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Solution uniquity of an inverse VLF problem: A case-study of the polar, ground-based, VLF radio signal disturbances caused by the ultra-energetic relativistic electron precipitations and of their southern boundaries

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Abstract

Here we present the results of a case study of the rare, abnormal, qualitatively specific behavior of Aldra (northern Norway) and GBR (UK) VLF transmitter signals (10–16 kHz) received at Kola Peninsula. The abnormal amplitude and the phase disturbances of signals were used as a proxy for ultra-energetic relativistic (solar?) electron precipitation (URE, ~100 MeV) into the middle polar atmosphere. The disturbances have been observed under quiet or moderately disturbed geomagnetic activity. Based on bearing results, it was established that the abnormal variations of the electric conductivity of ionized middle atmosphere (of a sporadic D_s layer under the regular ionosphere D layer) were characterized by the following: (i) the time function of height $h(t)$ of an effective spherical waveguide between the Earth surface and the sporadic D_s layer shows a minimum value equal to ~30 km and (ii) the reflection coefficient $R(t)$ of radio wave with a grazing angle of incidence from a virtual boundary with height $h(t)$ has a minimum value equal to ~0.4. The southern boundaries of the ultra-energetic relativistic electron precipitations have been found as well. They turned out to be not southerly than 61 degree of magnetic latitude and similar to the ones obtained in our previous study of the events for other dates under the similar geophysical conditions although we do not know anything definite about the rigidity and density of the electron fluxes.

A used calculation method of analysis is based on a necessary condition that a number n of input data should be greater than a number m of output parameter-functions. We have stated by numerical testing that a decrease of n from 6 to 4 generates a lack of uniqueness of an inverse VLF problem solution for $m = 2$. It is important for future VLF ground-based monitoring of the URE precipitation events.

Keywords: Ultra-energetic relativistic electrons; Precipitation; Bremsstrahlung X-rays; Geomagnetic cutoff; Space weather; VLF remote sensing

1. Introduction

The phenomenon of ultra-energetic relativistic electron precipitations (UREP's with the electron energy up to 100 MeV or greater) into the auroral middle atmosphere (Remenets and Beloglazov, 2013, 2015; Remenets and Astafiev, 2015) has become known due to the multi-frequency monitoring of VLF radio signals in the Polar Geophysical Institute of RAS (Kola Peninsular, Russia) from two radio stations in 1982–1992 years (Beloglazov and Remenets, 2010; Remenets and Beloglazov, 2015) and due to the computer and physics analysis of the pointed experimental data. This method of analysis is a self-consistent VLF computer method of inverse problem solution (Remenets and Beloglazov, 2013). Its peculiarity is the usage of over-constrainedness of the input data, giving relative variations of the input VLF magnitudes. This point is necessary for the determination of time variations

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(while a geophysics disturbance) of the magnitude *absolute* values. The last ones characterize the electric properties of the middle polar atmosphere. A brightest result of this kind was obtained for the geophysics events on 29 September 1989 (Remenets and Beloglazov, 1992). In this work the authors had a good luck to investigate a continuous sequence of 3 disturbances: a precipitation of the relativistic electrons (04:00–10:00 UT, UREP, quiescent geophysical conditions), X-ray flare on the Sun (since 11:00 UT) and a proton precipitation (since 12:00 UT) in the frames of mutual experimental VLF method of the measurements and of mutual analysis method. The disturbance of electric properties of the middle atmosphere in the first case (UREP) was comparable with the disturbances in the following events.

A list of registered events was published in the works (Beloglazov and Remenets, 2005; Remenets and Beloglazov, 2015). An analysis of individual UREP event with a purpose to get the time variations of electric conductivity of middle atmosphere was begun in the work (Remenets and Beloglazov, 1985). The analysis is a slow and scrupulous computer process because (i) every event is not stationary and individual (as the solar proton precipitations or the Sun X-ray flares), because (ii) the input data are the *relative* variations and are the result of interference phenomenon of 3 modes propagating, because (iii) for an every step of time analysis the physics variations of the magnitudes are comparable with the casual absolute errors, because (iv) the same time step must be relatively small in order to guaranty the correct usage of linear approximations in the theory, and because (v), when anybody determines 2 or more parameter-functions, the analysis may be stopped (while its making) by poor conditionality of an equation system. For an analysis with such peculiarities we do not know a standard procedure of error estimate and have only one way of estimation of the result reliability – to compare the input experimental functions of time with the calculated ones corresponding to the electric properties determined.

Before to address to the results being presented, we ought to point the place of our study in the field of relativistic electron population in the near-Earth space, ionosphere and atmosphere. For this we shall indicate several works from the enormous field of ones which are, as we consider, have the nearest relation to our investigation and which are a supplementation to the references given in (Remenets and Beloglazov, 2013; Remenets and Astafiev, 2015).

The results of ultra-relativistic electron (URE) investigation in the inner radiation belt of the Earth are represented in the works (Selesnick, 2015; Li et al., 2015; Shprits et al., 2013), the dynamics processes, related to the URE, in the outer radiation were studied in the publications (Janes et al., 2014; Meredith et al., 2015, 2016; Su et al., 2015; Turner et al., 2014; Run et al., 2016). The extreme value analysis of daily averaged $E > 2$ MeV electron fluxes from the GOES (with a geosynchronous orbit) during 19 years is represented in (Meredith et al., 2016) and a comparison of the ultra-relativistic electron fluxes ($E > 2$ MeV) with the less energetic fluxes is given in (Drosdov et al., 2015). An interaction of the solar wind with the Earth magnetosphere and with the electron component in the radiation belt, in particular, was analyzed in the works (Li et al., 2015; Shi et al., 2013).

The studies of high-energy proton precipitations and of geomagnetic cutoff effect for the GeV electrons (Smart and Shea, 2005; Bazilevskaya et al., 2010; Machmutov et al., 2015) is a pointer to the UREP's ones. The measurements of positrons and electrons with the energy 80–1500 MeV at the altitudes 350–600 km ($L \sim 1.2$) has given the following ratio of their fluxes: $e^+/e^- = 4$ (Michailov et al., 2016). The interactions of the energetic corpuscular fluxes of the near-Earth space with the ionosphere and atmosphere are the themes of reviews (Welling et al., 2015; Mironova et al., 2015).

This above brief review indicates on an update situation when the problem of UREP events stays to be out the field of direct measurements. Adding to it, we pay attention to the fact that its peculiarity not only in the values of electron energy ($\sim$100 MeV) but at the same time in their abnormally great population (density of fluxes) in the near-Earth space which causes up to several tens of thousand km^3 of the middle polar atmosphere to be significantly ionized.

In present work we solve the inverse problem for 5 UREP's. For 4 of them it was possible to estimate their southern boundaries, Sections 4–7. Making this study we have crossed over with not trivial and important for future VLF ground-based measurements fact. It turned out that 4 input relative variations of magnitudes were not enough for stable inverse solution for 2 parameter-functions with certain physics dimensionality, Sections 3 and 6. This peculiarity is a new and important point of present work too. In order to get a correct solution of the inverse problem we had to use not less than 6 input experimental functions.

Update, the number of events investigated as functions of time is relatively small (about 25 for about 200 registered and which it is possible to analyze). All powerful disturbances (PwD's; about 16 events) were described in the work (Beloglazov and Remenets, 2005), all strong disturbances (StD's) and moderate disturbances (MdD's) for 1982–1987 years were represented in the publications (Remenets and Beloglazov, 2015; Beloglazov and Remenets, 2010), and only for about 10 StD's the inverse VLF problem was solved, (Remenets and Beloglazov, 1992, 2013; Beloglazov and Remenets, 2005; Remenets and Astafiev, 2015). Therefore, this kind of time case-study should be continued.

An UREP phenomenon is characterized by the abnormal variations of amplitudes and phases of the VLF radio waves (10–14 kHz) for an auroral radio path on a background (rather frequently) of the quiescent geophysical conditions, id est., for different frequencies the VLF magnitudes are changing approximately in similar way, although,