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PERTURBATIONS OF THE TERRESTRIAL LOW IONOSPHERE CAUSED BY SOLAR FLARES

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Abstract. This paper considers the most important way of investigation of terrestrial low ionosphere by VLF waves as "ionospheric probes" and explains the significance of such studies. Also, the characteristics of the Belgrade VLF station located in Institute of Physics in Belgrade are described. Finally, the attention is focused to analyses of low ionosphere response to solar X-flares.

1. INTRODUCTION

The earth's gaseous atmosphere is under permanent influence of ionizing radiation of different origins. The resulting concentration of charged particles has local maxima in the region called ionosphere at altitudes somewhere between 60 km and 1000 km. The highest periodic daily changes of electron concentration at a specific location are related to the diurnal day-night and night-day transitions, which suggests the solar radiation being the dominant source of ionization.

The electron concentration in the low ionosphere is more then one order of magnitude higher during the day then at night. Because of this difference, the ionosphere in studies is generally divided into the daytime and nighttime ionosphere. At daytime, the influence of solar background radiation is rather strong so that only sufficiently large variations in the charged particle concentration can be detected. Contrary, during the night time, much smaller changes in electric concentration are measurable.

Solar radiation is the most important origin of ionization processes in the ionosphere. Variations of its affect on the earth's atmosphere can be regular and transient. Regular changes are diurnal, seasonal and solar cycle related (Bremer and Singer 1977). Transient variations are caused by solar flares (McRae and Thomson 2004, Nina et al. 2012a) and solar coronal mass ejections (Balan et al. 2008).

The ionizing radiation in the ionosphere can originate in the outer space but it may also have a terrestrial source. The $\gamma-$ray bursts from magnetars is one of the influences on the terrestrial ionosphere that comes from very distant origins (Fishman and Inan 1988). Also, some processes occurring in the earth atmosphere, like lightnings (Cummer 1997), and in the lithosphere, like earthquakes (Hayakawa et al. 2010), can cause ionization of the low ionosphere.

Processes in the terrestrial ionosphere are rather complex which makes their exact scientific studies practically impossible. Consequently, relevant models like the Sodankyla Ion Chemistry (SIC) model (Turunen et al. 1992) and the International Reference Ionosphere (IRI) model (Rawer et al. 1978) become necessary in studies of these phenomena.

The experimental data included in the theoretical models can be obtained by different techniques related to ground-based facilities, sounding rockets, and satellites.

In this paper the attention will primarily be focused on experimental and theoretical research of the daytime low ionosphere electron concentration changes induced by solar X-flares.

2. LOW IONOSPHERE INVESTIGATIONS

The methods used in investigations of the ionospheric layer are numerous and they depend on the altitude of the considered medium. The investigations of low ionosphere find applications in pure science as well as in information technologies. In science, they are of importance in ionospheric diagnostics, studies of physical and chemical processes, and for detections of different pure natural and man-induced events. On the other hand, knowing the structure and dynamics of the ionosphere is very important in telecommunications like radio communications, planning networks of new mobile communications satellites, applications of global navigation satellite systems of high precision, etc.

The main way to analyze the low ionosphere (altitudes between 60 and 90 km) is based on properties of propagating VLF waves. Namely, during propagation from a transmitter to a receiver, the signals are reflected from the low ionosphere. The wave reflection height depends on the electron concentration and its induced changes result into some characteristic time variations of the signal amplitude and phase. For this reason, the recorded signal properties can be used to analyze the ionospheric electron concentration in situ as we are going to show below.

The advantage of this method is a continuous emission of signals by transmitters. Also, the VLF signal transmitters and receivers (incorporated in several networks such as AWESOME, AbsPAL , SAVNET and AARDDVARK) are located worldwide which allows for analyses covering large areas.

In theoretical analyses, a few numerical programs, such are LWPC (Long-Wave Propagation Capability) (Ferguson 1998) and ModeFinder (Morfitt and Shellman 1976), are used for simulations of VLF signal propagations. Calculations in these programs are based on approximations of electromagnetic waves propagating inside a spherical waveguide bounded by the earth's surface and the ionospheric layer where the VLF wave reflection occurs.

3. BELGRADE VLF STATION

There are two different VLF receivers located in the Institute of Physics in Belgrade which are incorporated into AbsPal and AWESOME international receiver networks (Fig. 1).

The AbsPal receiver, with an electrical antenna, operates as of 2004 and it can simultaneously record 6 signals from different transmitters.

Figure 1: VLF receiver systems at Belgrade station: AbsPAL (left) and AWESOME (right) antennas.

The AWESOME receiver has two loop magnetic antennas and it can simultaneously record maximum 15 signals from different transmitters. It works as of 2008.

4. RESULTS AND DISCUSSIONS

During the daytime, the most important affects on the terrestrial ionosphere have solar flares (Nina et al. 2012a, 2012b). The electron concentration variations are dependent on radiation spectra and the local atmospheric characteristics in the considered periods. Such changes induce variations in signal amplitude and phase which makes the analisis of recorded VLF signal applicable in investigations of solar flares influences on low ionosphere.

In this paper, we choose the event that occurred on March 24, 2011 between 12:01 UT and 12:11 UT as a typical example of an ionospheric response to a solar X-flare. The radiative flux intensity variation, as recorded by GOES-15 satellite, is shown in Fig. 2, the top panel, while the signal amplitude and phase variations relative to values in the case of the unperturbed ionosphere and registered by the Belgrade AWESOME receiver are presented in the bottom and the middle panels, respectively. The considered signal is the one being transmitted by the DHO transmitter in Germany at 23.4 kHz.

In the theoretical analysis, we use the Wait's model for the ionosphere which is characterized by two independent parameters the sharpness β and the reflection height H'. The VLF signal propagation is simulated by the LWPC numerical program with input parameters β and H' while the output data we used in our calculations are the signal amplitude and its phase.

In the case of unperturbed ionosphere, the program gives 0.3 km^{-1} and 74 km for β and H', respectively. When the ionosphere is perturbed, these two parameters are chosen as a pair combination that gives the best matching of the amplitude and phase values obtained by LWPC with those recorded directly by the receiver. The time distributions of these parameters are presented in Fig. 3. In the considered case, we can see that H' has a minimum and β a maximum in the time of maximal ionospheric perturbation.

Knowing the time dependence of these values, the electron concentration $N(t,h)$ at altitude h and time t can be calculated from the Wait's theory by:

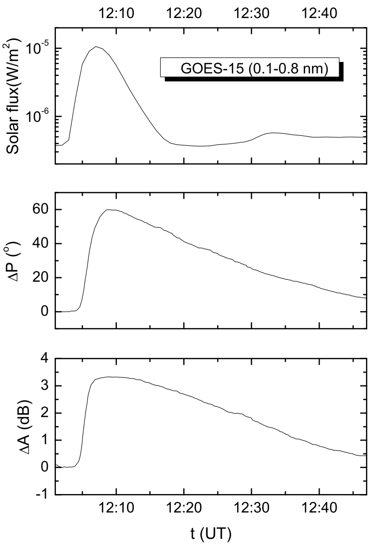

Figure 2: Solar flux registered by GOES-15 satellite and phase and amplitude changes of signal emitted from DHO transmitter (Germany) and recorded by the AWESOME receiver in Belgrade (Serbia) at the time of the observed flare. Zero values correspond to the amplitude and phase recorded when the ionosphere is unperturbed.

$$N(t,h) = 1.43 \times 10^{13} e^{-\beta(t)H'(t)} e^{(\beta(t)-0.15)h}. \tag{1}$$

The time distributions of the electron concentration at 70, 75 and 80 km are shown in Fig. 4. Very interesting is the fact that the start of rise and the maximum of the electron concentration $N(t,h)$ both occur with a time delay after the satellite recorded the related changes in the radiation flux as can be seen from a comparison of the top panel of Fig. 2 and Fig. 4.

The electron concentration dynamics in the low ionosphere can be analyzed by:

$$\frac{dN(t,h)}{dt} = G(t,h) - L(t,h). \tag{2}$$

This equation is very complicated in its general form because of the complexity of terms $G(t,h)$ and $L(t,h)$ that describe the electron gain and electron loss processes respectively.

The dominant electron gain process in the D-region at the daytime is the photo-ionization but below h =70-75 km also the contribution of cosmic radiation has to be taken into account. Moreover, a few processes, such as electron-ion, ion-ion and three-body recombination influence the electron loss mechanism. A quantitative analysis of these processes requires knowledge of the temperature and concentration of neutral and charged particles as functions of altitude, longitude, latitude, and time. However, these data are practically not available in real time and only results of approximate calculations are obtainable for specific models.

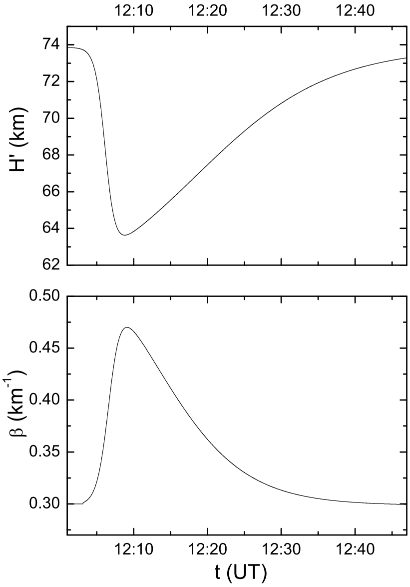

Figure 3: The reflection height H' and sharpness β obtained by comparative LWPC simulation and by the recorded signal characteristic values.

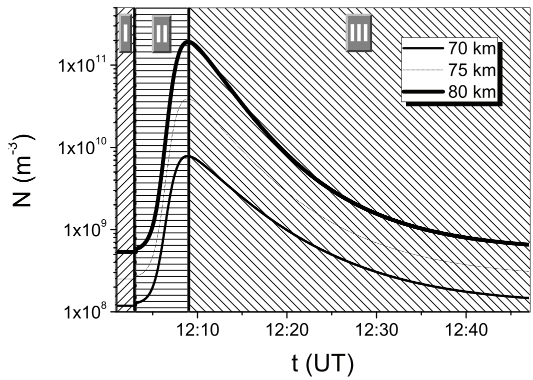

Figure 4: The time distribution of electron concentration during a quasi equilibrium (I), photo-ionization (II) and recombination regime (III) at altitudes 70, 75 and 80 km.

Fig. 5. shows the time distributions of the total electron concentrations rate.

Fig. 4 and Fig. 5 indicate that the ionospheric response can be divided into three regimes:

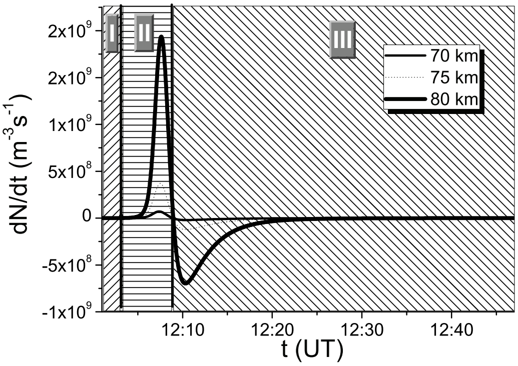

Figure 5: The temporal dependence of the electron concentration time derivative during the quasi equilibrium (I), photo-ionization (II), and recombination regime (III) at altitudes h=70, 75 and 80 km.

Regime 1 - the quasi equilibrium regime - where the flux increase does not cause electron concentration changes as the electron generation is instantaneously balanced by the electron recombination.

Regime 2 - the photo-ionization regime - where the photo-ionization dominates recombination resulting in electron concentration increase.

Regime 3 - the recombination regime - where the recombination dominates photo-ionization resulting in electron concentration decrease.

5. CONCLUSIONS

In this paper, we pointed out the significance of studies of low ionosphere by VLF waves and their applications in science and information technologies. Also, the Belgrade VLF station located in the Institute of Physics in Zemun is presented.

The main focus was on explanation of experimental and theoretical analyses of the low ionospheric response to a particular solar X-flare event by studying the recorded VLF signal characteristics. We showed an analogy of the time distributions of the radiation flux registered by GOES-15 satellite and those of the amplitude and phase time variations of the signal emitted by the DHO transmitter (Germany) and recorded by the Belgrade AWESOME receiver. The comparison of the electron concentration time distributions with that of the radiation flux reveals the evidence that ionospheric response to the solar X-flares has three regimes: the quasi equilibrium, photo-ionization and recombination.

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