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THE EFFECTS OF SOLAR ACTIVITY: ELECTRONS IN THE TERRESTRIAL LOWER IONOSPHERE

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Abstract: Solar flare X-ray energy can cause strong enhancements of the electron density in the Earth's atmosphere. This intense solar radiation and activity can cause sudden ionospheric disturbances (SIDs) and further create ground telecommunication interferences, blackouts as well as some natural disasters and caused considerable material damage. The focus of this contribution is on the study of these changes induced by solar X-ray flares using narrowband Very Low Frequency (VLF, 3–30 kHz) and Low Frequency (LF, 30–300 kHz) radio signal analysis. The model computation and simulation were applied to acquire the electron density enhancement induced by intense solar radiation. The obtained results confirmed the successful use of applied technique for detecting space weather phenomena such as solar explosive events as well for describing and modeling the ionospheric electron density which are important as the part of electric terrestrial-conductor environment through which external-solar wind (SW) electrons can pass and cause natural disasters on the ground like fires.

Keywords: solar activity, solar flares, terrestrial atmosphere, electron density

Introduction

The research methods of the terrestrial atmosphere are numerous. Depending on the ionospheric composition, ionospheric altitudes, preferred technics, geographical locations, for its investigation scientists usually use rockets, satellites, balloons, digisonde, GPS, different ground based measurements such as radars, radio measurements, optical instruments, etc. (see Farley, Ierkic, & Fejer, 1981; Schofield et al., 2015; Nina, Čadež, Popović, & Srećković, 2017 and references therein). At the altitude region 60–90 km called D-region,

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measurements are mostly based on radio wave propagation techniques (Šulić & Srećković, 2014).

The Very Low Frequency (VLF, 3–30 kHz) and Low Frequency (LF, 30–300 kHz) bands are below the critical frequencies[2] i.e. plasma frequencies of the D-region plasma (Davies, 1966). VLF/LF radio waves from transmitters propagate through waveguide bounded by the Earth's surface and the terrestrial D-region (Mitra, 1974; Walker, 1965). This propagation is normally characterized by good stability, both in amplitude and phase, particularly by day and exhibits relatively low path attenuation (Rawer, 1993, Folkestad, 2013). VLF/LF radiation tends to reflect from ionospheric layers at altitudes of 70-75 km during daytime and 80-90 km during nighttime (Kelley, 2009). The effective reflection height depends on the ionization levels of the D-region (Budden, 1961).

The monitoring of the lower ionosphere layers by the mean of the VLF/LF technique can play an important role for a better understanding of Space Weather conditions. It is now recognized that the plasma in the atmospheric D-region is a very sensitive medium to external forcing like moderate solar influence (Nina & Čadež, 2014; Ilić et al. 2017), stellar explosive radiation (see e.g. Šulić, Srećković, & Mihajlov, 2016; Bajčetić, Nina, Čadež, & Todorović, 2015; Nina, Simić, Srećković, & Popović, 2015), energetic particle intrusion (Radovanović, 2010). Processes like solar emission in far-UV and EUV regions (Mihajlov, Ignjatović, Srećković, & Dimitrijević, 2011, Mihajlov, Ignjatović, Srećković, Dimitrijević, & Metropoulos, 2013; Ignjatović, Mihajlov, Srećković, & Dimitrijević, 2014; Srećković, Mihajlov, Ignjatović, & Dimitrijević, 2014) strongly affect the Earth's atmosphere (Todorović Drakul et al., 2016; Nina, Čadež, Srećković, & Šulić, 2011). The role of sunspots, solar winds and radiation in climate change is important (Haigh, 2007; Hoyt & Schatten 1997; Rind, 2002; Ammann, Joos, Schimel, Otto-Bliesner, & Tomas, 2007; Kopp & Lean, 2011). The intense solar radiation and activity can cause sudden ionospheric disturbances (SIDs) and further create ground telecommunication interferences, blackouts as well as natural disasters like forest fires (see e.g. Milenković, Ducić, Babić, Yamashkin, & Govedar, 2017; Radovanović, Milovanović, Pavlović, Radivojević, & Stevančević, 2013; Radovanović, Gomes, Yamashkin, Milenković, & Stevančević, 2017).

Gomes and Radovanović (2008) believe that in some cases fires are connected with the activity of the Sun i.e. the solar wind (SW) charged particles. According

[2] Critical frequency is the limiting frequency at or below which a wave component is reflected by, and above which it penetrates through, an ionospheric layer. The critical frequency is almost totally a function of electron density.

to this theory, the SW particles can penetrate deeper in the atmosphere, reach the surface of the Earth, and cause fires by burning the plant mass (Radovanović & Gomes, 2009; Radovanović et al., 2017). In the interplanetary space, the current flow moves along the lines of the magnetic field of the Sun, and in the free atmosphere, it moves along the lines of the resulting magnetic field of the Sun and Earth. The movement of the SW charged particles creates a convection electric current. These external electrons in the form of jet with a certain circulating velocity have the ability to propagate at long distances and cause fires.

The electric conductivity i.e. ambient electron density in the ionosphere is very important as the part of this electric terrestrial-conductor. The focus of this contribution is on the study of electron density enhancement induced by solar X-ray radiation.

Data analysis method

Measured Data

In this contribution we focus our attention to the analysis of amplitude and phase data, acquired by monitoring VLF/LF radio signals emitted by worldwide distributed transmitters during SIDs. All the data were recorded at a Belgrade site by two receiver systems: Absolute Phase and Amplitude Logger (AbsPAL) system (Nina, Čadež, Srećković, & Šulić, 2012a; Nina, Čadež, Šulić, Srećković, & Žigman, 2012b) and Atmospheric Weather Electromagnetic System for Observation Modeling and Education (AWESOME)[3]. The details of the receiving site are provided in the Table 1. Locations of some transmitters and the receiving site are presented in the Figure 1. It should be noted that the signal characteristics strongly depend on relative positions of transmitters and receiver and their distance (Šulić, Srećković, & Mihajlov, 2016).

[3] http://solar-center.stanford.edu/SID/AWESOME/

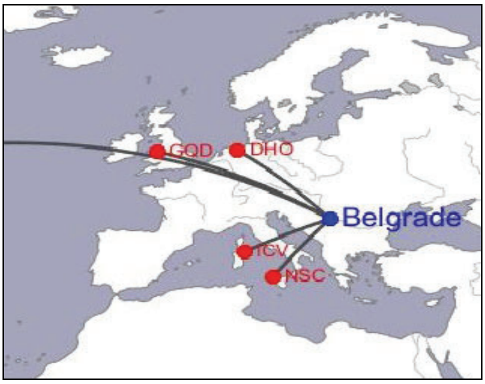

Figure 1. The geographic position of Belgrade system of VLF/LF receivers and the surrounding transmitters

Table 1. Main characteristics of Belgrade VLF/LF receiving system

Receiver	Class	Start year	Site	Geographic coordinates (deg)
AbsPAL	Electric antenna	2003	Belgrade, Serbia	44.85°N, 20.38°E
AWESOME	Loop magnetic antenna	2008	Belgrade, Serbia	44.85°N, 20.38°E

The analysis and the comparison of VLF data have been carried out together with the examination of the corresponding solar X-ray fluxes. The intensity of solar X-ray flux is recorded by the GOES satellites (Geostationary Operational Environmental Satellite)[4]. The GOES satellites record the X-ray fluxes in two wavelength bands: 0.1–0.8 nm, referred to as “long” or “XL” and 0.05–0.4 nm, referred to as “short” or “XS”. The most important data in our work are data of intensity of X-ray flux in the band 0.1–0.8 nm.

GOES X-ray Sensor: On all GOES satellite there are two X-ray Sensors (XRS) which provide solar X-ray fluxes for the wavelength bands of 0.05 to 0.4 nm called short channel and 0.1 to 0.8 nm called long channel. The measurements are obtained from two gas-filled ion chambers (one for each band). Measurements in these bands have been made by NOAA[5] satellites since 1974 and the design has changed very little during that time period (see Garcia, 1994 and GOES technical handbook).

[4] https://satdat.ngdc.noaa.gov/sem/goes/data
[5] https://www.ngdc.noaa.gov/

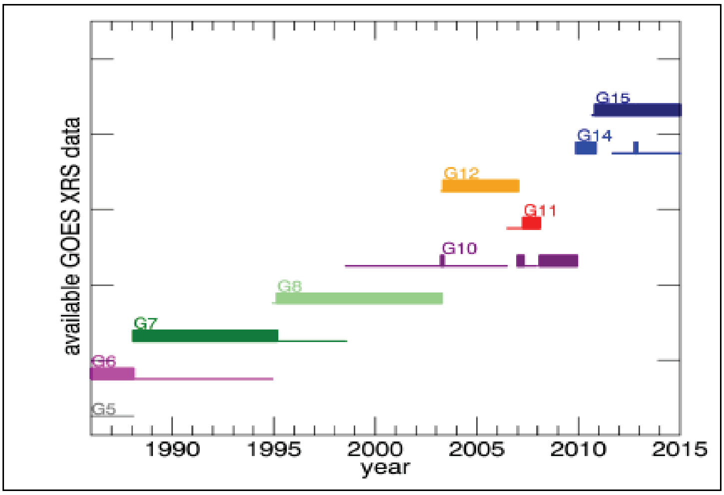

Figure 2. Primary (marked with thick lines) and secondary (marked with thin lines) GOES satellites for XRS data since the end of the 1980s. GOES 13 is not considered a primary or secondary satellite due to its instability (Source: https://www.ngdc.noaa.gov/stp/satellite/goes/doc/GOES_XRS_readme.pdf)

Figure 2 shows primary and secondary GOES satellites for XRS data since the end of the 1980s.

Modeling

Simultaneous observations of amplitude (A) and phase (ϕ) on VLF/LF radio signals during solar X-ray flares could be applied for calculations of electron density profile. The equation for the electron density in the D-region can be given by two-parameter analytical expression (Wait & Spies, 1964):

$$N_e(h,H') = 1.43 \cdot 10^{13} \exp(-0.15 \cdot H') \exp[(\beta - 0{,}15) \cdot (h - H')] \text{ m}^{-3}, \quad (1)$$

where h is the height in km and β and H' are model parameters (Wait's parameters) having units of km^{-1} and km, respectively. This model has been used to simulate altitude electron density profile in the D-region at regular conditions, as well as for the perturbed conditions (Šulić et al., 2016). A numerical procedure for the calculation is based on comparison of the recorded changes of amplitude and phase with the corresponding values obtained in simulations using the Long-Wave Propagation Capability (LWPC) numerical software package (Ferguson, 1998) as explained in Šulić and Srećković (2014).

Results and discussion

Solar flares are destructive explosions in the solar chromosphere which release radiation across entire electromagnetic spectrum accompanied by the energetic particles (Tandberg-Hanssen & Emslie, 1988; Prolls & Bird, 2004; Svestka, 2012). The Figure 3 shows an image of the solar flares that occurred on 6 March 2011. Sudden changes in the amplitude and phase of subionospheric VLF/LF propagations have been found in association with events of solar flares at daytime.

As instructive example, the variations of amplitude and phase on [6]DHO/23.40 kHz radio signal against universal time recorded at Belgrade during solar flares C3.1 (10:01 UT) and C5.1 (12:09 UT) on 6 March 2011 are shown in Figure 4.

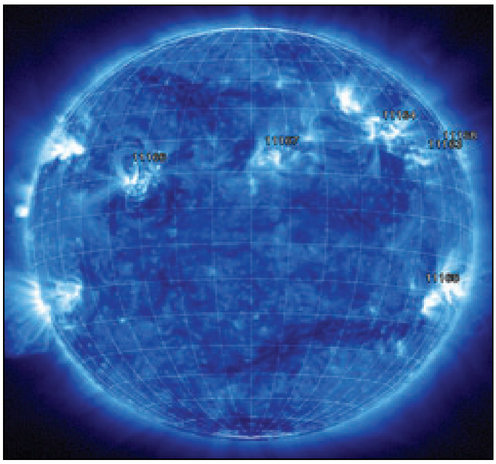

Figure 3. The solar corona in extreme ultraviolet light (17.1-nm band) at 10:03 UTC on 6 March 2011[7]

The corresponding GOES-15 data in the 0.1–0.8 nm band are represented by the red solid line. As it can be seen from this example, the amplitude and phase perturbations on VLF/LF radio signal are in correlation with the intensity and shape of X-ray flux.

[6] https://en.wikipedia.org/wiki/VLF_transmitter_DHO38
[7] https://solarmonitor.org

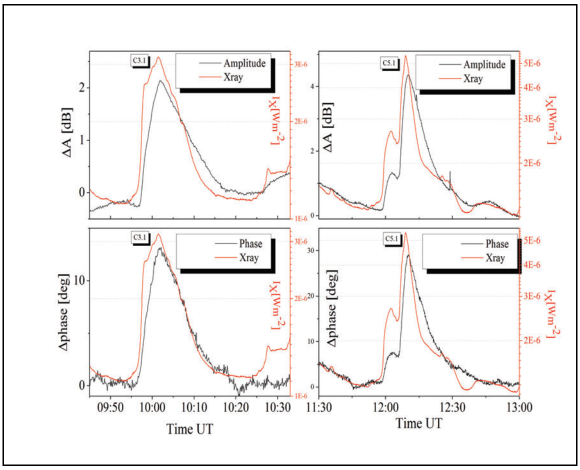

Figure 4. Upper panels: Time variation of X-ray irradiance measured by GOES-15 satellite (red lines), and observed perturbations of DHO signal amplitude (black lines) during Solar flares: C3.1 (10:01 UT); and C5.1 (12:09 UT) on 6 March 2011; Bottom panels: Time variation of ground based observed DHO signal phase (black line) for the same flare events. Zero values correspond to amplitude and phase recorded in non-perturbed plasma in the D-region

In the presence of ionospheric disturbances, the electron density *Ne* calculations can be obtained from the LWPC code and by Eq. 1. using standard procedure explained in details in Šulić and Srećković (2014). Solar flare events that occurred on 6 March 2011 were chosen as an example of electron density profile in the perturbed D-region (see Figure 5a,b).

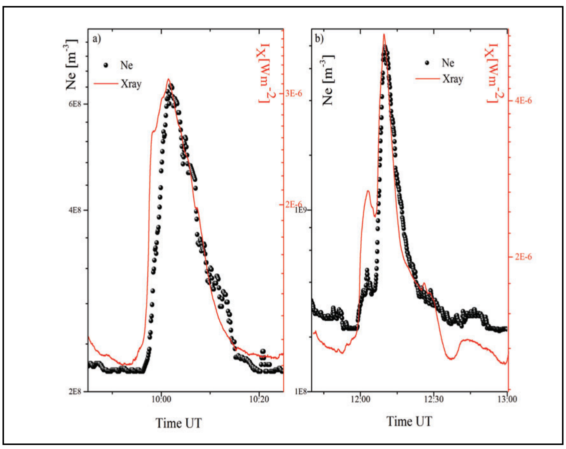

Figure 5. Variation of X-ray irradiance, as measured by GOES-15 satellite, and the corresponding electron density evaluated at height 74 km versus universal time UT on 06 March 2011. a) C3.1-class b) C5.1-class solar flare

The Figure 5 shows simultaneously the X-ray irradiance and electron density variation *Ne* at reference height *h* = 74 km during C3.1 and C5.1-class solar flares as a function of time. It can be noticed that the time distribution of the electron density follows the variation with time of the registered solar flux on the GOES-15 satellite.

The calculated electron densities at height *h* = 74 km as a function of maximum intensity of X-ray flux are shown in the Figure 6. The statistics was done for the whole year (2011) for 23.40 kHz signal. The size of the point is proportional to the amplitude change while the color depends on the phase change (darker color indicates larger phase change). It appears that electron density depends on both, amplitude change and signal phase change. From the Figure 6 it is evident that electron density is proportional to the logarithm of the X-ray irradiance maximum, with the Adjusted R-Square and Pearson's r coefficients equal to 0.801 and 0.902, respectively. In the fitting function $y=a+b*x$, coefficient a=15.0 and b=1.08995. Extrapolated values are given in red dashed line.

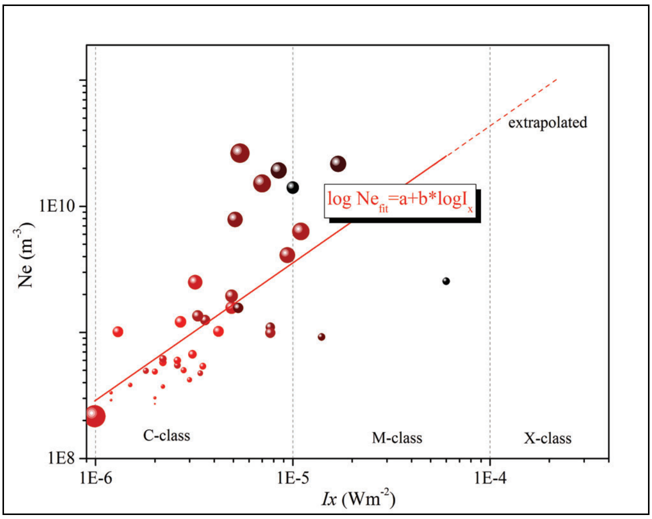

Figure 6. Values of electron density at height h = 74 km during flare occurrences, against maximum intensity of X-ray flux calculated on the basis of VLF/LF propagation data recorded at Belgrade for one year (the size of the point is proportional to the amplitude change while the color depends on the phase change - darker color indicates larger phase change; the red line indicates linear fit)

The Figure 6 i.e. fitting function enables to approximately determine electron density in the perturbed ionosphere at reference height, just based on the intensity of the solar X radiation. This makes it easier to analyze this significant area during different solar disturbances.

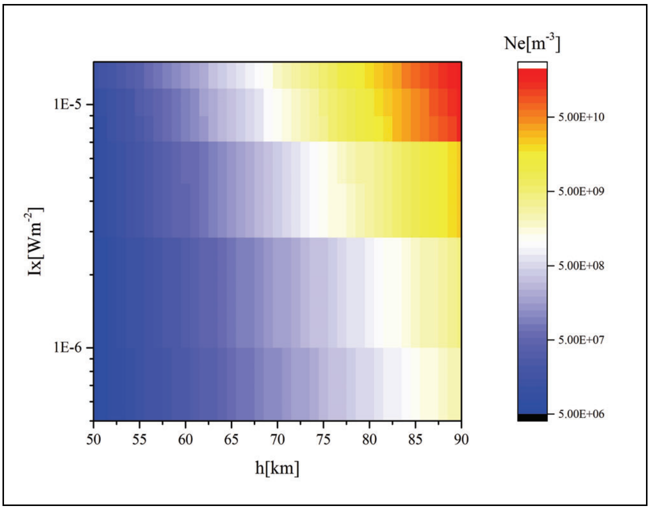

Figure 7. Electron density height profiles during a C to M class X-ray solar flare occurrence

Also, the Figure 7 shows the vertical electron density profile during the intense X-ray solar radiation. The Figure 7 enables to estimate the electron density at selected altitudes during flare occurrence just using the X-ray irradiance intensity. The results were obtained on the basis of static analysis of numerous events. Of course, it should be kept in mind that the ionosphere is a complicated structure and that its reaction during a perturbation is not so simple and not always the same (Mitra, 1974).

Conclusions and perspectives

In this contribution, the effect during the enhancements of X-ray flux due to the solar flares, on the propagating radio signal have been studied. The model computation is applied to determine the perturbation structures in the terrestrial D-region, during occurrences of solar flares. From these results it can be concluded that the solar explosive events lead to an increased rate of electrons production and electron density can increase depending on flare intensity.

The obtained results confirmed successful use of applied technique for detecting space weather phenomena such as solar explosive events as well for describing and modeling the ionospheric electron density which is important as the part of electric terrestrial-conductor environment through which external-SW electrons can pass and cause natural disasters on the ground like fires. Also, our future work is connected with further investigation of connections between activity of the Sun and natural disasters e.g. (forest fires) as well as and further modelling.

Our plan is to present the results obtained during this investigation in database which can be accessed directly through http://servo.aob.rs as a web service similarly to the existing MolD[8] database (Marinković et al., 2017; Srećković, Ignjatović, Jevremović, Vujčić, & Dimitrijević, 2017).

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[8] http://servo.aob.rs/mold

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