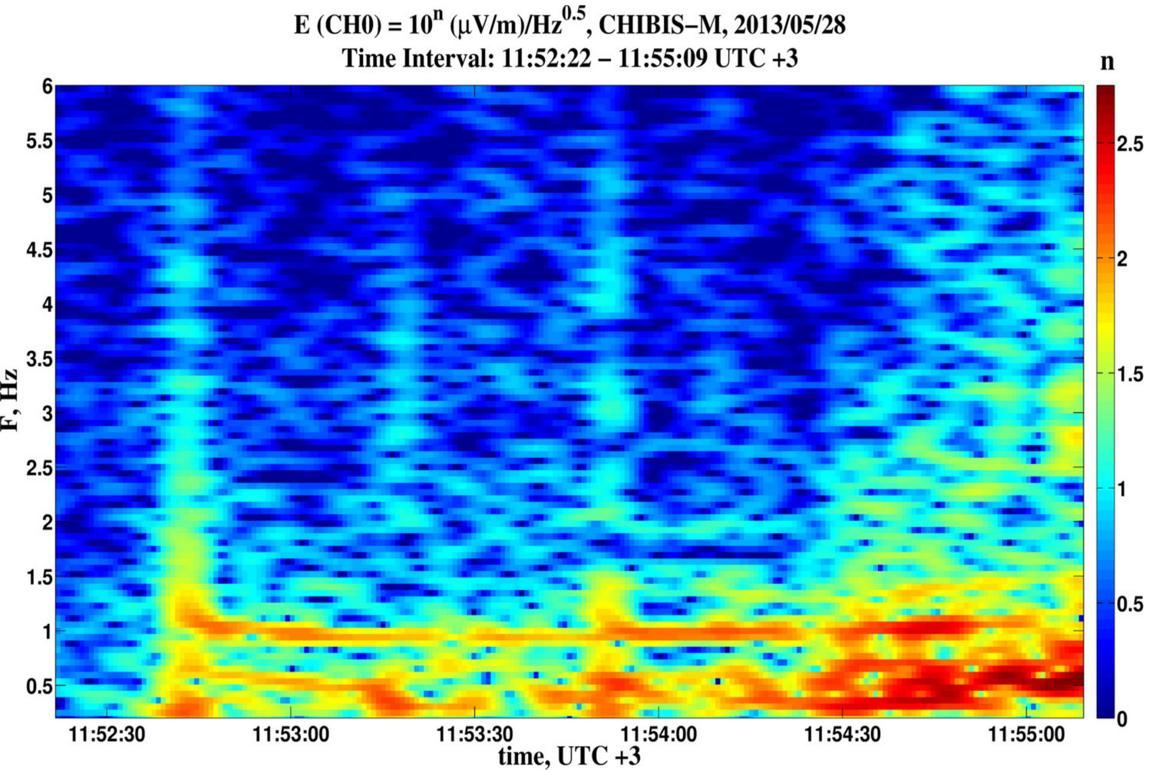




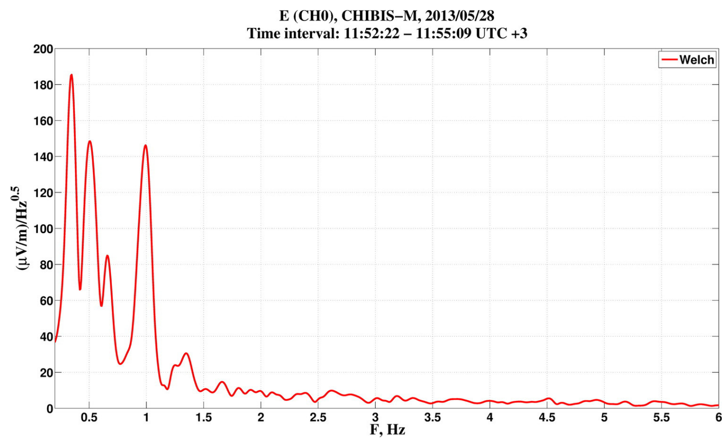
Triggered excitation of IAR (2013/05/28)

Broadband bursts demonstrate fine spectral structure: *f*~0.35, 0.55, 1.0 Hz are highlighted. Initial disturbance may be produced by an intense lightning center, as evidenced by the WWLLN system. It triggers a response at several IAR harmonics lasting up to few 10 s.

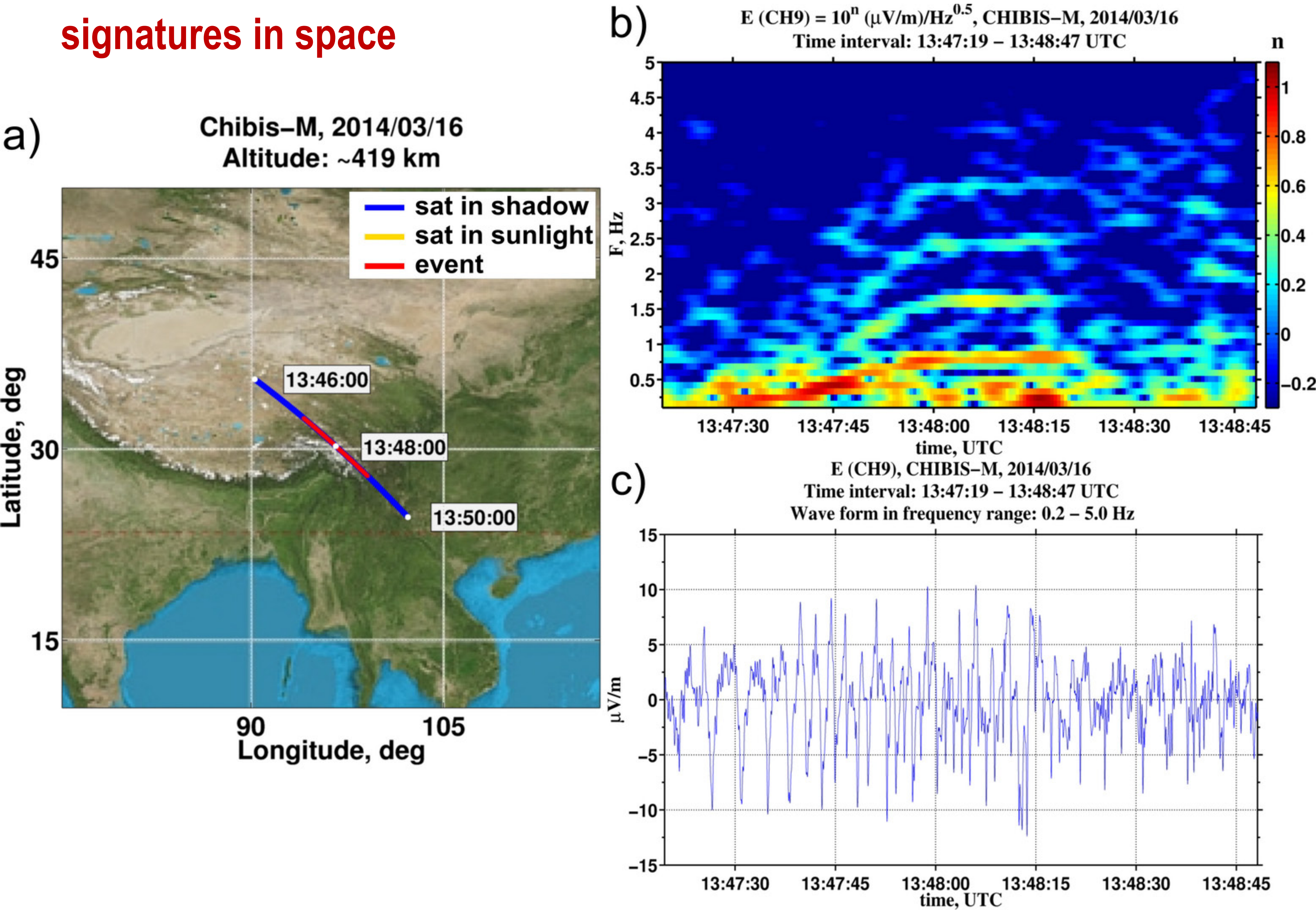




Spectral amplitude reaches E_f~33 μV/m/Hz$^{1/2}$.



Waveforms of the IAR signatures in space



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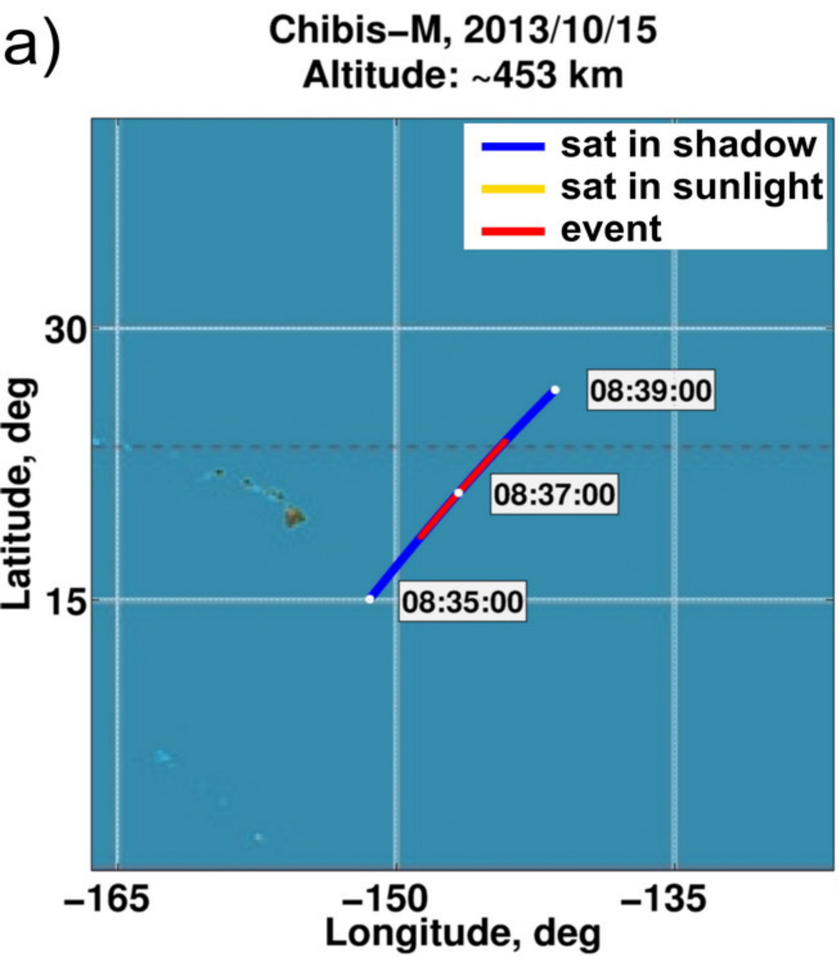

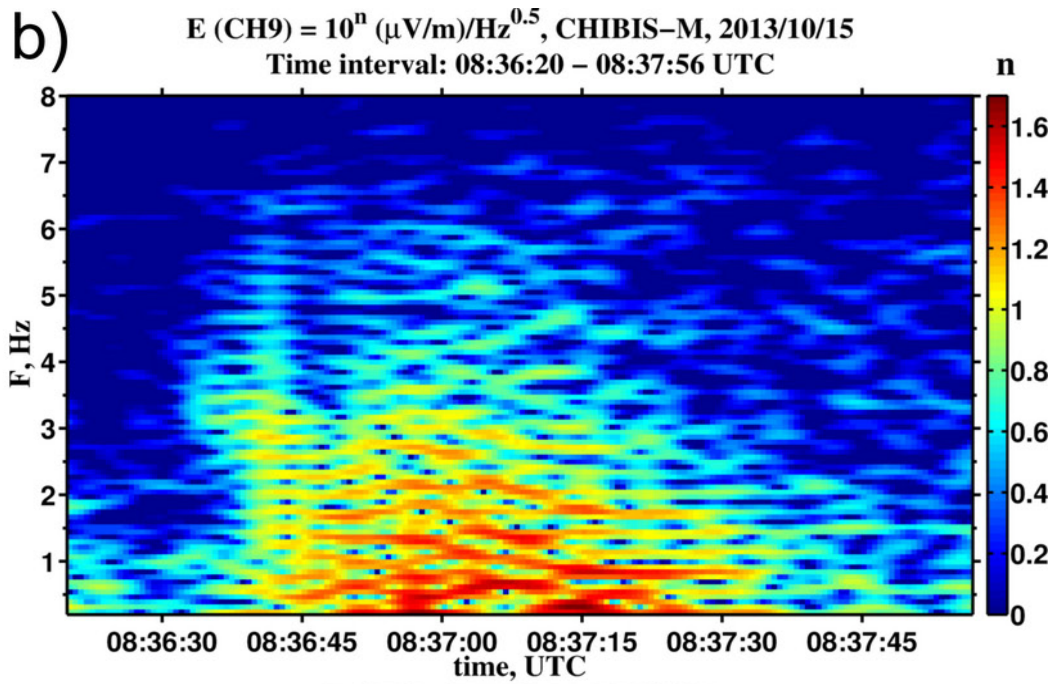

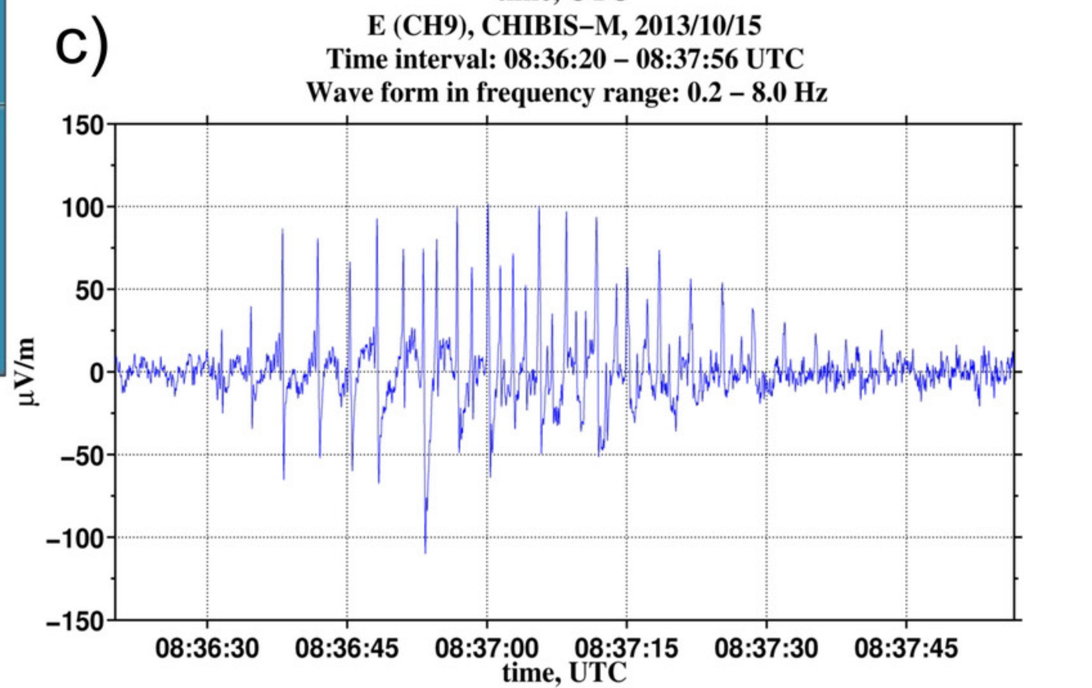

Chibis-M: modeling & observations

Observations confirmed the new paradigm the IAR excitation mechanism:

On the ground the IAR spectral signatures is formed due to the occurrence of an initial stroke pulse and echo-pulse reflected from the upper IAR boundary;

Modeling of the IAR response to an initial pulse from the bottom ionosphere has demonstrated that waveforms and spectra are to be different <u>inside</u> and <u>above</u> the IAR:

- **Inside IAR**, a composition of upward and downward propagating pulses with an irregular time delay and strong dispersion deteriorates regular IAR spectral structure and makes it less evident.
- **In topside ionosphere, well above IAR** upper boundary, only upward propagating Alfvenic pulse can be observed, whereas secondary impulse reflected from the bottom ionosphere would be significantly suppressed.

This may explains a rarity of expected IAR signatures in LEO satellite observations.

Nonetheless, from Chibis-M E-field data we found evidence that multi-band spectral structure in the IAR frequency range is indeed the result of a sequence of lightning-produced pulses.