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DIAGNOSTICS OF THE SOLAR X-FLARE IMPACT ON LOWER IONOSPHERE THROUGH THE VLF-NAA SIGNAL RECORDINGS

Aleksandra Kolarski[1], Davorka Grubor[2] and Desanka Šulić[3]

[1] *Institute for Geophysics, Batajnički drum 8, 11000 Belgrade, Serbia; aleksandrakolarski@gmail.com*

[2] *Faculty of Mining and Geology, Physics Cathedra, University of Belgrade, Djušina 7, 11000 Belgrade, Serbia; davorkag@eunet.rs*

[3] *Faculty of Ecology and Environmental Protection, Union – Nikola Tesla University, Belgrade, Cara Dušana 62-64, 11000 Belgrade, Serbia; dsulic@ipb.ac.rs*

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Abstract. An analysis of four solar flare X-ray irradiance effects on VLF signal amplitude and phase delay variations on the NAA/24.0 kHz signal trace during the period from 2005 September to 2006 December was carried out. Solar flare data were taken from the GOES12 satellite one-minute listings. For the VLF data, recordings at the Institute of Physics, Belgrade were used. It was found that solar flare events affect VLF wave propagation in the Earth-ionosphere waveguide lowering the changes of the ionosphere electron density height profiles. This follows from the variation during the solar flare events of the following propagation parameters: the sharpness of the lower edge of the ionosphere and the reflection height.

Key words: solar flares, VLF signal perturbation, Earth-ionosphere waveguide

1. INTRODUCTION

The X-ray flux emitted from the Sun during flare events causes photoionization of all neutral constituents in the lower ionosphere, and as the source of ionization, becomes major mechanism taking place in this region. Electron density increases as the result of additional ionization of lower ionosphere constituents and changes lower ionosphere electron density height profile, affecting Earth-ionosphere waveguide characteristics (Mitra 1974). As a consequence, propagation parameters of VLF signals also change, producing perturbation of emitted VLF signal phase delay and amplitude, otherwise stable under undisturbed solar conditions. For receiving, monitoring and storage of NAA/24.0 kHz signal amplitude and phase delay data (propagating along W-E mostly oversea path 6540 km long, from Main, USA to Belgrade, Serbia), the AbsPAL system was used, operating at the Institute of Physics in Belgrade. Influence of four isolated solar flare events and their manifestation on NAA signal trace was studied and is presented in this paper.

Table 1. Considered flare events on the NAA signal trace.

Date	Time	Class	Quiet day	N_e (74 km) for $I_{\max}$
2006 April 7	08:03 UT	C9.7	2006 April 8	$7.16 \cdot 10^9$ m^{-3}
2006 July 6	08:36 UT	M2.5	2006 July 5	$3.30 \cdot 10^9$ m^{-3}
2006 December 6	12:58 UT	C4.8	2006 November 24	$2.22 \cdot 10^9$ m^{-3}
2005 September 7	12:24 UT	C9.6	2006 September 10	$2.11 \cdot 10^9$ m^{-3}

2. RESULTS AND DISCUSSION

The analyzed X-ray flare events are presented in Table 1. The NAA signal amplitude and phase delay perturbations and unperturbed signals during the periods enclosing considered flare events are shown in Figures 1–4 with the corresponding X-ray irradiances (0.1–0.8 nm, right axis). Characteristic signal states during these events are marked by arrows and numbers 1–13. The solar X-ray flares have caused phase delay and amplitude perturbations on the NAA signal trace, however, the "pattern" of perturbations is not the same for these events, because the signal propagates through very different waveguides due to diurnal and seasonal changes of lower ionosphere, and also because of different characteristics of the events. The common feature for all four events is the peak amplitude time delay, Δt = 1–2 min, after the X-ray irradiance peak, attributed to the "sluggishness" of the ionosphere in reaching the flare-induced peak electron density in D-region, caused by recombination processes (Appleton 1953; Žigman et al. 2007).

The incidence of the X-ray radiation to the Earth's ionosphere during the solar flare causes not only the enhancement of maximum of the electron density, but also changes the distribution of ionization from the upper to lower edge of D-region. In other words, the change of electron density height profile takes place. In general, the lower edge of the ionosphere (the upper boundary of VLF waveguide) descends, and becomes "sharper". The propagation model given in Wait & Spies (1964), describes the electron density in the waveguide by two parameters: reflecting edge sharpness, denoted by β and reflecting edge height, denoted by H'. This model has been used to simulate VLF propagation through Earth-ionosphere waveguide at regular conditions, as well as for the conditions corresponding to the flare peak irradiance (Thomson & Rodger 2005), and the obtained results are in good agreement with VLF signal measurements. The Earth-ionosphere waveguide was modeled for several characteristic moments during the each flare event. Electron density profile $N_e(z)$, with altitude z in a range of 50–90 km, for given parameters β and H', was calculated using the expression given by Wait & Spies (1964):

$$N_e(z, H', \beta) = 1.43 \cdot 10^{13} e^{-0.15H'} e^{(\beta-0.15)(z-H')} . \quad (1)$$

By means of LWPCv21 program (Ferguson 1998), the propagation paths of NAA/24.0 kHz were simulated, and the goal was to estimate the best fitting pairs of parameters β/H' to yield values closest to real measured phase delay and amplitude at the Belgrade receiver site, for each characteristic state of the each flare event considered. The calculated amplitude and phase delay values obtained by LWPCv21 program are in good agreement with measured values at the Belgrade receiver site. Therefore, it could be taken in further simulations that numerically modeled signals had been transmitted in modeled ionospheric conditions which are in good agreement with real ionospheric conditions held at that time and measured

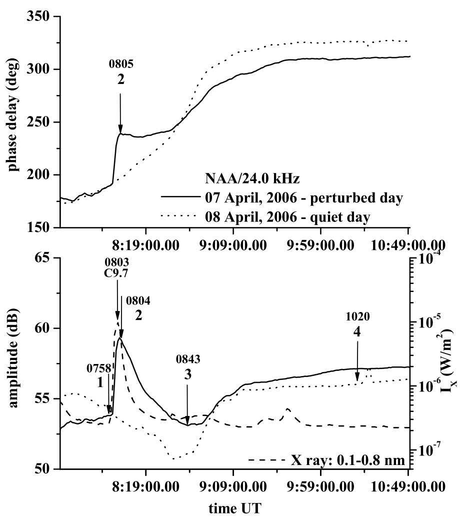

Fig. 1. NAA signal perturbation during a C9.7 class X-ray solar flare event.

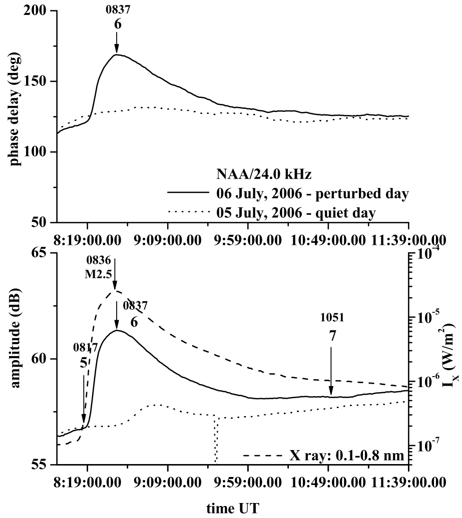

Fig. 2. NAA signal perturbation during a M2.5 class X-ray solar flare event.

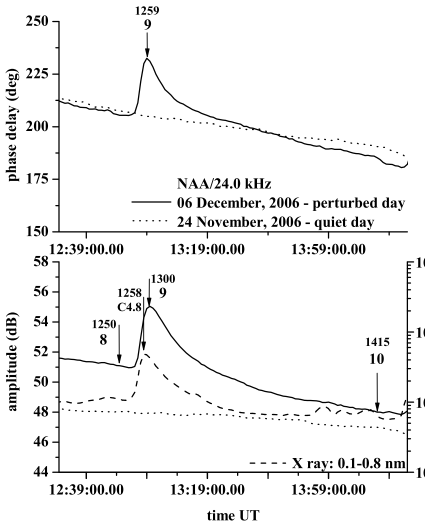

Fig. 3. NAA signal perturbation during a C4.8 class X-ray solar flare event.

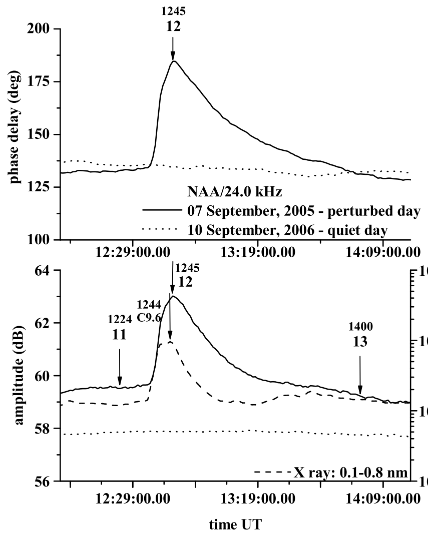

Fig. 4. NAA signal perturbation during a C9.6 class X-ray solar flare event.

at the receiver site. Since the NAA signal from transmitter to receiver propagates along path 6540 km long, parameters β/H' change along the trace according to the zenith angle. For this purpose, constant "average value" of otherwise variable parameters β/H' were chosen and used along the whole trace, depicting "average ionospheric conditions" held along the whole trace for each simulation. For each considered flare event, for characteristic unperturbed preflare state, perturbed flare state and "recovered" postflare state, the vertical electron density profiles through ionospheric D-region (50–90 km altitude) are calculated using (1). Changes of the

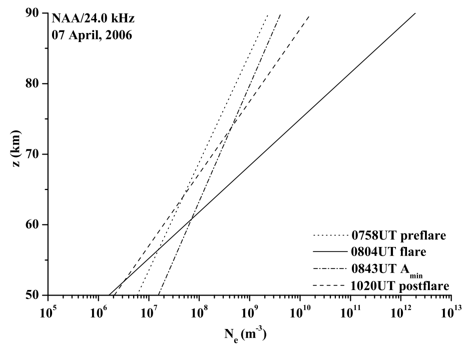

Fig. 5. Electron density height profiles during a C9.7 class X-ray solar flare event.

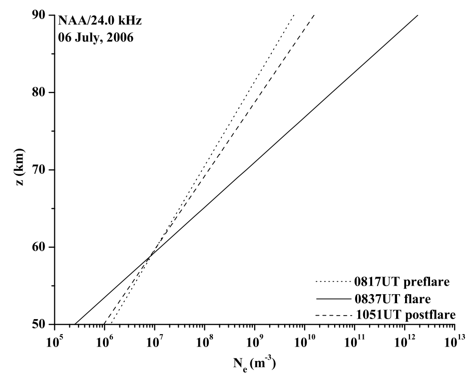

Fig. 6. Electron density height profiles during a M2.5 class X-ray solar flare event.

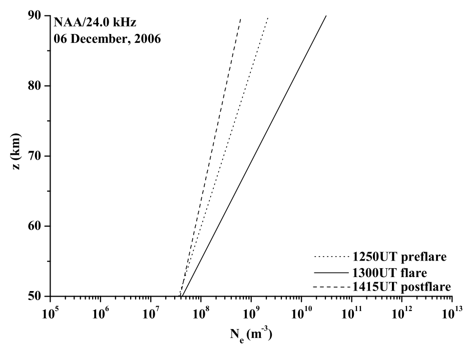

Fig. 7. Electron density height profiles during a C4.8 class X-ray solar flare event.

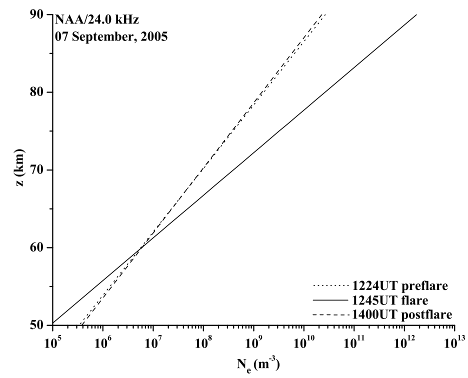

Fig. 8. Electron density height profiles during a C9.6 class X-ray solar flare event.

electron density height profile at characteristic times, for each flare event on NAA signal trace on perturbed days, are shown in Figures 5-8, respectively.

NAA signal amplitude and phase delay that undergo perturbations due to four considered solar flare events, occurred between 2005 September and 2006 December, are simple and entirely depicting X-radiation intensity change during these flare events. Sudden electron density increases in D-region due to solar flare X-radiation caused sharpening of D-region upper boundary, and at the same time, NAA signal reflection height lowering, producing both amplitude and phase delay increase. Changes of the electron density height profile through the ionospheric D-region during considered flare events at 74 km altitude are realistic (increase of 1 order of magnitude), but because of possible fail of the model at the D-region boundaries results for electron density in these cases should be taken with caution.

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