Effect of solar flares on ionospheric VLF radio wave propagation, modeling with GEANT4 and LWPC and determination of effective reflection height

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Abstract

Solar flares are among the most prominent transient events affecting the radio wave propagation in the ionosphere. In this paper we model the ionizing effect on VLF wave, reflected from D-layer of the ionosphere during different classes of flares and compare with observed VLF modulation. A well known detector simulation software GEANT4 is used to calculate the ionization produced in different heights ($\sim$ 60 - 80 km) of the D layer. The chemical balancing between the ions and neutrals in the region is taken into account with a simplified chemical model, the GPI model. The VLF modulation is reproduced with LWPC. We have seen that the peaks of electron density arise at different times at different heights. Matching with the time delay of the VLF signals we have proposed an alternative effective reflection height during such events.

1 Introduction

Very low frequency (VLF) part (3-30 kHz) of the radio wave is a useful probe of lower ionosphere (D-region in day time) to extract the information on perturbations and modulations of various phenomena, such as Earth quake, lightning, various ionizing extra-terrestrial events like SGR, GRB and solar flare etc. The effect of solar flares on the reflected VLF wave has been a topic of extensive research (Rowe et al., 1974; Mitra, 1981). These modulating effects are produced due to the extra ionization of X-ray from flares. mainly the soft X-ray ($\sim$ 2 - 12 keV) is responsible for the ionization at D-layer heights during these events.

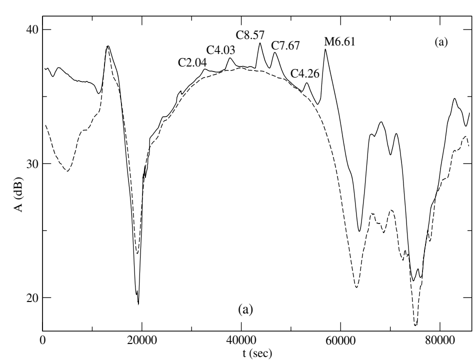

Figure 1: The figure demonstrates an example of a whole day VLF (19.8 kHz) amplitude profile transmitted from the NWC station and recorded at IERC(ICSP), Sitapur on 18^{th} February 2011. The time (in UT + 5.5 hr) profile shows six solar flares of different classes. A solar-quiet day, corresponding to 12^{th} February 2011 data is also presented (dotted line).

We have used a widely popular and efficient detector simulation program, GEANT4 (Agostinelli et al., 2003) to calculate the ionization by X-rays at the heights between $\sim$ 64 to 80 km as this is the height where the usual reflection of VLF takes place. Assuming the time scale is insufficient for the transport of ions between layers we have employed a simple four ion component, Glukhov Pasko Inan (GPI) (Glukhov et al., 1992) chemical scheme to tackle the chemical balancing between the production and loss processes in the D-region. The evolution of free electron density during flares is given due attention, as the effect of ions on the VLF signal is negligible compared to this.

The Long Wave Propagation Capability (LWPC) code (Ferguson, 1998) has been used to simulate the VLF signal modulation. To compare the simulation result on the change in the VLF signal during the solar flare events and the decay profile of the peak due to long recovery time we have taken observed VLF data of two different classes of flares, one X2.2 (occurred on 15^{th} Feb 2011) class and one M3.5 (occurred on 24^{th} Feb 2011) class. The data are taken in a ground based VLF receiver of the Ionospheric and Earthquake Research Centre (IERC) under Indian Centre for Space Physics (ICSP).

From the outcome of the chemical model we have noticed an interesting phenomena, the peaks of the electron density at different heights of the D-region corresponding the flare intensity peak appear at different time. Comparing with the VLF signal peak time delay we have proposed a method to calculate the effective reflection height of the VLF signal.

2 Observation and Model

For the first attempt of modeling with X-ray ionization (for more weaker flares like C or B classes the effect of ionization of increased ultra violet (UV) radiation must be taken into account.) only, we have simulated the VLF signal effect of two strong flares, one X2.2 class and one M3.5 class. VLF data for the NWC (19.8 kHz) to IERC/ICSP propagation path (distance 5691 km) is used for comparison with the model outcome.

In the first stage of the modeling the thorough calculation of ionization due to X-ray from flares are done with GEANT4 Monte Carlo simulation program, The ionosphere is constructed as stratified structure in the Detector construction class. The neutral densities, temperature and other parameters are taken from NASA-MSISE-90 atmospheric model of the atmosphere. All the required physics for the production of electron ion pair in the atmosphere by energetic photon interactions, such as initial photo ionization, inelastic scattering, compton effect, collision of molecules with secondary electrons etc. are employed. Instead of approximating a value ($\sim$ 35 eV as assumed by Glukhov et al., 1992) of the average energy for production of an electron-ion pair to find the numbers, we let our simulation to follow down to lowest energy interactions ($\sim$ 10's of eV), and obtain the value of average ionization energy $\sim$ 31 eV. We have taken into account the zenithal variation of solar position in calculations.

In the next phase we have gone through the atmospheric chemistry involved in the balancing process with a simple model, called the GPI model (Glukhov et al., 1992). In GPI model we solve four differential equations containing terms corresponding to production and loss processes of four broad categories of ion species, namely electrons, positive ions, negative ions and positive cluster ions. The positive ions N^+ comprise of mainly O_2^+ and NO_2^+. The negative ions N^- include O_2^-, CO_3^-, NO_2^-, NO_3^- etc. The positive cluster ions N_x^+ are usually of the form $H^+(H_2O)_n$. We are not going into the details of the model here, for the differential equations, the coefficients and the values adopted for them in solving those equations etc. readers are referred to Palit et al., 2013 and Glukhov et al., 1992.

The output of the GPI model, viz, the electron density variation with time at different height during the flare evolution is fed into the Long Wave Propagation Capability (LWPC) code to find the corresponding VLF modulations. For the electron-neutral collision frequency we have used the profiles described by Kelley (2009).

3 Results

The output of the GEANT4 Monte Carlo simulation in terms of electron production rate per unit volume at the time of peak of the flare is shown in Figure 2. From the figures we can find that the height of maximum electron density produced during the peaks of the two flares are different (89 km for the M class one and 81 for the X class). It is due to the fact that the X-class spectrum is relatively harder than that of the M class.

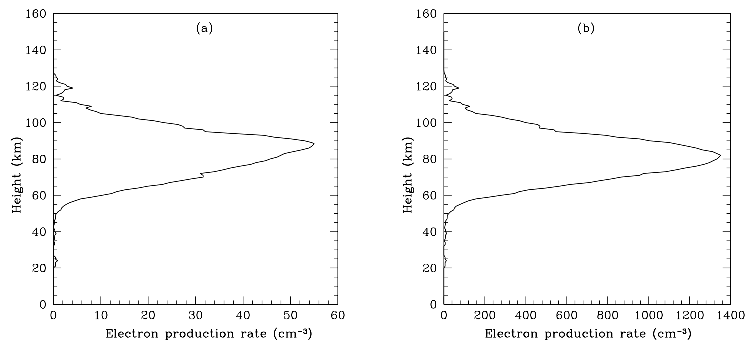

Figure 2: Peak time electron production rates per unit volume for the (a) M-class and (b) X-class flare

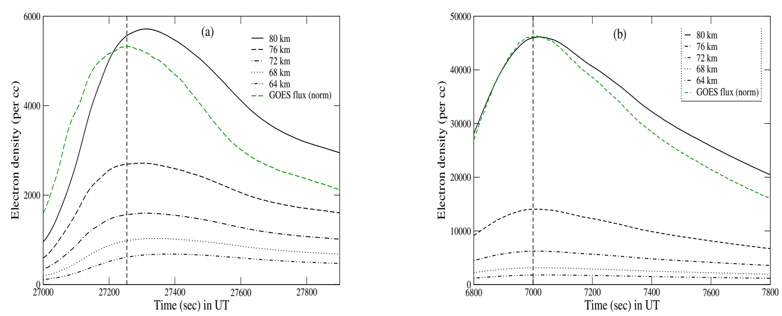

Figure 3: The time variations of electron density at different heights in D-region of the ionosphere near the peaks of the X-class(a) and M-class(b) flares

The time variations of the electron densities for the two flares as obtained from the GPI model are shown in the Figure 3. We find that the peaks of the electron densities appear at different times at different heights. We have calculated the peak time delay values of electron densities at all the heights and compared the values with those of VLF peak time delay ($\sim$ 32 sec for X class and 68 sec for the M class flare). From the assumption that the VLF signal modulations follow the electron density changes at the height of reflection immediately, we can say by comparison that the VLF reflection heights for the X and the M class flares are respectively 62.9 km and 65.2 km.

The comparisons between the simulated modulation of the VLF signals for the two flares with those observed are given in Figure 4.

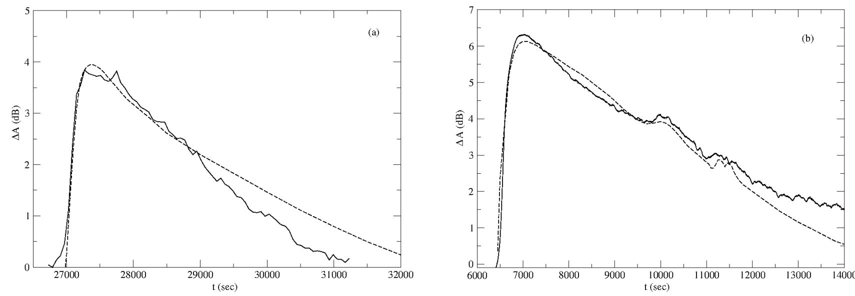

Figure 4: Simulation results of VLF amplitude perturbations (dotted line) and corresponding observed VLF data (solid line) are plotted with UT for (a) M-class and (b) X-class solar flares respectively.

4 Conclusion

We have done the modeling of the effect of solar flares (X and M class) on the VLF radio wave signal and show that they match quite satisfactorily with the observed signal. The process consists of three steps, results of each step is presented in the paper. From the comparison of electron peak time delay with those of VLF we get reasonable values of effective reflection heights.

5 Acknowledgments

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6 References

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