Initial results on solar flare effect on 24.8 kHz subionospheric propagation over long path to Suva

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1 INTRODUCTION

Solar flares are explosions on the surface of the sun that release a large amount of electromagnetic energy in the form of radio waves at the long wavelength end, through optical emission to X-rays at the short wavelength end. It has long been known that the solar flares, particularly associated with X-rays having wavelengths typically of tenths of nm, penetrate the lower region of the ionosphere (D-region) and increase the electron density via extra ionization (Mitra 1974). The normal unperturbed daytime D-region from which Very Low Frequency (VLF) signals are reflected is maintained mainly by Lyman-α radiation (121.6 nm) from the sun that partially ionizes the minor neutral constituent nitric oxide (at height around 70 km). Under normal conditions, the solar X-ray flux is too small to be a significant source for ionizing the D-region. However, when solar flare occurs, the X-ray flux increases significantly which with wavelengths below 1 nm penetrates down to the D-region and markedly increases the ionization of the neutral constituents particularly nitrogen and oxygen hence increases the electron density. The lower ionosphere can be characterized as the "Wait ionosphere" defined by a reference height H' in km and the exponential sharpness factor β in km^{-1} (Wait and Spies 1964). Researchers have reported changes in the ionospheric parameters, H' and β as a function of solar X-ray flux (Thomson *et al*. 2004, 2005; Grubor *et al*. 2005; Zigman *et al*. 2007). The increase in the D-region electron density can produce significant perturbations in the phase and the amplitude of VLF signals propagating in the Earth-ionosphere waveguide.

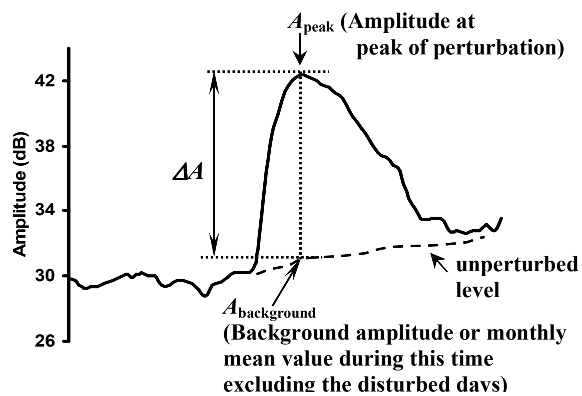

Figure 1 Method of determining the perturbation (enhancement) in the amplitude of VLF signals during the solar flares.

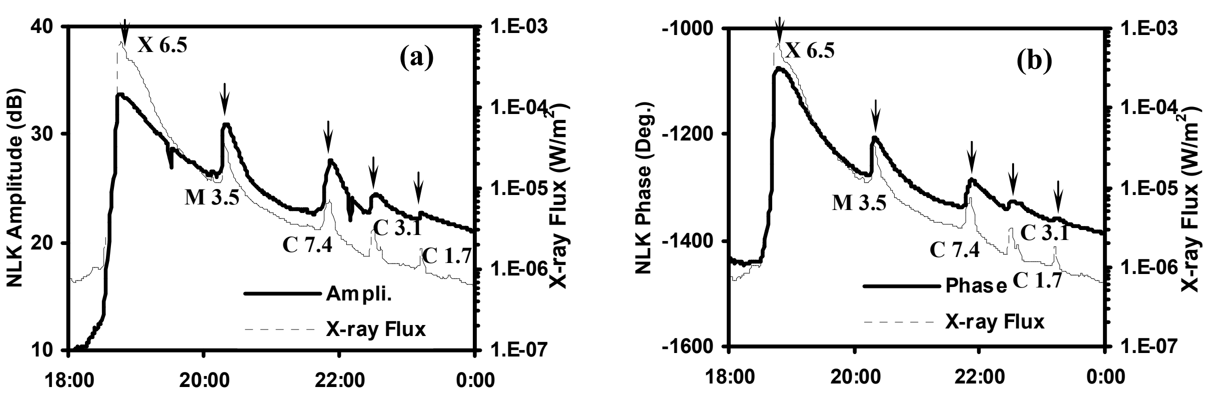

Figure 2 (a, b) Variation in the amplitude (**a**) and phase (**b**) of NLK signal along with the GOES X-ray flux during the solar flares on 6 December 2006.

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In this paper, we present initial observations of the effect of solar flares on the amplitude and phase of the NLK (24.8 kHz) signal from Jim Creek, Washington (48.2º N, 121.9º W, 192 KW) transmitter monitored at Suva (18.1º S, 178.5º E), Fiji, during the period November 2006 - January 2007. The period of data analysis corresponds to solar minimum (average sunspot number $R_z = 12$) of the current solar cycle. We have used 1-min averaged amplitude and phase data recorded at 0.1 s resolution.

2 EXPERIMENTAL DATA AND RESULTS

The signal at 24.8 kHz is received at Suva using the World-Wide Lightning Location Network (WWLLN) VLF setup (Dowden *et al*. 2002) at Physics division, USP, and is recorded using Software based Phase and Amplitude Logger (SoftPAL). The signal is recorded at 0.1 s resolutions by SoftPAL and run using Chart for Windows software. The signal from NLK transmitter propagates a large path in the north-to-south direction with significant part in east-to-west direction as well. The propagation is transequatorial almost over sea covering a total path length of 9.43 Mm.

The solar X-ray fluxes are recorded in two wavelength bands: (1) 0.1-0.8 nm, referred to as "long" or "XL", and (2) 0.05-0.4 nm, referred to as "short" or "XS" by the X-ray imager on the Geostationary Operational Environmental Satellites (GOES). The XL band has the greater fluxes of solar flares as compared to the XS band. Solar flares are classified as A, B, C, M, and X classes according to the peak flux (in watts per square meter, W/m²) in the XL band with class A flare as the weakest and class X as the strongest. Within a class, there is a linear scale from 1 to 9. For example, an X2 flare is twice as powerful as an X1 flare and is four times more powerful than a M5 flare. The solar flux data in the XL band at one minute averages are obtained from the website http://spidr. ngdc.noaa. gov/ spidr/ dataset.do. Solar flare-induced perturbations in the amplitude (ΔA) of VLF transmission were determined using the method proposed by Todoroki *et al*. (2007) as demonstrated in Figure 1. The value of ΔA is obtained by $\Delta A = A_{\text{peak}} - A_{\text{background}}$, where A_{peak} is the value of peak amplitude and $A_{\text{background}}$ is the monthly mean value of amplitude at the time of peak amplitude perturbation. The perturbation in phase for all solar flares could not be determined as it was unstable during most of the flares. Solar flare-induced perturbations in all cases showed an enhancement in the amplitude and an increase in the phase under stable phase conditions. Solar flare effect was observed only when the Transmitter-Receiver Great Circle Path (TRGCP) was entirely or partly in the daylight region. The effect of recent solar flares that occurred on 06 November 2006, 06-14 December 2006, and 29 January 2007 with classes B8.5 to X6.5 are analysed. On 06 December 2006, a series of solar flare events were recorded by GOES which enhanced the amplitude and phase of the signal. The variation of the X-ray flux in logarithmic scale during five flare events of classes X6.5, M3.5, C7.4, C3.1, and C1.7 along with the amplitude and phase of signal are shown in Figure 2 (a) and (b) respectively. During the time interval, 18-00 hrs UT (LT = UT + 12 hrs), in which these flares occurred, the NLK-Suva TRGCP was completely in the daylight.

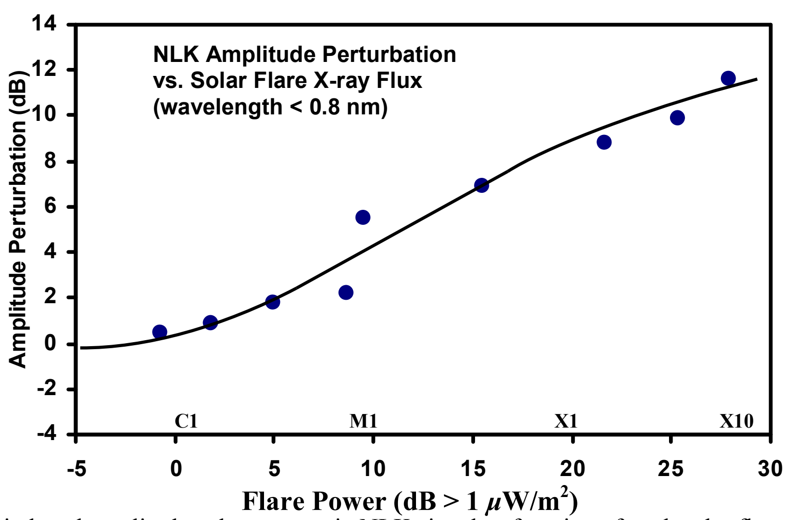

Figure 3 Solar flare induced amplitude enhancement in NLK signal as function of peak solar flare X-ray flux in dB (relative to 1 μW/m^2) in the 0.1-0.8 nm band.

Both the amplitude and the phase of NLK signal showed proportional variation with the X-ray flux intensities during these flares. The ΔA values were 11.6 dB, 6.9 dB, 2.2 dB, 1.8 dB, and 0.5 dB for the flares of classes X6.5, M3.5, C7.4, C3.1, and C1.7 respectively. The amplitude of the signal remained above the normal day unperturbed level after each successive flare until the last C1.7 flare finished. This could be due to the occurrence of later solar flares that generate extra ionization before the ionization settles to the initial values caused by the previous solar flares. Hence, the amplitude remained more than the unperturbed level before the onset of next flare. A solar flare (not shown here) of class C8.8 occurred on 6 November 2006, which produced ΔA of 5.5

dB. It started at 17:43 UT (05:43 LT) and ended at 18:06 UT. On 13 and 14 December, the flares of class X3.4 and X1.5 occurred producing ΔA of 9.9 dB and 8.8 dB respectively. Two solar flare events occurred on 29 January 2007; 1) of class B8.5 that began at 21:34 UT (09:34 LT) and ended at 21:45 UT, and 2) class C1.5 that began at 22:32 UT (10:32 LT) and ended at 23:21 UT. The values of ΔA were 0.4 dB and 1.0 dB for the B8.5 and C1.5 classes respectively. During these flares, the phase of the signal was not stable enough to be analyzed for the perturbation. From the data analysis it was found that both the amplitude and phase vary in good proportion with the logarithm of the X-ray flux. The amplitude and phase could be useful and convenient for extrapolating the X-ray flux to determine the actual flux intensities when the GOES detectors saturate during very strong solar flares. GOES detectors saturate for solar flares stronger than X17 class (Thomson et al. 2005). The ΔA at the time of peak of the nine solar flares are plotted in Figure 3 as a function of X-ray solar flare power in dB over 1 μW/m2. The flares ranged from B8.5 to X6.5 classes. All the flares studied here occurred when the TRGCP of NLK signal was in the daylight. The best-fit curve for the amplitude perturbation versus the flare power resembles the form previously obtained by McRae and Thomson (2004) and Thomson et al. (2005). However, the data points are less compared to those reported by these authors. It can be noted that the curve is steeper and linear between the flare power levels of 5 dB to 20 dB. Below 5 dB, the curve gets less steep and flattens towards -5 dB flare power level. It also gets less steep above 20 dB but does not flatten fully as previously reported by McRae and Thomson (2004). The peak phase perturbation could not be plotted with the respective peak flare power because the phase was not stable most of the time, hence enough data points could not be obtained. The enhancement in the amplitude of NLK signal with the increase in the solar flare intensity can be explained qualitatively as follows. As the flare flux increases, two phenomena might take place, 1) the increase in the D-region electron density and 2) redistribution of the electron density with height which lowers the D-region (Grubor et al. 2005). The upper boundary of the waveguide might become more sharp and lower and as a result, VLF signal is reflected at sharp boundary with comparatively less penetration into the D-region and hence undergoes less attenuation/absorption than under the normal propagation conditions. The lower ionosphere has different sensitivity to solar flares depending upon solar activity, being more sensitive when the sun is less active (low solar activity) (Pacini and Raulin 2006), therefore, the perturbations due to weak solar flares from C1 to B8.5 class could also be observed during the period of study presented here.

3 CONCLUSIONS

Results presented indicate that solar flares produce perturbations in the amplitude and phase of VLF transmission only when the TRGCP is in the daylight. Both the phase and amplitude vary nearly proportionally with the logarithm of the X-ray flux in the XL band. For NLK signal, the best-fit curve for the peak amplitude enhancement versus the flare power (dB) gives an almost linear variation between the flare power levels of 5 dB to 20 dB. Below 5 dB, the curve gets less steep and flattens towards -5 dB flare power level and also it gets less steep above 20 dB but does not flatten fully. Our results indicate that solar flares with lower class up to B8.5 can show detectable change in the amplitude and phase of long subionospheric VLF propagation during the low solar activity period.

4 ACKNOWLEDGEMENTS

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