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Methods for determining the perturbations in VLF in the Earth-ionosphere waveguide and TEC for ionospheric monitoring of catastrophic events in the Lithosphere-Atmosphere-Ionosphere-Magnetosphere (LAIM) system

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A new analytical model has been developed to determine the characteristics of the VLF complex eigenmodes in the waveguide Earth-Ionosphere (WGEI). The developed analytical model, in combination with appropriate numerical methods, provides all important characteristics of (i) complex eigenmodes and their excitation by external electric current source in WGEI, (ii) radiation from WGEI of ELF waves into the upper ionosphere/magnetosphere. After propagation of electromagnetic waves over a certain distance (~ 100 km) from input antenna, either set of complex modes or input boundary conditions for an effective beams may be determined and then the theory [1] for coupled VLF beams in WGEI may be applied. This approach is considered in the context of Nonlinear evolution equations for wave processes in layered structures (NEELS) method for modeling wave processes in layered artificial/natural media [2] (i) taking into account importance of boundary conditions at the input of waveguide region, where the external current source is located, as well as complex impedance boundary conditions at WGEI boundaries [1] and (ii) using appropriate system of evolution equations for coupled wave beams. The measurements of VLF in Japan (from Hayakawa Institute of Seismo Electromagnetics) were used in this study. Fluctuations in VLF amplitudes are revealed with the periods of (i) 2-3 hours; (ii) 5-10 minutes corresponding to the fundamental mode of acoustic-gravity waves (AGW) near the Brunt-Väisälä period (to the best of our knowledge for the first time it has been done based on VLF signals). There is also a weekly antropogenic trend in VLF data. Since 2019, a number of VLFs and LF signals (radiated mostly by European transmitters) have been monitored at NCCSSAU and demonstrate the quasi-wave disturbances with periods of ~10 minutes. The analysis of the relevant data indicates the need to eliminate the impact of hardware effects. Significant influence on the distribution of TEC geomagnetic perturbations was found, in particular, during analysis of

St. Patrick's Day geomagnetic storm (March 17, 2015). To use global TEC maps for studying ionospheric processes, including possible precursors of the most powerful earthquakes, it is recommended to use data with less than one minute time resolution. Different spectral methods for data processing and entropy approach for detecting pre-catastrophic state of LAIM system are discussed. The developed methods can be useful for ionospheric monitoring of catastrophic events in the LAIM system, based on the complex studies (i) of ionospheric disturbances in VLF and TEC, in particular caused by the same source located in the lithosphere/lower atmosphere, magnetosphere or ionosphere; and (ii) the impact of AGW on VLF characteristics in WGEI.

[1] Rapoport Y., Grimalsky V., ... Grytsai A., Fedun V. et al. Model of propagation of VLF beams in the waveguide Earth-Ionosphere. Principles of tensor impedance method in multilayered gyrotropic waveguides, *Ann. Geo.*, 2020, 38, 207–230.

[2] Boardman A.D., Alberucci A., ... Rapoport Yu. G., ... Ivchenko V.M. [et al.]. Spatial Solitonic and Nonlinear Plasmonic Aspects of Metamaterials // *World Scientific Handbook of Metamaterials and Plasmonics*, 2017, 4, 419-469.