ELECTROMAGNETIC FIELD IN THE UPPER IONOSPHERE FROM ELF GROUND-BASED TRANSMITTER WITH A FINITE LENGTH

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The electromagnetic response in the ionosphere to natural (e.g., thunderstorms) and man-made (e.g., radio transmitters) sources has been well studied in the VLF range (>1 kHz). Much less attention has been paid to the ULF range (<Schumann resonance) and ELF range (<<1 kHz).

Noticeable ULF/ELF emission efficiency may be expected only from extremely large-scale systems, such as

- ❑ aerials for communication with submarines (e.g., ZEVS)
- ❑ decommissioned power lines as a horizontal radiating antenna for deep MT sounding of the lithosphere
- ❑ networks of electric power transmission 50/60 Hz unbalanced lines
- ❑ rail transportation systems (e.g., BART)

E/m emissions from such systems can be observed at vast territories and even leak into the outer space:

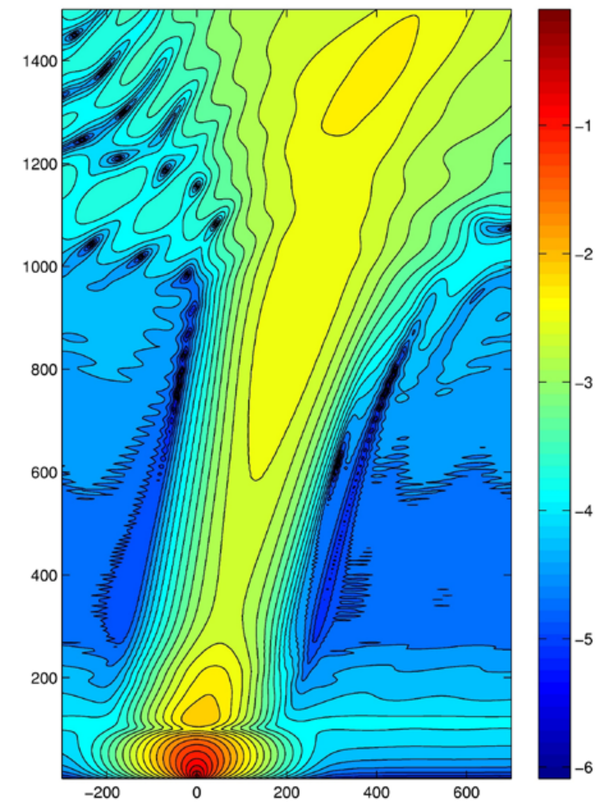
- ➢ 50/60 Hz power line emission (PLE).
- ➢ ZEVS 82 Hz emission was detected by the DEMETER satellite during overflights above the transmitter
- ➢ No attempt to detect ULF/ELF emissions in space during experiments with MT sources were performed

E/m field propagation along the Earth surface from ELF/ULF emitting dipole in the ground-ionosphere waveguide has been well modeled.

At the same time, ULF/ELF wave energy transmission from ground sources towards LEO has not been adequately examined with a realistic ionospheric model. In contrast to VLF emitters, a source of ULF/ELF emissions cannot be modeled as a point dipole, but its finite scale, often exceeding the height of the lower ionosphere, must be taken into an account.

- *Fedorov et al.* (2020) presented a numerical model of e/m response of a realistic IRI ionosphere in the vertical B to a near-ground infinite linear current.
- This theoretical model was advanced by *Fedorov et al.* (2021) by consideration of arbitrary *I*. The model with inclined B has shown that PLE is partially guided by geomagnetic field, so the maximal intensity in the upper ionosphere is shifted equatorward and diminishes upon the Φ decrease, but not significantly.

Here we further investigate theoretically the efficiency of the ULF/ELF wave excitation in the upper ionosphere by a linear near-Earth current of a finite length. We have elaborated a numerical model with a realistic ionospheric profile (derived from IRI model) in a vertical B. The expected wave amplitude at LEO for various types of ULF/ELF transmitters has been estimated.



The initial problem is obviously devoid of axial symmetry, while it turns out that the potential and vortex components separately have such symmetry.
Thus, the representation of e/m field via potentials is used. In this formalism the field can be split into potential and vortex (eddy) components

$$\begin{aligned}\mathbf{B} &= \mathbf{B}_A + \mathbf{B}_F = \nabla A \times \hat{\mathbf{z}} + (ik_0)^{-1}\nabla_\perp \partial_z \Psi - (ik_0)^{-1}\nabla_\perp^2 \Psi \hat{\mathbf{z}}, \\ \mathbf{e} &= \mathbf{e}_A + \mathbf{e}_F = -\nabla\Phi + ik_0 A\hat{\mathbf{z}} + \nabla\Psi \times \hat{\mathbf{z}}.\end{aligned}$$

Thanks to this, it becomes possible to separate variables using the Hankel transform and come to a boundary problem for a system of ordinary differential equations (ODEs).

From Maxwell'equations and expressions the system of equations describing the potentials follows

$$\nabla_\perp^2 \partial_z A = ik_0 \varepsilon_\perp \nabla_\perp^2 \Phi + k_0 g \nabla_\perp^2 \Psi + \mu_0 \,\mathrm{Div}\, \mathbf{j}_\perp$$

$$\nabla_\perp^2 (\partial_z^2 + \nabla_\perp^2 + k_0^2 \varepsilon_\perp)\Psi = -ik_0^2 g \nabla_\perp^2 \Phi + ik_0 \mu_0 \,\mathrm{Curl}\, \mathbf{j}_\perp$$

$$\partial_z \Phi = ik_0[1 + (k_0^2 \varepsilon_{||})^{-1} \nabla_\perp^2] A - (ik_0 \varepsilon_{||})^{-1} \mu_0 j_{||}$$

It is helpful to introduce matrix Y, similar to impedance matrix relating electric and magnetic components.
This method facilitates the solution of Maxwell's equations for fast growing and decaying wave modes.
Matrix Y obeys the nonlinear differential equation of the Riccati type, which has been numerically solved

ZEVS transmitter

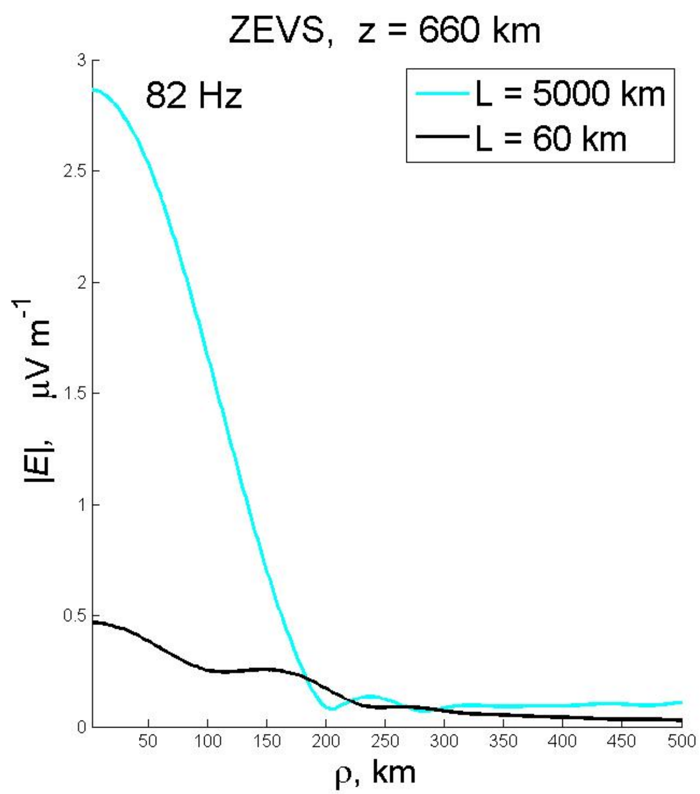
ELF transmitter ZEVS on the Kola peninsula consists of two parallel elongated in the E-W direction grounded antenna L=60 km that emits at f=82 Hz. The generator pumps current up to 200-300 A.

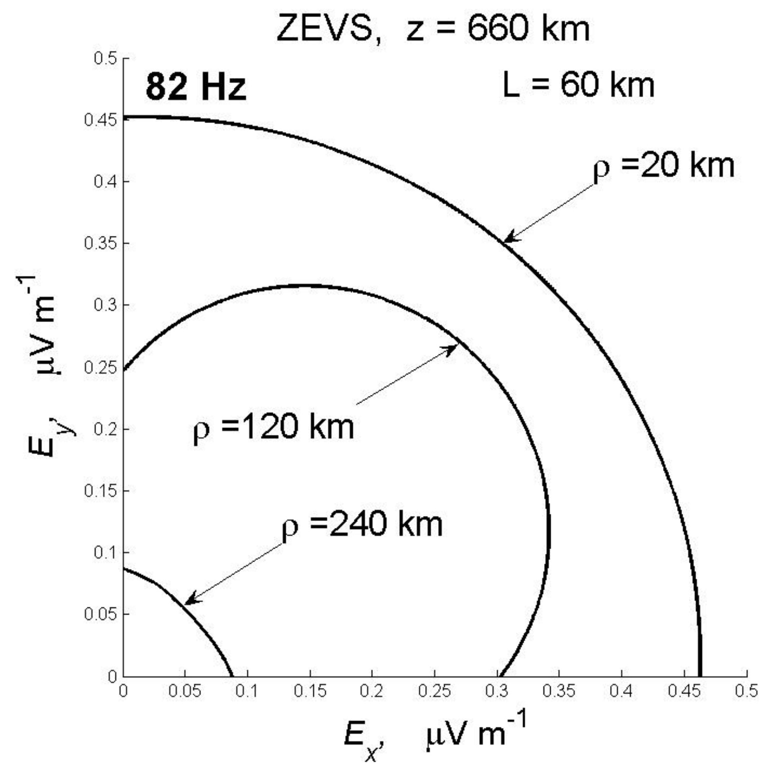
Normalized (J=1 A) response of the ionosphere to horizontal grounded emitter with f=82~Hz and different L:

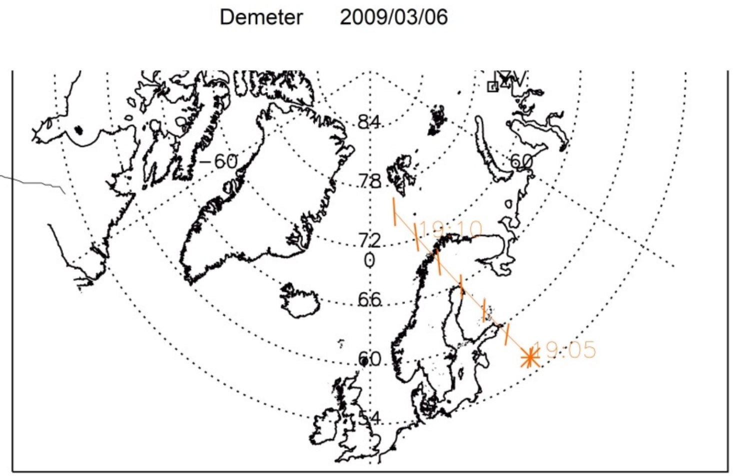
- For L=5000 km (corresponds to the infinite line model) amplitude of transverse electric field E~2.9 μV/m.
- For L=60 km, the amplitude decreases down to ~0.5 μV/m.

The assumption of an infinite scale overestimates the E-field in the upper ionosphere by a factor of ~6.

The field decrease from a source is very slow, upon separation by 200 km amplitude drops 2.8 times only, but at larger distances, the E-field drops significantly.

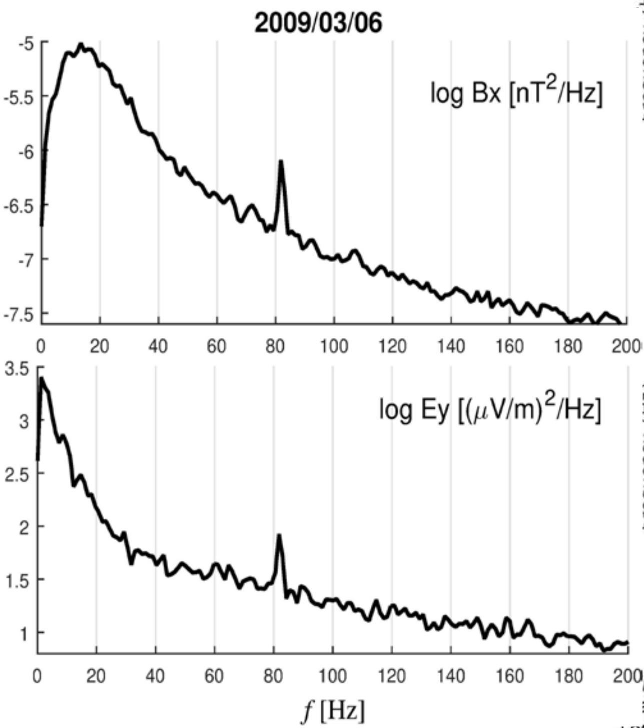


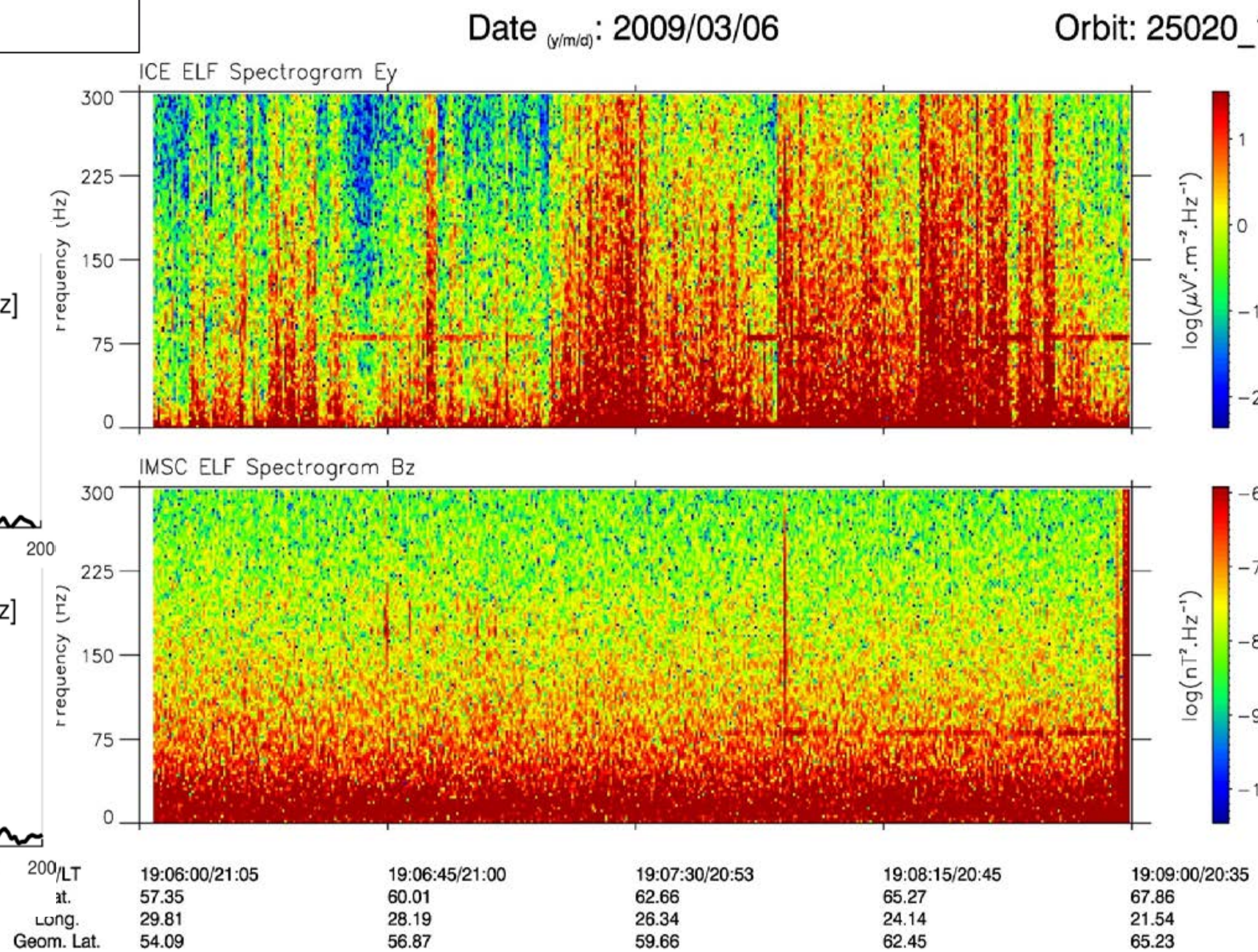




DEMETER detected during nighttime at R~530 km a narrowband ~82 Hz emission

Power spectral densities converted into a signal's amplitude give By~1.4 pT, and Ey~15.4 μV/m.





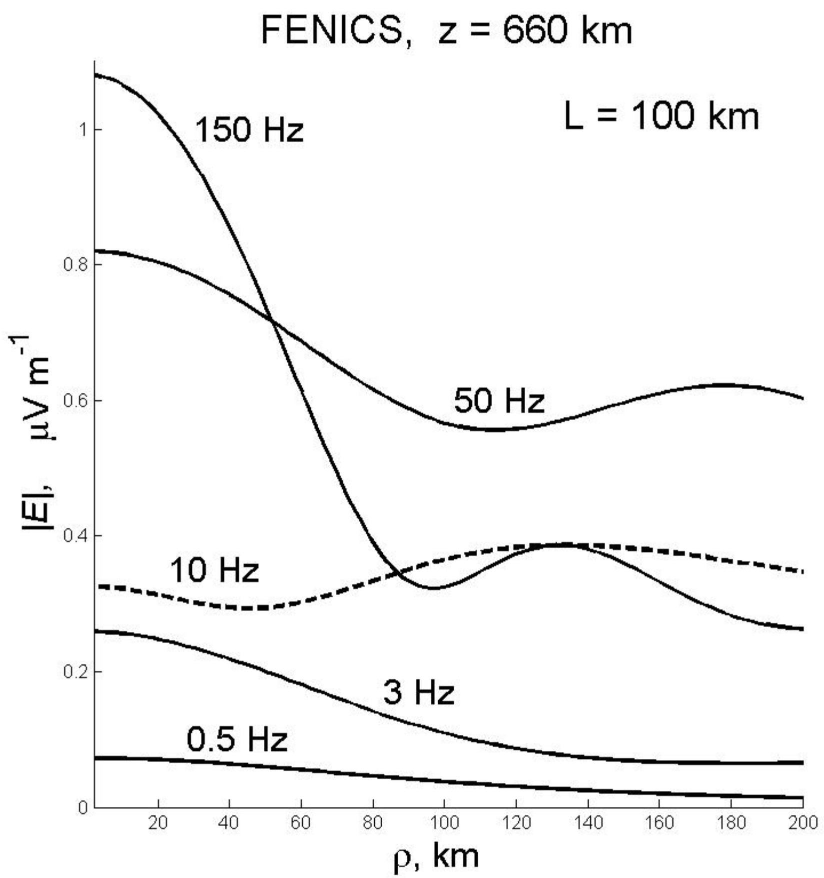
Fennoscandian Electrical conductivity from soundings with the Natural and Controlled Sources installation

Experiments FENICS are conducted at Kola Peninsula with the use of decommissioned power transmission lines with L=100 km and L=120 km. The generator yields AC from 240 A at *f*<10 Hz to 20 A at *f*~200 Hz.

Just above the installation (ρ=0), wave transmission into the ionosphere becomes better with increase of *f:* upon increase from 0.5 Hz to 150 Hz E-field increases from 0.07 μV/m to 1.1 μV/m, that is ~16 times.

Normalized (J=1 A) emission intensity from FENICS transmitter in the upper ionosphere for various f

For typical J=100 A, 10 Hz emissions can leak into upper ionosphere with amplitudes up to ~300 μV/m. Such magnitudes could be detected by electric sensors on modern LEO satellites. However, no attempt to detect the response in space to FENICS has been undertaken.



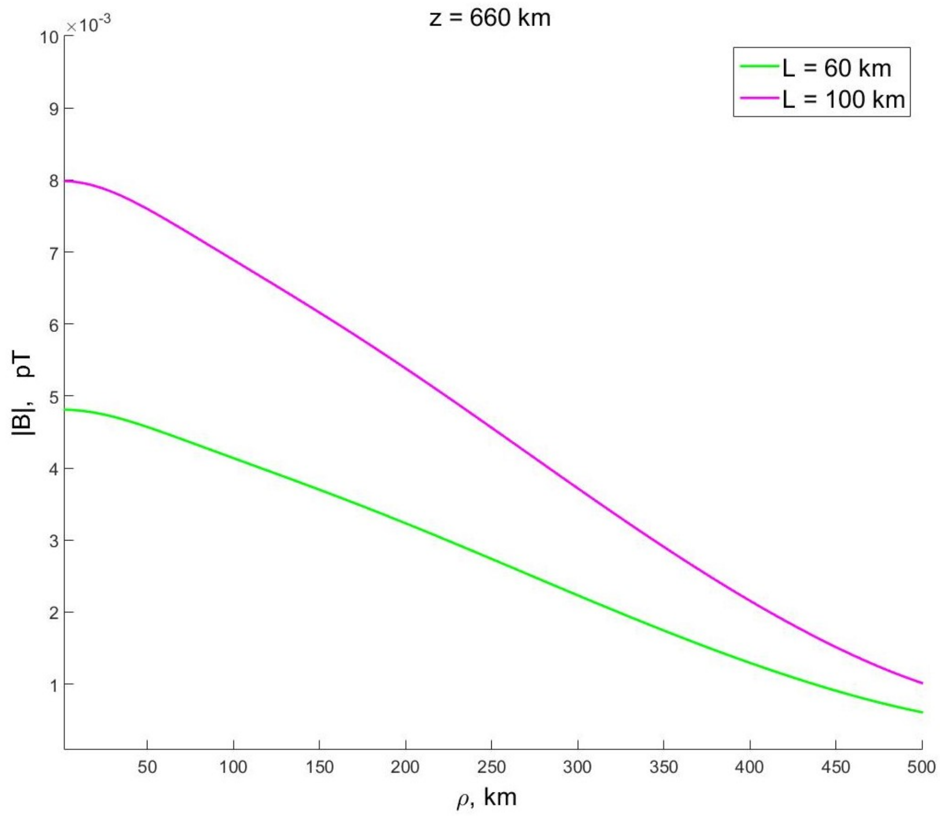
Amplitude of the B-component excited by ground linear current at *f*=0.5 Hz

For ZEVS/FENICS installation (60-100 km) the amplitude of the emitted emission reaches ~0.008 pT. Thus, to launch artificial Pc1 pulsations (0.5 Hz) with amplitude |B|~1 pT and |E|~10 μV/m in the topside ionosphere it would be necessary to drive the installation with J>100 A.

ULF waves in the Pc1 range are of special significance for space physics. Through the wave-particle interactions, EMIC waves can precipitate relativistic electrons into the atmosphere, and suppress the radiation belt.

Radio heating facilities (e.g., HAARP) can stimulate artificial Pc1 pulsations, but this method is very costly.

Modeling has shown that an installation with scale ~100 km and >100 A current is sufficient under favorable conditions to stimulate emission in the Pc1 band.



Power lines of different lengths

How does the amplitude of 50-Hz emission in the upper ionosphere vary depending on the linear scale of power transmission line with unbalanced current J=1 A?

Just above (ρ=0) very large-scale (L=500 km) line the electric amplitude reaches E~2.7 μV/m.

Upon decrease of L the intensity of PLE in the ionosphere decreases down to

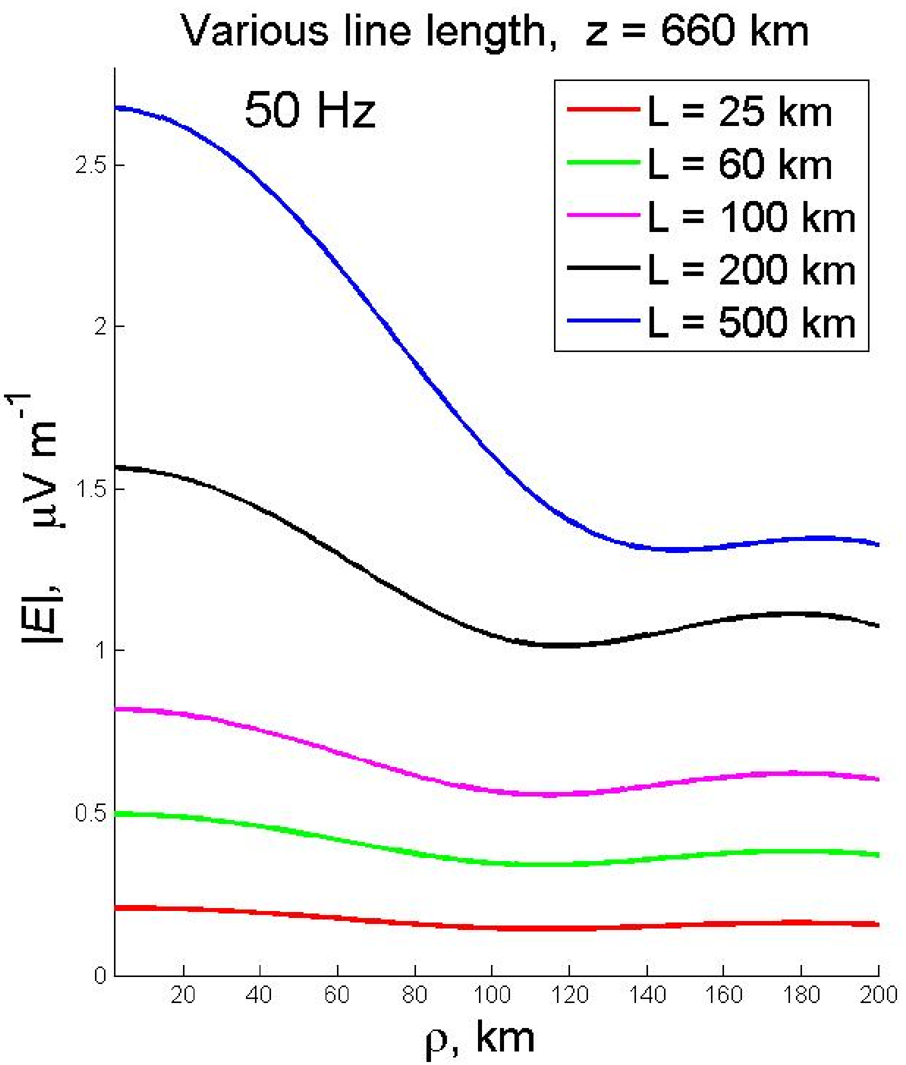
|E|~1.6 μV/m for L=200 km,

|E|~0.8 μV/m for L=100 km,

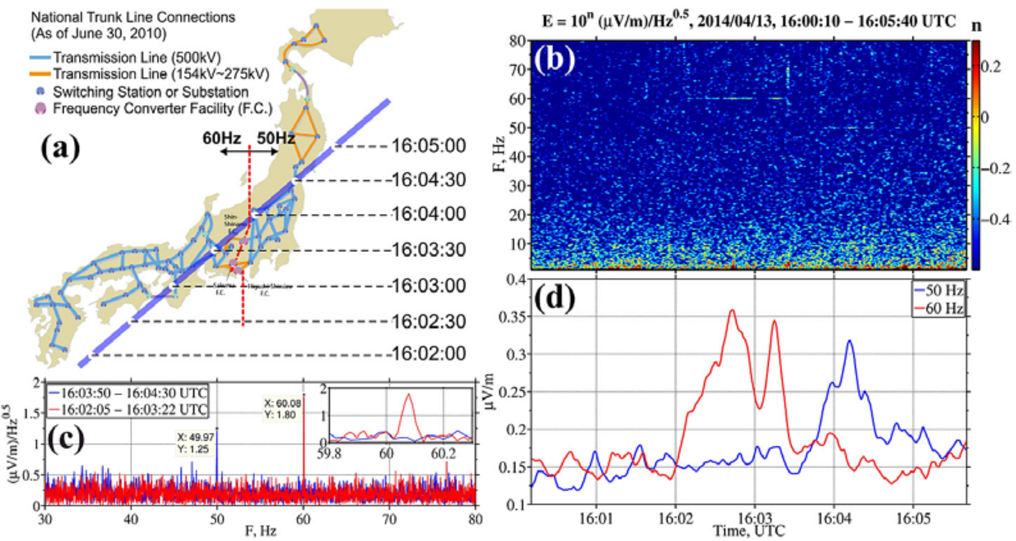
|E|~0.2 μV/m for L=25 km.

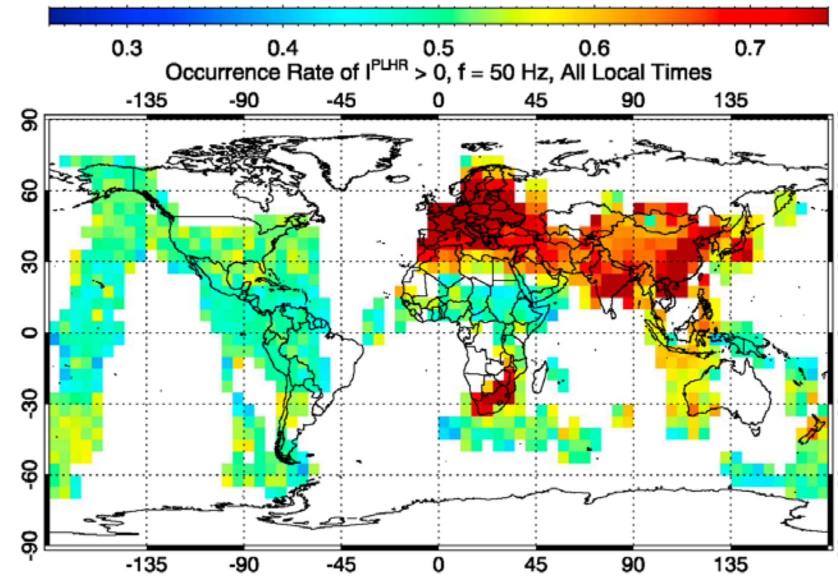
Thus, unbalanced current 10 A can produce PLE ~8-27 μV/m above large scale (>100 km) power lines.

PLE with amplitudes about few tens of μV/m have been indeed detected by electric sensor onboard DEMETER and Chibis-M satellites.

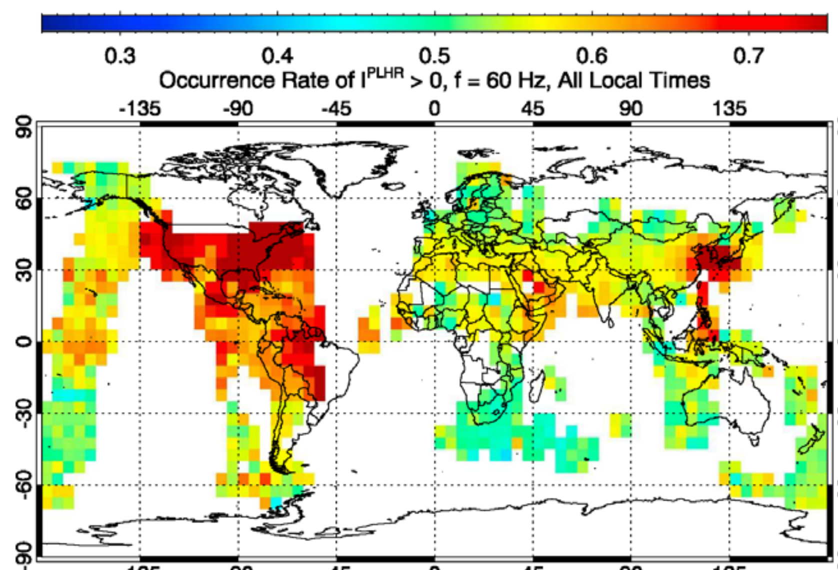


Электромагнитное «загрязнение» околоземного пространства излучением ЛЭП 50-60 Гц (PLE)





Статистика наблюдений PLE на спутнике DEMETER (~700 km) (*Nemec et al.*, 2015).



Geographic maps of PLE occurrence show remarkable agreement with world map of power consumption!

Discussion and fantasies

The DEMETER satellite observations revealed that an amount of global emitted energy by transmission lines has been ever increasing in time since the world total electric generation power increases. Theoretical model predicts that in nightside ionosphere above 50-80 Hz transmitter with L=60-100 km on a resistive ground and driven by 200 A current, the amplitude up to E~60-160 μV/m may be expected.

This modeling result corresponds to the most favorable conditions:

- satellite is exactly above the source (<several hundreds of kilometers)
- larger absorption of ELF emission in the daytime ionosphere as compared with nighttime conditions
- high conductivity of the underlaying crust also decreases the power emitted into the ionosphere.

Our planet was found to exist in an electromagnetic environment, at least in some frequency bands, created by rather industrial activity than by natural processes.

FENICS installation at Kola Peninsula at latitude corresponding to central part of the outer radiation belt can be used as a cheap alternative to deplete the relativistic electrons by triggering artificial EMIC waves.