Response of D-region ionosphere due to solar flares during solar cycle 24 using VLF measurement

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Abstract

The effects of solar flares on the propagation of subionospheric VLF signals from NWC transmitter station monitored at a low-latitude station, Varanasi (lat. 14° 55′N, long. 154° E), India, during solar cycle 24 have been analyzed. The amplitude and phase enhancements associated with solar flares were observed in the signals which are due to an increase in the electron density of the D-region as a result of extra ionization caused by the solar flares. The solar flare-induced perturbations in the VLF signals were used to determine D-region ionospheric parameters: H′ (the ionospheric refection height) and β (rate of increase in electron density with height) using Long Wave Propagation Capability (LWPC) modeling. H′ decreases in proportion to the logarithm of the X-ray flux intensity. It is found that there is a typical reduction in H′ which occur from a midday unperturbed value of about 71 km to about 58 km for an X6 class solar fare where as β increases from 0.39 km^{-1} to a saturation level of about 0.52 km^{-1}.

1. Introduction

The lower D-region (~50–70 km) of the atmosphere is ionized mainly by solar EUV radiation and galactic cosmic rays. The partially ionized lower D-region forms the upper boundary of the Earth-ionosphere waveguide, while the oceans and ground form the lower boundary. Usually these boundaries are stable and allow VLF waves (~3–30 kHz) propagation with little or no perturbation.

Solar flares, mainly having X-ray wavelengths of the order of tenths of nanometers, permeates the D-region of the ionosphere and enhance the electron density by extra ionization [1]. McRae and Thomson [2] found that flares of C to X classes perturbed the subionospheric VLF signals during a period of low to moderate solar activity period between 1994-1998. Grubor et al [3] studied solar flares using VLF sudden phase anomalies (SPAs) on NDAK (North Dakota, USA, 13.1 kHz), HAI (Haiku, USA, 13.6 kHz) and ARG (12.9 kHz) transmitter signals received at Atibaia (ATI), Brazil. Their results suggest that the occurrence of SPAs due to weak solar fares, of class C and below, was higher during solar minima, but the occurrence of SPAs was not dependent on the solar activity for stronger class fares. Singh et al [4] studied the ionospheric D-region parameter changes, H′ and β, as a function of solar X-ray flux by using solar flare-induced perturbations to the VLF amplitude and phase of the NWC (Australia) signals received at Varanasi, India during ascending phase of solar cycle 24. H′ is a measure of the ionospheric reference height in kilometer and β is the electron density sharpness in km^{-1} of the D-region. The effects of solar flares on the propagation of subionospheric VLF signals from NWC and NLK transmitter stations monitored at a low-latitude station, Suva (18.2°S, 178.4°E), Fiji, during solar minimum and solar maximum years have been reported by Kumar and Kumar [5]. They reported a comparative analysis of the ionospheric D-region parameter changes which shows a greater increase in β and decrease in H′ during low-solar activity period than during moderate-solar activity period, for the same class of flares. Recently, Raulin et al [6] studied the effects of 26 solar flares of classes C2.6 to X3.2, on the amplitude of the NWC (Australia) signal recorded at a low-latitude site at Tay Nguyen University, Vietnam. They found that during the solar flares, β increased from 0.3 to 0.506 km^{-1}, while H′ decreased from 74 to 60 km. In the current study, the relationship between flare power and changes in H′ and β is presented using an extensive amount of solar flares data analyzed during solar cycle 24 for the years 2008-2018.

2. Observation & Experimental Details

The AWD (Automatic Whistler Detector) VLF receiver has been installed at the campus of Banaras Hindu University. Recorded VLF data are stored in a recording PC at 100 kHz, 16-bit sampling rate and 10 micro-seconds time resolution. These sampled data are analyzed by codes developed in MATLAB and modified by us to suit our data recorded at the low latitude station Varanasi. The solar flare produced additional ionization in the D-region perturbs (usually enhancements) the amplitude and phase of the VLF signals transmitted from the phase stable transmitters. The observed amplitude changes are modeled using the Long Wave Propagation Capability (LWPC) waveguide codes to find the values of H′ and β [2].

3. Results and discussion

Solar flare effects on subionospheric VLF propagation: We have analyzed the intense solar flares occurred during the solar cycle 24 from 2008-2018. All the solar flare-induced VLF perturbations displayed enhancements in amplitude and phase. The effects of solar flares on VLF signals were only observed when a portion of the TRGCPs were present under daylight conditions. Number of daytime solar flares of X, M and C class during solar cycle 24 are tabulated in Table 1. The consistent variation of amplitude and phase with solar flux indicates that XL band radiation is well correlated with extra D-region ionization during solar fares.

Table 1: Number of daytime solar flares of X, M and C class during solar cycle 24.

S.NO.	Class of solar flare	No of solar flare observed
1	X Class	5
2	M Class	77
3	C Class	91

Solar flares of June 21, 2015

A series of solar fare events, recorded by GOES satellites, perturbed the amplitude and phase of the NWC signal on 21 June, 2015. The variation of X-ray flux during the two flare events of classes M2.0, and M3.8 together with the amplitude of the NWC signal, is shown in Fig. 1. These flares occurred during 00–05 h UT and 10–15 h UT and the NWC to Varanasi TRGCP was completely in daylight. The NLK signal was of-air, so no effect could be observed in it. During these flares, the NWC amplitude and phase enhancements showed clear proportional variation with the X-ray flux intensity. The ΔA values for NWC ranged from 1.4 dB (C7.1) to 2.6 dB (M4.7) for other flares.

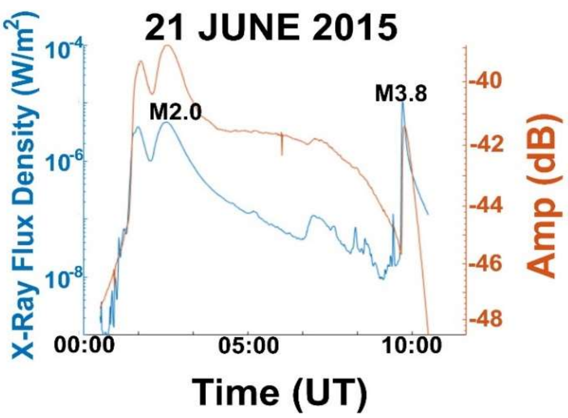

Figure 1. Variations in the amplitude of the NWC signal during the June 21, 2015, solar fares along with the GOES X-ray flux in W/m^2.

Throughout this period, the signal strength was above the normal daytime value because the next flare was occurred before the full recovery of amplitude. The peaks of the amplitude of the signal appear to be well aligned with the peak of the X-ray flux during all the flares.

Solar flare of August 9 2011

Figure 2 shows variation of the amplitude of 19.8 kHz NWC signal measured at Varanasi and the X-ray flux of class X 6.9 solar flare observed from GOES 15 satellite on the flare day of 09 August 2011. The wave amplitude showed identical variation with X-ray flux and a maximum was observed at around 08:05 UT. The computed ΔA value from VLF measurement is 3.40 dB. Using this value of ΔA the Wait parameters H′ and β are evaluated to be 65.03 and 0.48 km^{-1} respectively. The electron density during the solar flare period can be computed using these values and compared to those which is obtained with the unperturbed electron density, i.e. using H′ = 71 km and β = 0.43 km^{-1}.

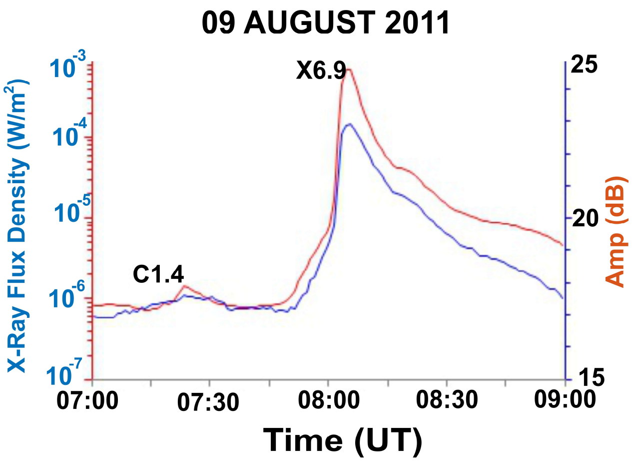

Figure 2. Temporal variation of X-ray flux and VLF signal (19.8 kHz) received at BHU, Varanasi during solar flare event of 09 August 2011.

Solar flares of July 23, 2016

Figure 3 shows The variation of X-ray flux during the two flare events of classes M5.0, and M7.6 together with the amplitude of the NWC signal. During these flares, the NWC amplitude and phase enhancements showed clear proportional variation with the X-ray flux intensity.

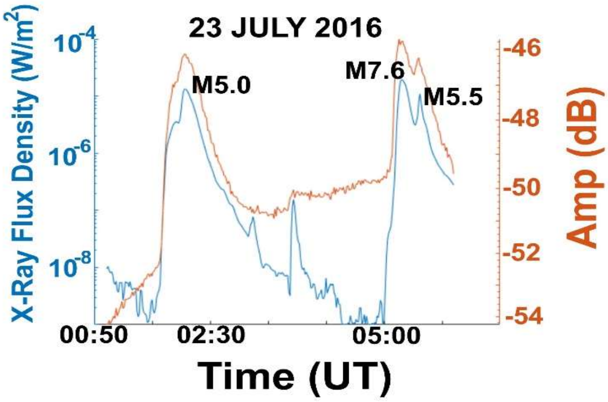

Figure 3. Variations in the amplitude of the NWC signal during the July 23, 2016, solar flare along with the GOES X-ray flux in W/m^2.

Effects of solar activity on solar flare-induced VLF perturbations

From all the solar flares recorded, measurable effects of 48 flares were observed on signals from NWC signal during the period of low solar activity. VLF perturbations might not be observed during daylight hours, for all the flares, because either the VLF transmitters were not in working mode (or no data were available) or weaker flares of class C and below may not have produced any detectable VLF perturbations. The ΔA associated with solar fares for NWC during the periods of solar cycle 24 has been plotted as a function of X-ray solar flare power as shown in Fig. 4.

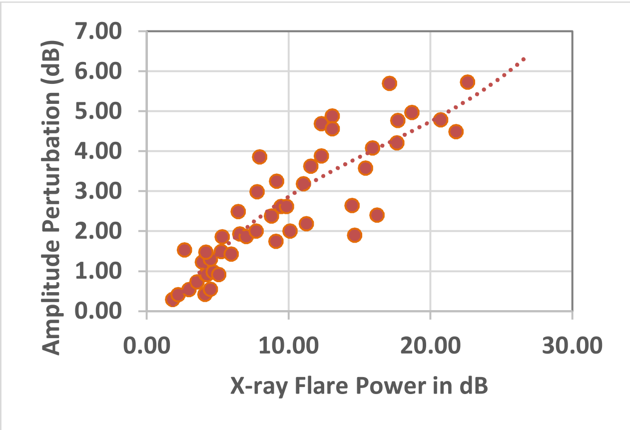

Figure 4. VLF amplitude perturbations for NWC measured at Varanasi, as function of solar fare X-ray flux measured in dB.

VLF signal perturbations due to solar flares were used to determine the accompanying changes in D-region parameters (H′ in km and β in km^{-1}) using the LWPC code. The perturbed values of ionospheric H′ and β during solar flares were obtained by varying the values of H′ and β so as to match the observed perturbed amplitude (A + ΔA). This was done by adjusting the values of H′ (at intervals of 0.05 km) and β (at intervals of 0.001 km^{-1}).

The variations of H′ and β for the solar flares

With varying intensity, ranging from weak (C1.0) to strong (X6.5) classes, the ionospheric D-region parameters β and H′ are plotted in Fig. 5 and Fig. 6 respectively for the NWC signal as functions of solar flare power during the solar cycle 24 for low and moderate and intense solar activity conditions.

β, as seen from the Fig. 5, shows a sigmoidal variation, increasing quite linearly with respect to the flare power in the range 5–20 dB for the NLK and NWC signals during low-, moderate and intense-solar activity periods. Below 5 dB, the flat curves for both signals flatten approaching a minimum β of approximately 0.32 km^{-1}, while they become less steep above 20 dB but do not fatten completely.

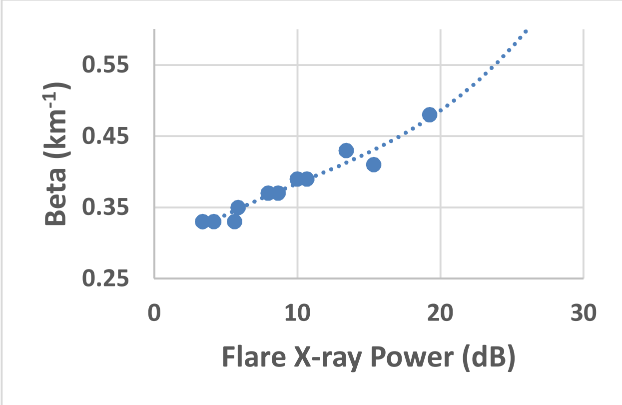

Figure 5. Ionospheric D-region parameters β, found as functions of solar X-ray flare power from the VLF amplitude perturbations of NWC signals received at Varanasi.

The Fig. 6 shows that H′ decreases in direct proportion to the increasing logarithm of the X-ray flux. H′ drops to 56 km for the strong X6.5 flare and 70–71 km for weak C1.0 class flares from normal typical daytime value of about 70.7 km.

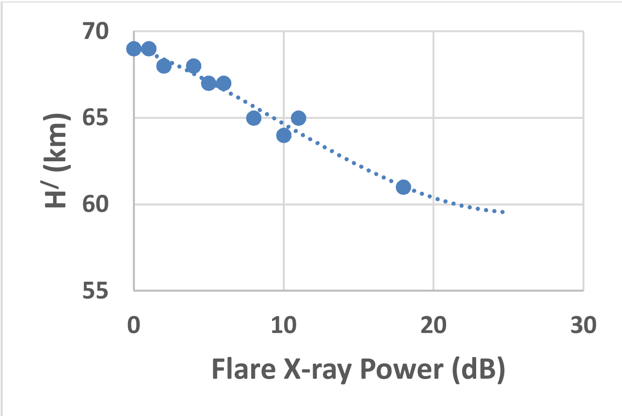

Figure 6. Ionospheric D-region parameters H′, found as functions of solar X-ray flare power from the VLF amplitude perturbations of NWC signals received at Varanasi.

Classes C1.0 and X6.5 correspond to 0 and 28 dB flare power, respectively. An interesting feature of the variation in H′ with X-ray flux is that there is a difference in the reduction in H′ for the same class of solar fares depending on the level of solar activity

4. Conclusions

Based on the results, the following conclusions are reached:

1. It is observed that the D-region electron density shows an abrupt enhancement with the enhancement of X-ray fluxes of the solar flare events. Electron density is much

more pronounced during X-class flare as compared to M-class flare.

2. The increased ionization from the solar flare lowers the effective reflecting height, $H^{/}$, from a typical mid-day unperturbed value of about 71–72 km down to about 65 km roughly in proportion to the logarithm of the X-ray flares intensity.

3. The sharpness, β, of the lower edge of the D-region is also significantly increased by the solar flares. It is found that β increases from around 0.43 km^{-1} (for the near midday NWC-Varanasi path) to a general saturation level of about 0.49 km^{-1}.

4. Solar flares of similar class produced higher values of ΔA during low solar activity than during periods of intense solar activity.

5. Acknowledgements

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6. References

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