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UNTYPICAL PERTURBATIONS ON LF RADIO SIGNALS DURING SOLAR FLARES

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Abstract. The perturbations in the D-region induced by solar flares were studied using monitored amplitude and phase data from European very low and low frequency transmitters, in period 2008 - 2014. All data were recorded at the Belgrade station(44.85^0 N, 20.38^0 E) by the Stanford University ELF/VLF Receiver Atmospheric Weather Electromagnetic System for Observation Modeling and Education (AWESOME) installed in 2008. Statistical results show that in large number of examined events during small solar flares, the amplitude perturbation excess of NSC/45.90 kHz signal is in correlation with intensity of solar X-ray flux. The focus of this work is on the study of untypical change of perturbed amplitude on NSC/45.90 kHz signal. For example, on short path (D = 952 km) in December 2009 one C3.34 class solar flare induced great excess of perturbed amplitude $\Delta A = 4.58$ dB and reduced the effective reflection height H' from 74 km down to 71 km.

1. INTRODUCTION

The ionosphere is the part of the atmosphere and contains ionized gases, with tendency to separate in different regions, despite of the fact that different processes dominate in different latitudinal domains. D-region is the lowest region of the ionosphere, $50 \leq h \leq 90$ km. A range of dynamic phenomena occur in the D-region. Diurnal effect is result of changes in incident solar UV and EUV radiation. The passage of the seasons also has an impact on local ionospheric conditions. Both of these variations are stable and predictable. Phenomena, such as particle precipitation from the radiation belts and solar flares also influence the ionosphere, but they are unpredictable and associated with space weather. Radio signals in Very low frequency (VLF, 3 - 30 kHz) and Low frequency (LF, 30 - 300 kHz) ranges propagate from transmitters through a waveguide bounded by the Earth's surface and the D-region. This propagation is stable both in amplitude and phase and has a relatively low attenuation.

2. RESULTS AND DISCUSSION

Method of simulation VLF/LF data - Theoretical base for propagation of VLF/LF radio signals under normal ionospheric condition is developed by Wait & Spies (1964).

The influence of the D-region is taken into account by using the so called Wait's parameters: the sharpness β [km^{-1}] and the reflection height H' [km]. The NOSC, San Diego, USA has developed a computer program, the LWPC- Long Wave Propagation Capability, for simulation of VLF/LF propagation along any particular great circle path under different diurnal, seasonal and solar cycle variations in the ionosphere (Ferguson 1998). The LWPC program can take arbitrary electron density versus altitude profiles supplied by the user to describe the D-region and thus the ceiling of the waveguide. The electron density profile increases exponentially with height and can be associated with the above defined equations. The equation for the electron density in the D- region: $N_e(h, H') = 1.43 \cdot 10^{13} e^{0.15H'} e^{(\beta-0.15)\cdot(h-H')}$ derived by Thomson (1993) and we also use it in our work to calculate the vertical density profile in the range 50 - 90 km. Our intention was to calculate the electron density profile versus height, and/ or versus time during occurrence of solar flare.

Using the LWPC code the propagation path of NSC/45.90kHz signal was simulated in normal ionospheric condition, with goal to estimate the best fitting pairs of Wait's parameter β and H' to obtain values closest to the measured A and ϕ for selected day. The next step is to simulate propagation of NSC/45.90kHz signal through the waveguide in the disturbed D-region induced by additional X-ray radiation for selected moments during the solar flare development. The best fitting pairs of β and H' we used to calculate values of amplitude and phase at the receiver site.

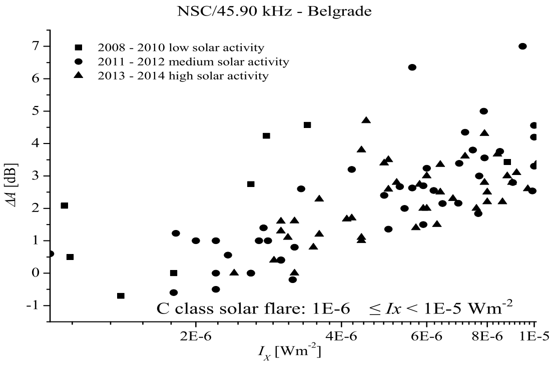

Figure 1: Measured amplitude excesses on NSC/45.90 kHz radio signal as a function of X-ray irradiance.

<u>*Statistical results*</u> -Simultaneous observations of amplitude (A) and phase (ϕ) in VLF/LF radio signals during solar flares could be applied to calculations of electron density profile. Therefore, the perturbation of amplitude was estimated as a difference between values of the perturbed amplitude induced by flare and amplitude in the normal ionospheric condition: $\Delta A = A_{per}$ - A_{nor}, where "per" means the perturbed and "nor" means normal condition. In the same way the perturbation of phase was estimated as: $\Delta\phi = \phi_{per}$ - ϕ_{nor}. During the occurrence of solar flares, classified as a minor and small flare up to the C3 class, the amplitude of the signal NSC/45.90 kHz does not have significant perturbations. A solar flare in the range from C3 to M3 classes induced an increase of the amplitude, which corresponds nearly proportionally to the logarithm of the X-ray irradiance maximum (Šulić & Srećković, 2014). Solar flare data were taken from GOES-15 satellite measurements of X-ray irradiance.

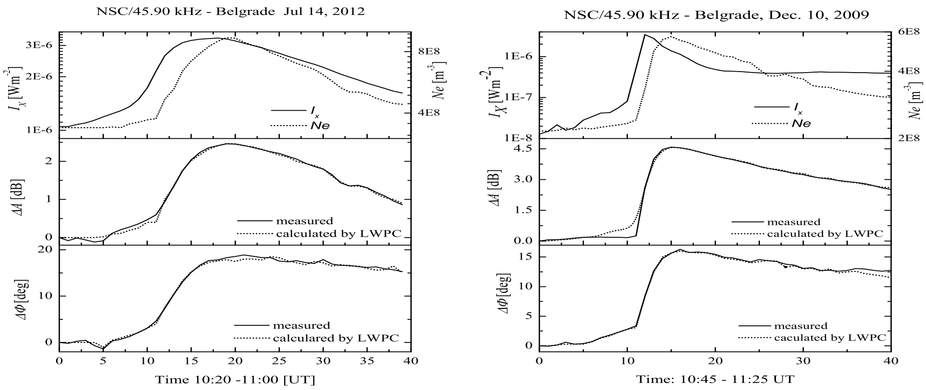

Figure 2: The time variations of the measured and calculated amplitude and phase excesses on NSC/45.90 kHz signal recorded on July 14, 2012 and December 10, 2009 (lower and middle panels). Time variation of the X-ray irradiance measured by the GOES-15 satellite and evaluated electron density profiles (upper panels).

Fig.1 shows the measured excesses of perturbed amplitude on NSC/45.90 kHz signal recorded at the Belgrade station as a function of the X-ray irradiance, in the range 1E-6 $\leq I_X <$ 1E-5 Wm^{-2}. The examined events were recorded around midday with solar zenith angle $\chi \leq 60^0$. during periods of low (2008 - 2010), medium (2011 -2012) and high (2013-2014) solar activity. There are some exceptions in measured excesses of perturbed amplitude induced by solar flares with very similar values of intensity. One of them is event caused by C3.44 class solar X-ray flare which occurred on December 10, 2009. The amplitude did not respond proportionately to the intensity of solar flare irradiance and the excess is $\Delta A = 4.58$ dB. This is an untypical perturbation of amplitude in comparison with other fourteen events induced by C3 class solar flares, with irradiance: 3E-6 $\leq I_X <$ 4E-6 Wm^{-2}. These solar flares had very similar characteristics and induced additional ionization in the D-region, causing perturbations of amplitude on NSC/45.90kHz signal. The measured excess of amplitude has values -0.2 $\leq \Delta A \leq$ 4.45 dB.

On July 14, 2012 were recorded eight solar flares and among them was C3.3 class solar flare with peak at 10:29 UT. The 1-min average values of solar flux, amplitude and phase of NSC/45.90 kHz radio signal are considered for analysis for the time interval of 40 minutes. In Fig.2a there are the X-ray irradiance, measured and calculated by LWPC code perturbations of amplitude and phase on NSC/45.90kHz signal versus time. During development of this solar flare intensity of X-ray irradiance changed from I_X =1.05E-6 Wm^{-2} to I_{Xmax} = 3.3E-6 Wm^{-2} and induced perturbations of amplitude $\Delta A = 2.46$ dB and phase $\Delta\phi = 19^0$ on NSC/45.90kHz signal. As presented in Fig.2a, the shapes of perturbed amplitude (middle panel) and X-ray irradiance (upper panel) are very similar to each other.

The bottom edge of the midday middle latitude ionosphere during summer condition was thus found to be well modeled by $\beta = 0.44$ km^{-1} and $H' = 71$ km (Thomson, 2010). With this starting pair of Wait's parameters we calculated changes in amplitude and phase on NSC/45.90 kHz signal and used them in evaluating electron density

profile versus time. Figure 2a, upper panel, shows simultaneously the X-ray irradiance and calculated electron density at a reference height $H = 71$ km, as a function of time from 10:25 to 11:00 UT. 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. Main numerical results are:
1. the sharpness increased from β =0.44 km^{-1} to β = 0.50 km^{-1};
2. the reflection height was reduced from H' =71 km to H' = 69 km;
3. at reference height electron density increased from Ne =3.4E8 to 9.36E8 m^{-3};
4. time delay of the peak electron density after the peak of X-ray irradiance is 1min.
Untypical perturbations on LF radio signal during solar flare - Few solar flares occurred during period of the low solar activity, but the effect of even weak solar flares can be seen on VLF/LF radio signals. One of them is C3.44 class solar X-ray flare, which occurred on December 10, 2009 with maximum at 10:57 UT.

Figure 2b shows time variation of X-ray irradiance (upper panel). Intensity of X-ray irradiance dramatically changed in few minutes from $I_X \sim$ 5E-8 Wm^{-2} to I_{Xmax} = 3.44E-6 Wm^{-2}. Radiation increased by $\sim$ 100 times. The middle and low panels show measured and calculated perturbations by LWPC program in amplitude and phase on NSC/45.90 kHz signal versus time, respectively. Additional X-ray radiation caused the increase of electron density in the D-region, making perturbations of amplitude and phase on LF signal. The amplitude did not respond proportionately to the intensity of solar flare flux intensity, ΔA = 4.58 dB. Simultaneously measured phase excesses are in correlation to the intensity of X-ray irradiance.

Fig.2b shows simultaneously the X-ray irradiance and calculated electron density at a reference height $H = 74$ km, as a function of time from 10:45 to 11:25 UT. It can be noted that the time distribution of the electron density follows the variation with time of the registered solar flux on the GOES 15 satellite. During solar flare characteristics of D-region were changed as:
1. the sharpness increased from β =0.30 km^{-1} to β = 0.324 km^{-1};
2. the reflection height was decreased from H' =74 km to H' = 71 km;
3. at reference height electron density increased from Ne =2.16E8 to 5.71E8 m^{-3};
4. time delay of the peak electron density after the peak of X-ray irradiance is 3min.
Discussion -During solar flare characteristics of D-region were changed as: β increased; H' was reduced; at reference height electron density increased and there is the time delay of the peak electron density after the peak of X-ray irradiance. The untypical perturbation of amplitude was caused by small solar flare C3.34 class in duration of six minutes. In December 2009 from day to day averaged intensity of X-ray irradiance was $\leq 10^{-7}$ Wm^{-2}. During this weak and short solar flare radiation increased by $\sim$ 100 times and induced larger amplitude excess according to the statistical results.

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