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MONITORING OF LOWER IONOSPHERE: POSSIBLE EARTHQUAKE PRECURSORS AND APPLICATION IN EARTH OBSERVATIONS BY SATELLITE

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Abstract. Ionospheric observations can be used for indirect detection of various processes in the outer space and Earth. In addition, the ionosphere affects the propagation of electromagnetic signals used in numerous practical applications. Here, we present the latest research based on the observation of the low ionosphere by very low frequency radio signals recorded in Belgrade related to a possible new type of earthquake precursor, and the impact of the perturbed ionospheric D-region on the propagation of satellite signals used in Earth's observations.

1. INTRODUCTION

Research of the ionosphere is of great importance for both science (first of all for geosciences) and modern technologies based on the use of satellite and ground based electromagnetic signals. Practical applications of these studies are important for many contemporary area of human life including telecommunications, GPS positioning and Earth observations. Namely, disturbances of the ionosphere can strongly affect propagation of these electromagnetic waves and induce significant errors in measurements and modelling of different parameters (Nina et al., 2020b). In addition, there are many studies which indicate connections between ionospheric disturbances and natural disasters (Nina et al., 2017; Pulinets and Boyarchuk, 2004; NaitAmor et al.,2018; Kumar et al. 2016). Some of these ionospheric perturbations are recorded before events which are following by large catastrophes (Maekawa et al., 2006; Maurya etal.,2016; Molchanov et al, Yamauchi et al., 2007) and for this reason their investigation is of high priority.

The lower ionosphere can be monitored by several techniques including those based on propagation of very low/low frequency (VLF/LF) radio signals in the Earth-ionosphere waveguide. The advantages of this method in analysis of the atmospheric layer between 50 km and 90 km are (1) continuous monitoring of signals with time resolution that is usually better than 1 s, and (2) observation of large part of the lower ionosphere which is provided by numerous worldwide located transmitters and receivers.

In this paper we present recent investigation based on data collected by the Belgrade VLF/LF receiver station located at the Institute of Physics Belgrade. We pay attention to two studies related to disturbances in periods around earthquake (EQ) events (Nina et al., 2020a) and during a solar X-ray flare influence (Nina et al., 2020b). In first study attention is focused on analysis of possible connections between an earthquake and changes in electrical properties of the lower ionosphere. In the second study we analysed influence of the intensive perturbed ionospheric D-region by a solar X-ray flare on satellite signals.

2. OBSERVATIONS, DATA PROCESSING AND MODELLING

In our research we use data obtained in the lower ionosphere observation by VLF signals emitted by the ICV, GQD and DHO transmitters located in Italy, the UK and Germany (see Table 1) and recorded by Belgrade receiver station. The propagation paths od these signals are shown in map given in Fig. 1.

Table 1: Transmitter locations and frequencies for the considered VLF signals.

	Transmitter location	Frequency (kHz)
ICV	Isola di Tavolara, Italy	20.27
GQD	Rhauderfehn, Germany	22.1
DHO	Anthorn, the UK	23.4

We analyse data recorded by the Absolute Phase and Amplitude Logger (AbsPAL) and Atmospheric Weather Electromagnetic System for Observation Modeling and Education (AWESOME) receivers in the first and second analysis, respectively. We analyse data sets for all three signals with time sampling of 0.1 s and for DHO signlal with time sampling of 1 s, respectively.

2. 1. NOISE AMPLITUDE REDUCTION AS POSSIBLE EARTHQUAKE PRECURSOR

There are many studies which indicate relationships between EQ events and ionospheric disturbances (see, for example, Biagi et al., 2001; Nina et al. 2020a; Pulinets and Boyarchuk, 2004). These studies are primarily based on the comparison of variations detected during different days. In Nina et al., 2020a, variations in natural short period noise amplitude are analysed for time period around the Kraljevo EQ (Mw=5.4) occurred on 3 November, 2010. We analysed data recorded by the 0.1-s time resolution in order to investigate signal changes several hours before and after the considered EQ event.

In addition, three EQs with magnitudes 4.3, 4.4 and 4.5 are analysed. One of them (Mw=4.4) occurred at location that was very close to the epicentre of the main EQ, while the epicentres of other events were at longer distance from the signal propagation paths than in the first two cases. For all of these events it is common that magnitudes were greater than 4 and that they occurred in the night-time period.

In this analysis, three signals emitted in Italy (ICV), the UK (GQD) and Germany (DHO) and recorded in Belgrade are analysed. The noise amplitude is calculated from the amplitude deviation from smoothed curve during the considered time periods.

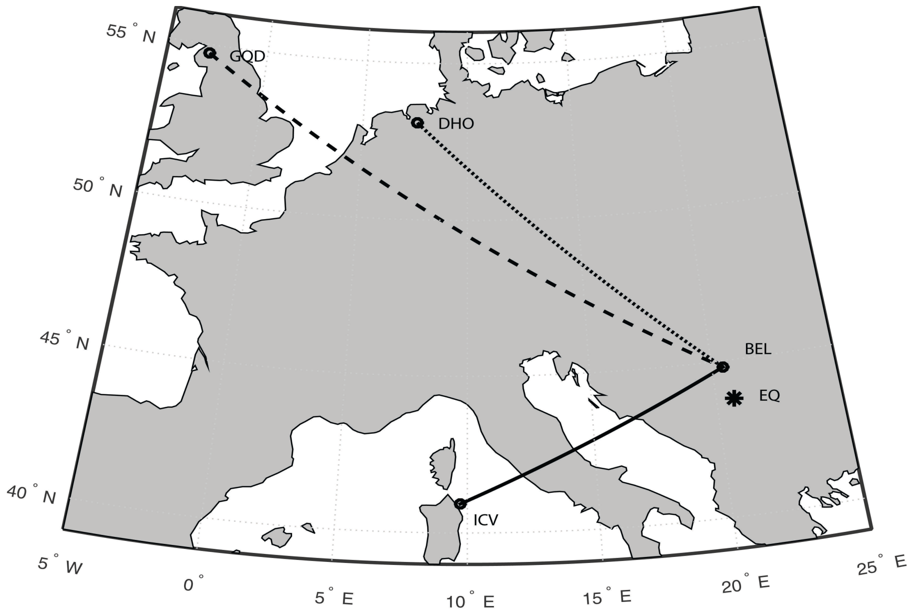

Figure 1: Propagation paths of the VLF signals recorded by the Belgrade receiver station (BEL) in Serbia and emitted by the transmitters ICV in Italy (solid line), GQD in the UK (dashed line), and DHO in Germany (dotted line). Locations of the Kraljevo earthquake is shown as stars.

2. 2. INFLUENCE OF THE D-REGION ON SATELLITE SIGNAL PROPAGATION

There are numerous models that are used in calculations of the ionospheric contribution in the signal delay, so called ionospheric delay, (Nava et al., 2008; Zhao and Zhou, 2018). Mostly, they use observational data as input and use analytical expressions for modelling of the ionospheric delay. If the observational data relates to one or more altitudes, a particular model is single or multiple layer model, respectively. In both cases these altitudes are above 100 km because upper areas has larger influences on signal propagation due to larger electron density. For this reason, calculations of the total electron content (TEC), which is required for modelling of the signal delay, are based on approximations that electron density vertical distribution can be obtained from the observational data at fixed altitudes and used expressions. Because of the fact that ionospheric parameters can be significantly changed in a localized area during some time interval, two questions should be considered: (1) Are the used expressions applicable during intensive disturbances? and (2) Can local disturbances below 100 km be important?

In Nina et al., 2020b influence of a solar X-ray flare which primarily disturbs the D-region (50 km- 90 km) on GNSS and Synthetic Aperture Radar (SAR) signal delay is considered. Error in modelling of the signal delay $P_{\rm D} = C \cdot TEC_{\rm D}/f^2$ if the D-region is not included in consideration depends on the total electron content in D-region, $TEC_{\rm D}$, which is given by expression:

$$\mathrm{TEC_D} = \delta H_\mathrm{D} \sum_{i=1}^{N_\mathrm{D}} N_\mathrm{ei} n_\mathrm{i} [{n_\mathrm{i}}^2 - (n_0 \sin(\Theta_0))^2]^{-0.5}. \quad (1)$$

where δH_D is the thickness of horizontally uniform layers in the D-region, N_ei and n_i are the electron density and refractive index in layer i, respectively, and Θ_0 is the wave propagation angle in the D-region.

3. RESULTS

3. 1. NOISE AMPLITUDE REDUCTION AS POSSIBLE EARTHQUAKE PRECURSOR

Significant reduction of the noise amplitude is recorded for ICV signal emitted in Italy whose propagation path lies the closest to the EQ epicentre. The beginning of this reduction is before the EQ which indicates possibility that this type of variation can be consider as EQ preqursor. Variations in the noise amplitude are also recorded for other two signals but they are not specific for the considered night and they can not be connected with EQ event.

To examine influences of the epicentre distance from the signal propagation path and to examine noise amplitude reduction recorded in the other time periods additional analyses of the ICV signal amplitude are performed. They were related to:

- Time evolution of the amplitude noise in periods around three EQs of magnitudes 4.4 (the same epicetre location like for the main EQ event), and magnitudes 4.3 and 4.5 (epicentres at larger distance than in the first two cases);
- Time evolutions of the noise amplitude during hole three days.

The noise reduction is also recorded for EQ with epicentre near the epicentre of Kraljevo EQ. In the other two cases these reductions are not recorded which indicates importance od epicentre distance from the signal propagation path.

To examine the regular daily variations in the noise amplitude (this analysis is important for the extraction of the sudden from periodic variations) the short-period noise amplitude is analysed during three whole days: 3 and 4 November when two EQs near Kraljevo occurred, and 9 November when significant reduction of the noise amplitude is also recorded in analysis of two months in periods of 1 hour around time of Kraljevo EQ (0:56:54.4 $\pm$ 0:30 UT). During these day, 46 EQs (excluding 29 that occurred in a few hours after Kraljevo EQ when extraction of their influence is not possible) were detected with epicentres not far from the ICV signal propagation path (`http://www.emsc-csem.org/Earthquake/`). The most intensive were two EQs with Mw>5 (near Kraljevo (Mw=5.4) and in Tyrrhenian Sea (Mw=5.1)) and two EQs with Mw>4 (near Kraljevo (Mw=4.3) and in Western Mediterranean Sea (Mw=4.3)). Only 13 of these EQ events had the magnitude greater than 3. Analysis of the noise amplitude during these three days shown:

- The short-period amplitude reduction starting before the EQ event is recorded for all 4 detected EQs with magnitude greater than 4.
- 8 of 10 EQs near Kraljevo (i.e. 80%) with magnitude greater than 2.5 are connected with the noise amplitude reduction.

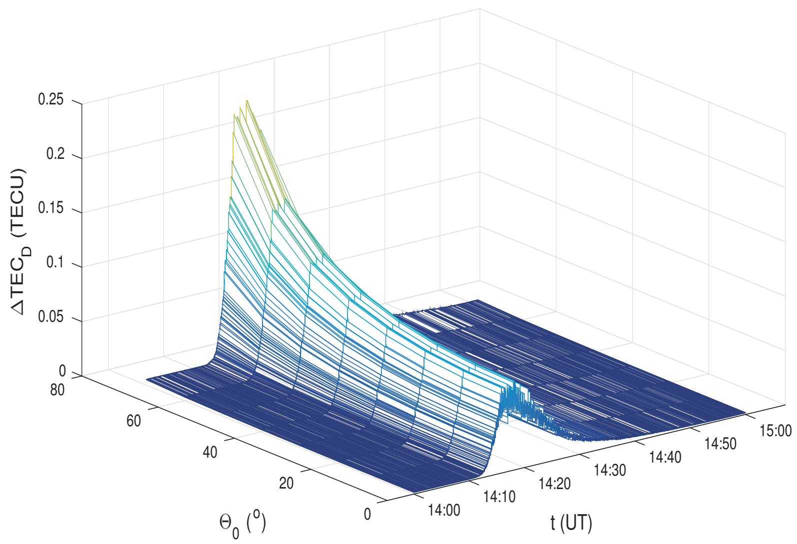

Figure 2: Time evolution of changes in the total electron density within D-region, ΔTEC_D, for different incident angles, Θ of signal in this area during influence of a solar X-ray flare occurred on 1 May 2013.

- Thirteen out of a total of 15 (or 87%) decreases of the short-period noise amplitude can be related to EQ events.

In addition, it is very important to point out that reductions of the short-period noise amplitude are recorded in all day periods.

3. 2. INFLUENCE OF THE D-REGION ON SATELLITE SIGNAL PROPAGATION

As one can see in Fig. 2, changes in TEC_D can be intensive. Results presented in Nina et al., 2020b show that, for more intensive flares, the D-region can provide the signal delay of more than 1 m for large incident angles. Keeping in mind that delays of 1 cm are included in signal propagation modelling it can be concluded that, although quiet D-region does not affect satellite signal propagations, its influence cannot be ignored in periods of intensive disturbances because errors in modelling can be important.

4. SUMMARY

In this work we present review of the recent results obtained in the lower ionosphere investigation based on data obtained by VLF/LF receiver station in Belgrade. We present analyses of (1) possible new type of earthquake precursor visualized as reduction of the signal noise amplitude before the earthquake event, and (2) influence of the ionospheric D-region which is disturbed by a solar X-ray flare on delay of satellite signals.

The main results of these studies indicate that:

- Reduction of VLF signal noise amplitude is recorded before several earthquakes and that confirmation of connection of these changes with earthquake events requires more detailed statistical analysis.
- Influence of the significantly disturbed D-region on propagation of satellite signals can be important and its contribution in signal delay should be involved in modelling.

These studies open many questions important for practical application of ionospheric research and they will be in focus forthcoming studies.

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