Study of the X-Ray Flare Induced Lower Ionosphere Changes by Simultaneous Monitoring of Two VLF Signals: GQD and NAA

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Abstract

A simultaneous analysis of solar flare M2.5 class X-ray irradiance effects on VLF signal amplitude and phase delay variations on the GQD/22.1 kHz and NAA/24.0 kHz signal traces was carried out. Solar flare data were taken from GOES12 satellite one-minute listings. For VLF data recordings at the Institute of Physics, Belgrade, Serbia, the AbsPAL system was used. It was found that solar flare event affected VLF wave propagation in the Earth-ionosphere waveguide in way that lower ionosphere electron density height profile changes, according to variation of estimated parameters, sharpness and reflection height, being different for two traces.

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 [1]. Electron density increase as the result of additional ionization of lower ionosphere constituents and changes lower ionosphere electron density height profile, affecting Earth-ionosphere waveguide characteristics [2]. As the consequence, propagation parameters of very low frequency signals (VLF) also change, producing perturbation of emitted VLF signal phase delay and amplitude, otherwise stable under undisturbed solar conditions [3, 7].

The Absolute Phase and Amplitude Logger (AbsPAL) receiving system, developed at VLF group Otago University, located at Belgrade, was used for receiving, monitoring and for storage amplitude and phase delay data for two signals on frequencies 22.1 kHz and 24.0 kHz, GQD signal trace (Skelton, UK), and NAA signal trace (Main, USA), respectively. The phase delay and amplitude signal perturbations produced by M2.5 class X-ray solar flare event occurred at time 0836 UT on 06 July, 2006, at local summer daytime, and its influence and manifestation on two previously mentioned traces were studied and are presented in this paper.

2. Solar Flare Event and the corresponding Perturbations of VLF Signal Amplitude and Phase Delay

According to GOES12 one-minute data listings of the X-ray (0.1-0.8 nm) irradiance, the M2.5-class flare event occurred on 06 July, 2006 with peak value $I_X = 2.51 \cdot 10^{-5}$ W/m^2 that took place at 0836 UT. The X-ray irradiance during the period of the flare event is shown in the upper panel of Figs.1a, b. The VLF signal diurnal variation (local summer, daytime), observed in the period enclosing the flare event on the disturbed day 06 July, 2006, i.e. phase delay (middle panel) and amplitude (lower panel), for both GQD/22.1 kHz and NAA/24.0 kHz, are shown in Fig1.a and Fig1.b, respectively (violet). The diurnal phase delay and amplitude variation for both signals, in the same daytime period, but on the nearest quiet day, 05 July, 2006 (dark green) are added to the middle and lower panel of Fig. 1 respectively.

As evident from Fig.1, solar X-ray flare caused phase delay and amplitude perturbation on both GQD and NAA signals. However, the “pattern” of perturbation is not the same for two signals. It can be expected because the signals are propagating through the very different waveguides. While GQD signal propagates along NW-SE, short (GCP distance D = 1982 km), mostly overland path, NAA signal propagates along W-E, long (GCP distance D = 6540 km), and mostly oversea path. The common feature for both signals is the time delay of the peak amplitude after the peak of X-ray irradiance, Δt = 1 min. The time delay is attributed to the “sluggishness” of the ionosphere in reaching the flare induced peak electron density in D region, caused by recombination processes [4, 5].

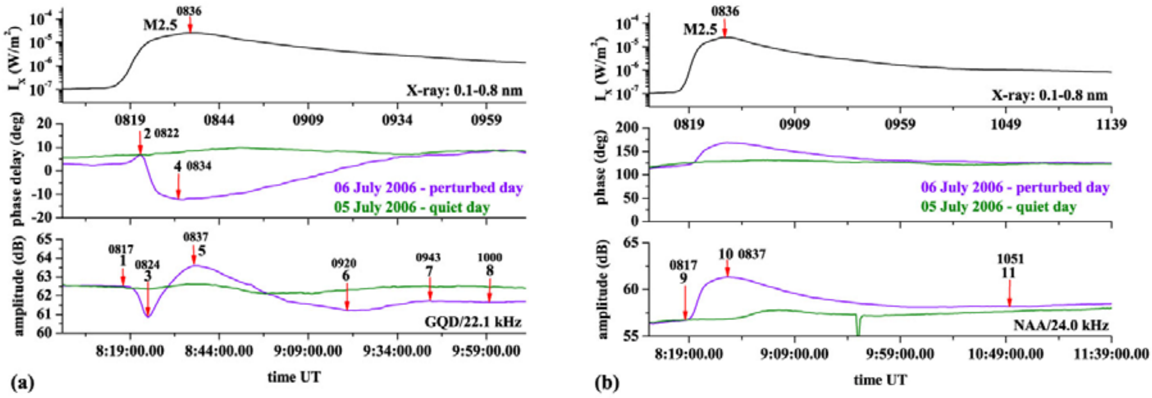

Fig. 1. Diurnal variation of the X-ray irradiance on 06 July, 2006, during the M2.5 (upper panel), simultaneous VLF signal phase delay (middle panel) and amplitude (lower panel) variations on 06 July, 2006 (blue lines) and on 05 July, 2006 (dark green lines). Characteristic states during event are marked by arrows. (a) GQD; (b) NAA.

The detailed inspection of GQD signal variation shows, that as I_X increases after preflare state at 0817 UT (characteristic state 1 on Fig. 1a), the amplitude rapidly drops to the first minimum (the major one) at 0824 UT (state 3), but its decreasing terminates before the X-ray irradiance reaches the peak value at 0836 UT. Further, the amplitude rises up the intermediate maximum at 0837 UT (state 5), delayed 1min with respect to the of X-ray peak irradiance, and consecutively through the second minimum at 0920 UT (state 6), wider and “shallower” than the first one. After the second increase at 0943 UT (state 7), and slight decrease 1000 UT (state 8), the amplitude very slowly recovers tending, but not reaching the preflare value for next several hours. The amplitude intermediate peak, exceeding the preflare value for 1 dB, is the dominant feature in the amplitude oscillation during the flare event. The phase delay variation is characterized by short lasting, small increase at 0822 UT (state 2), followed by significant decrease down to minimum at 0834 UT (state 4), and postflare recovery at 1000 UT. The difference between the amplitude peak value at 0837 UT on 06 July, and the value of amplitude at the same time, but on the nearest unperturbed day, 05 July, is $\Delta A = +1.0$ dB. The difference between phase delays, corresponding to the time of amplitude maximum on 06 July and at the same time on 05 July, is about -15˚.

Manifestation of flare effect on NAA signal shows no such complicated morphology as in case of GQD signal. From 0817 UT (state 9), the NAA signal amplitude increases readily following the increase of X-ray irradiance, and reaching maximum at 0837 UT (state 10). In the descending branch, amplitude change follows the descending of the X-ray irradiance. The recovery of the amplitude takes place at 1051 UT (11). The phase delay shows very similar behavior, with maximum occurring at 0837 UT, and terminating the recovery about the same time as for amplitude. The difference between the amplitude peak value at 0837 UT on 06 July, and the value of amplitude at the same time, but on the nearest unperturbed day, 05 July, is $\Delta A = +4.4$ dB. The difference between phase delays, corresponding to the time of amplitude maximum on 06 July, and at the same time on 05 July, is about 40˚.

3. Solar Flare induced Electron density Height Profile changing

The incidence of the X-ray radiation to the Earth’s ionosphere during the solar flare cause not only the enhancement of maximum the electron density, but also change the distribution of ionization from upper to lower edge of the D region. In other words, the change of electron density height profile takes a place. In general, the lower edge of ionosphere (the upper boundary of VLF waveguide) descends, and becomes “sharper”. The propagation model given in [6], describes the electron density in the waveguide by two parameters: sharpness, denoted by β and reflection height, denoted by *H'*. This model has been used to simulate VLF propagation through Earth-ionosphere waveguide at regular conditions [3, 7], as well as for the conditions corresponding to the flare peak irradiance [8, 9] and the obtained results are in good agreement with VLF signal measurements. By guidelines of the method used by these authors, we attempt to model the Earth-ionosphere waveguide for several characteristic moments during the flare event. For this purpose we calculated electron density profile $N_e(z)$, for given β and *H'* using the expression given in [6]:

$$N_e(z, H', \beta) = 1.43 \cdot 10^{13} \exp(-0.15H') \exp[(\beta - 0.15)(z - h')] \tag{1}$$

By means of LWPCv21 program [10], the propagation paths of VLF waves on frequencies 22.1 kHz and 24.0 kHz were simulated and the goal was to estimate the best fitting pairs of parameters β/*H*' (reflecting edge sharpness/reflecting edge height) to yield values closest to real measured phase delay and amplitude at Belgrade receiver site, for each characteristic state of the flare event considered. The calculated amplitude and phase delay values obtained by LWPCv21 program for unperturbed conditions, are in good agreement with measured values at Belgrade receiver site, for both traces. Therefore it could be taken in further simulations that synthetic signals had been transmitted in modeled ionospheric conditions which are in good agreement with real ionospheric conditions held in that time and measured at the place of receiver.

Because the GQD signal trace from transmitter to receiver crosses only two time zones, the same pairs of chosen parameters β/*H*' held along the whole trace for each simulation. Since the NAA signal trace from transmitter to receiver crosses six time zones, parameters β/*H*' change along the trace. In this case, 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. Measured phase and amplitude perturbations, estimated parameters β and *H*' and corresponding electron densities at 74 km, calculated using (1) for three times during the flare and for each signal trace, are given in Table 1.

Table 1.Parameters characterizing propagation conditions at flare event on 06 July, 2006.

Flare event M2.5; 0836 UT	Times of characteristic states, UT					
	GQD/22.1 kHz			NAA/24.0 kHz		
	0817	0837	1000	0817	0837	1051
ΔP (˚)	-3.44	-20.25	-0.44	-5.02	40.01	3.07
ΔA (dB)	0.04	1.0	-0.79	-0.03	4.49	0.52
β (km^{-1})	0.345	0.36	0.425	0.355	0.54	0.395
H' (km)	72	67	70	73.5	69	72
N_e (m^{-3}) [*H*'=74 km]	$4.3 \cdot 10^8$	$2.7 \cdot 10^9$	$1.2 \cdot 10^9$	$2.6 \cdot 10^8$	$3.2 \cdot 10^9$	$4.8 \cdot 10^8$

For the characteristic times of unperturbed (preflare) state, perturbed, flare state and "recovered" postflare state, marked with numbers 1, 5, 8, 9, 10 and 11 on Fig. 1, for both signal traces, the vertical electron density profiles through ionospheric D-region are determined. Changes of the electron density height profile (from 50 – 90 km altitude), at three characteristic times: 0817 UT (1), 0837 UT (5), and 1000 UT (8), for GQD/22.1 kHz and 0817 UT (9), 0837 UT (10), 1051 UT (11), for NAA/24.0 kHz signals are shown on Fig 2. (a) and (b), respectively. The changes of electron density profiles are further analyzed in more details.

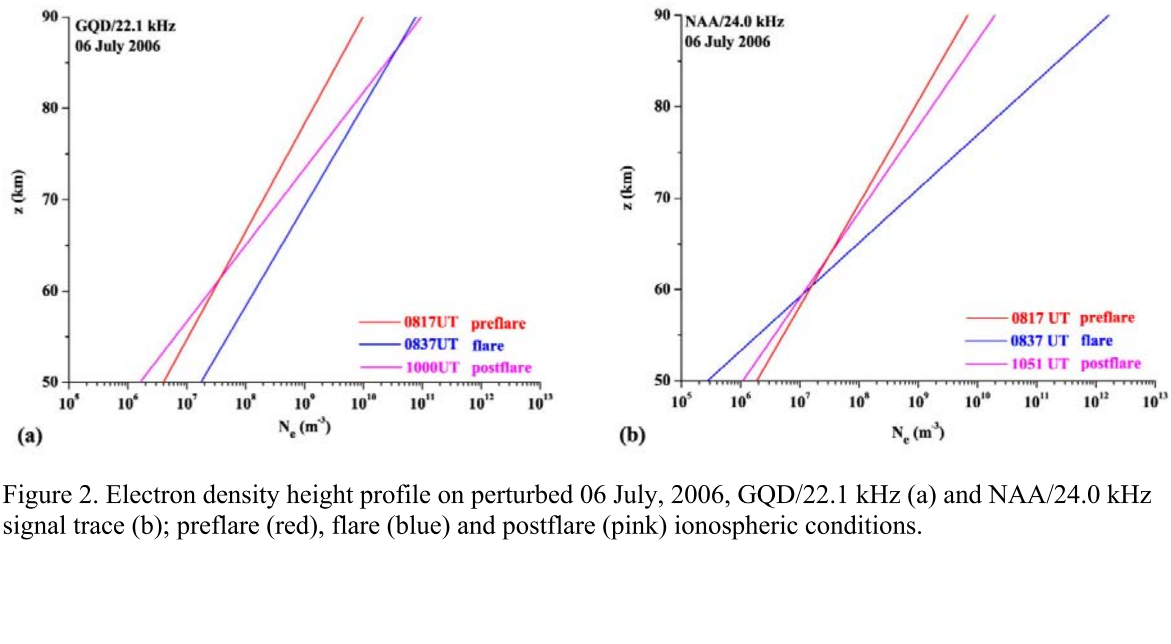

Figure 2. Electron density height profile on perturbed 06 July, 2006, GQD/22.1 kHz (a) and NAA/24.0 kHz signal trace (b); preflare (red), flare (blue) and postflare (pink) ionospheric conditions.

The electron density height profile obtained from (1) with β and H' parameters corresponding to unperturbed, preflare state at the time 0817 UT, for both GQD and NAA signal have similar slope, the same order of magnitude, but differ slightly in the whole D region altitude range. Electron density as estimated from GQD signal is about 2 times higher then one estimated from NAA signal. At the state of greatest signal perturbation (0837 UT), one minute after the X-ray peak irradiance, there is the substantial difference between the electron density profile as deduced from GQD and NAA signal measurements: according to GQD measurements, $N_e(z)_{\mathrm{GQD}}$ slope in Fig. 2a, indicates a moderate change of the electron density from 10^7 - $5\cdot10^{10}$ (m^{-3}) in 50-90 km range, while $N_e(z)_{\mathrm{NAA}}$ slope in Fig. 2b, predicates a sever change from very low $N_e = 3\cdot10^5$ (m^{-3}) at 50 km, to very high $N_e = 1.7\cdot10^{12}$ (m^{-3}) at 90 km. These values are not likely to be realistic, and are probable due to the fail of the model at the D region boundaries. Nevertheless, at 74 km, $N_e(z)_{\mathrm{GQD}} \approx N_e(z)_{\mathrm{NAA}} \approx 3\cdot10^9$ (m^{-3}), that is in agreement with result from other studies [5, 8]. According to NAA measurements, the ionosphere recovers completely in about two hours (1051 UT) after the flare maximum, while GQD signal the recovery is not reached in that time.

4. Conclusion

The changes of the electron density caused by solar X-ray flare impact as deduced from VLF wave phase and amplitude perturbations of two different signals: GQD/22.1 kHz and NAA /24.0 kHz recorded at Belgrade, suggest that corresponding Earth-ionosphere waveguides undergo different changes, even induced by the same flare event.

5. Acknowledgements

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6. References

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