

# Waves-like signatures in the D-region ionosphere generated by solar flares

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## Abstract

The present study reports presence of periodic Wave-Like Signatures (WLS) in the D-region ionosphere detected using NWC, Australia, VLF navigational transmitter signal (19.8 kHz) observed at Allahabad, an Indian low latitude station. The observed WLS are associated with series of solar flares which includes 12 C, 3 M and 2 X class flares occurred during the month of May 2013. Significant variations are observed on NWC-VLF amplitude and phase due to different classes of flares which occurred at different solar zenith angles. The wavelet analysis of VLF amplitude on control day reveals presence of WLS with periods 40-180 minutes during day/night and night/day transition times which are probably generated due to passage of dusk and dawn solar terminator. Flare day WLS are observed with period varying 90-200 minutes and are remarkably different in their period, occurrence duration/time and amplitude depending on the class and occurrence time of flare and are more prominent during morning and evening times when D-region is in developing stage. The WLS on flare day are probably generated by solar flare induced gravity waves which may cause periodic changes in temperature, electron density, and plasma conductivity in the ionosphere. The present observations seem to shed additional light on the current understanding of gravity wave induced D-region dynamics.

## 1. Introduction

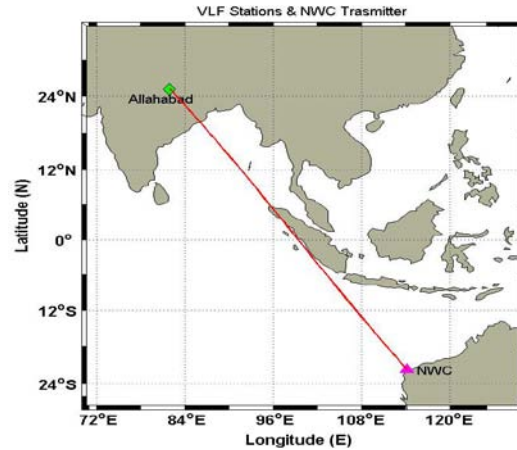
The Solar flares are one of the most powerful events in the solar system and are characterized by sudden and rapid release of energy stored in the twisted magnetic fields in the active regions of sun. Flare produces burst of energy in wide range of electromagnetic spectrum from radio wave to X-rays and gamma rays but maximum energy in the bands of X-ray and Extends to ultraviolet (EUV) range [1].

It is well known from several decades that Solar flares affect the sunlit side of Earth's ionosphere and can be studied using various techniques [2], [3], [4]. The X-rays radiation from solar flares in the wavelength range between 0.2 to 0.8 nm penetrates deep in to the D-region ionosphere and ionizes all the neutral constituents along with the major species O<sub>2</sub> and N<sub>2</sub> [5]. It modifies the electron density concentration in D-region ionosphere and hence changes the propagation conditions for Very Low Frequency (VLF) waves in the naturally formed Earth-ionosphere waveguide (EIWG) between lower ionosphere and Earth's surface [6]. The probing of D-region ionosphere is difficult due to its low altitude range and low electron density. Fixed frequency VLF narrowband signals from various VLF transmitters located across the world propagate by multiple reflections through the EIWG, form the novel tools for remote detection of the D-region perturbations associated with Solar flares [6].

The solar flare effects on the D-region of ionosphere have been studied using amplitude and phase of VLF navigational transmitters signal recorded at various locations around the world [4]. But neither of the work had focused on the possible wave/periodic signature of solar flares in the D-region which may be caused by short term modulation of D-region electron density by solar flare radiation or solar flare induced gravity waves which are associated with changes in temperature and electron density in the D-region. In the present work we are focusing on the first preliminary results of solar flares generated Wave-like signatures (WLS) estimated by the Morlet wavelet analysis of NWC (19.8 kHz) VLF signal recorded at low latitude Indian station Allahabad during recent flare events of C, M and X class that occurred during May 2013 at different local solar zenith angles.

## 2. Experimental setup and data

The NWC transmitter (geographic lat. 21.80°S; long. 114.20°E) amplitude and phase were recorded with AWESOME VLF receiver [7] installed at a quiet location near Allahabad (geographic lat. 25.41° N, long. 81.93° E; geomagnetic lat. 16.05° N, long. 153.70° E,  $L = 1.08$ ), India. The Local Time (LT) of Allahabad is Universal Time (UT) + 5.5 hr. The detailed map of Indian low latitude receiving station and NWC VLF transmitter along with Transmitter Receiver Great Circle Path (TRGCP) is shown in Fig. 1. The receiver is capable of recording both narrowband and broad band VLF signals. The frequency response of the AWESOME VLF receiver is 300 Hz to 47.5 KHz [7]. We obtained the X-ray flux 1 minute average data from the GOES satellite, via the website [www.sec.noaa.gov](http://www.sec.noaa.gov).



**Fig. 1:** Map showing the locations of NWC Australian VLF transmitter and Allahabad VLF receiver station and TRGCP between NWC and Allahabad.

### 3. Observational results and discussion

#### 3.2. Control day Wave Like Signatures (WLS)

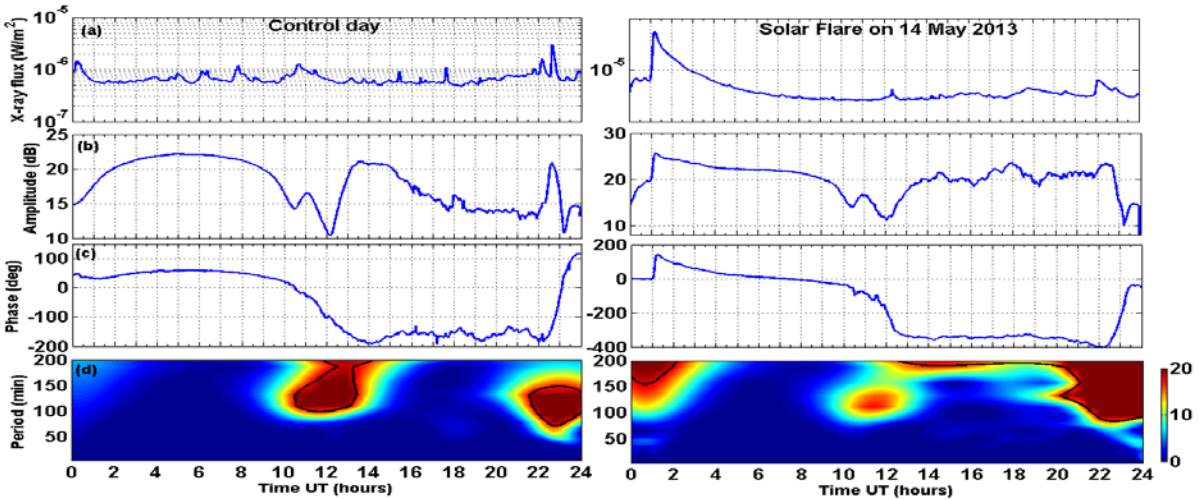
Fig. 2 (a-d), left panel, shows the solar flare X-ray flux data, NWC VLF signal amplitude, phase and wavelet spectra based on Morlet Wavelet technique [8] on control day (21 May 2013). Solar flare X-ray flux (Fig. 2a) was almost within range of  $10^{-6}$  W/m<sup>2</sup> during day time (00-12:00 UT) which indicates that there were no flare events. NWC VLF signal amplitude (Fig. 2b) showing smooth variation during day time due to absence of any flare event (except two characteristics minima at 11-12 UT and 23-24 UT, which corresponds to the day/night and night/day terminator time). Similarly, VLF signal phase (Fig. 2c) also shows smooth variation during daytime. Fig. 2d, shows the Wavelet spectra for amplitude of NWC VLF signal, which clearly shows WLS during two different periods on control day: First during 9:20 -14:30 UT (14:50 – 20:00 LT), WLS with period varying 80-180 minutes and amplitude 10-20 dB, and second during 20:20 – 24 UT (01:50 – 05:30 LT) with period varying 40-180 and amplitude 10-20 dB, were present. There were no WLS seen during rest of 24 hour period. The passage of dawn and dusk terminator during night/day and day/night transition periods which generates internal gravity waves (IGWs) are probably the most important cause of observed WLS on control day [9]. This is more probable as the periods of observed WLS correspond to the periods of GWs, which have periods between minutes to several hours. High variability of the nighttime D-region ionosphere also seems to be source of WLS in the transition periods/times.

#### 3.2 Flare day Wave Like Signatures (WLS)

Fig. 2(a-d), right panel, shows the example plot for X3.2 solar flare with intensity  $3.2 \times 10^{-4}$  (W/m<sup>2</sup>) that occurred at 1:12 UT on 14 May 2013. We can clearly see that WLS are present during 00-04:30 UT, with period between 90-200 minutes with amplitude (intensity) between 10-20 dB. WLS are more prominent (crossing 95% confidence level, thick black contour) during 00-02 UT, with periods between 170-200 and 20 dB amplitude. Table 1 give the details of total 09 days flare events considered in the present study. It includes total of 17 flare events, including 12 C class, 03 M class and 2 X class flares.

**Table 1:** Details of flare events, flare generated WLS and flare associated amplitude and phase changes.

WLS				Flare class	Peak X-ray Intensity ( $W/m^2$ )	Time UT (hours)			VLF Amp (dB)	VLF Phase (deg)
Date	Duration (UT)	Period (min)	Amplitude (dB)			start	max	end		
1/5/13	00-03	120-200	10-12	C9.6	9.6E-06	1:24	1:30	1:50	3.4	34
1/5/13	00-03	120-200	10-12	C4.1	4.1E-06	01:49	01:57	2:25	1.7	24
1/5/13	No			C2.7	2.7E-06	4:10	4:21	4:32	0.6	10
1/5/13	No			C2.0	2.0E-06	6:50	6:58	7:11	0.4	4
1/5/13	No			C5.5	5.5E-06	7:24	7:32	8:06	0.9	6
2/5/13	No			M1.1	1.1E-05	5:01	5:13	5:42	2.3	71
9/5/13	No			C3.4	3.4E-06	5:20	5:25	6:00	0.8	6
10/5/13	0:10-1:50	90-180	9	M3.9	3.9E-05	00:46	0:58	2:20	7.0	88
10/5/13	No			C3.1	3.1E-06	2:43	2:51	2:57	0.3	4
10/5/13	No			C2.1	2.1E-06	3:00	3:05	3:30	0.4	5
10/5/13	No			C1.9	1.9E-06	4:02	4:11	4:30	0.6	6
14/5/13	00-04:30	90-200	10-20	X3.2	3.2E-04	0:05	1:12	4:34	7.2	141
15/5/13	00-5:30	110-200	10-20	X1.2	1.2E-04	1:18	1:48	5:00	5.8	139
17/5/13	No			C5.0	5.0E-06	4:37	4:43	5:10	0.9	23
17/5/13	8:30-9:30	90-140	9-10	M3.2	3.2E-05	8:40	09:0	10:17	4.1	80
18/5/13	No			C6.0	6.0E-06	3:32	3:48	4:36	1.9	52
24/5/13	0-2:30	130-200	10	C2.5	2.5E-06	1:22	1:29	1:50	0.1	2



**Fig. 2:** Left panel: Control day (21 May 2013) (a) X-ray flux intensity (b) VLF NWC signal amplitude (c) VLF NWC signal phase and (d) Wavelet spectra for WLS, Right panel: Solar flare day (14 May 2013) (a) X-ray (X3.2 class) flux intensity (b) VLF NWC signal amplitude (c) VLF NWC signal phase and (d) Wavelet spectra for WLS

The change in VLF signal amplitude and phase is found to be different for different class of flares and maximum increase is for X3.2 flare event. The change in VLF NWC signal is due to additional ionization caused by X-rays generated by the solar flares. This extra ionization causes the D-region or upper boundary of the EIWG to descend up to several km depending on the intensity of solar flare flux [6]. When NWC VLF signal propagated over region of enhanced ionization on upper boundary of waveguide, it faced a mirror type of reflection [4] that increased VLF amplitude and phase recorded at the station.

Out of total 09 days of flare events; we have not observed WLS for flares on 02 days. For rest 07 days, the WLS were not observed for all the flare events. In general, we observed WLS were associated with flares which occurred between 00-5:30 UT and 8:30-9:30 UT and this cutoff is found to be different for different class of solar flares. For C class (including 12 events) cutoff is between 00-2:30 UT, for M class (3 events) 00-2:30 UT and 8:30-9:30 UT and for X class (2 events) between 00-5:00 UT. From above discussion, we can see that WLS are observed only when there is sharp and significant increase in the X-ray flux that can cause significant electron density and plasma conductivity gradients in the D-region. During morning time, when D-region started developing, even a small power flare (e. g. C2.5, 24 May 2013) could cause WLS and when ionosphere is almost developed (during 5:00-8:30 UT), no WLS even for

M1.1 flare (e.g. for 2 May 2013 at 5:13 UT), were detected. It may not be true for X class flares as X class flares. The possible reason for observed WLS during these periods is solar flare caused sudden changes or gradients in temperature, electron density, and plasma conductivity of the ionosphere. The fluctuations in these parameters are probably caused by GWs at different altitudes caused by the sudden heating and ionization of the ionosphere by solar flares. To our knowledge, there is only one report by [9], on solar flare induced WLS at F-region (190-250 km) altitude, having 10-120 minute period for 05 hrs duration for mid latitude ionosphere. They had related the observed WLS to the generation of internal gravity waves (IGWs) in the aurora region due to ionospheric heating during flares and their propagation along the meridian direction to mid latitude. Such IGWs wave associated with travelling ionospheric disturbances which can also propagate to the low latitudes. The WLS observed here during the increase of solar flare radiation and associated simultaneous changes in the amplitude and phase indicate that IGWs are also generated in the low latitude D-region ionosphere causing electron density fluctuations which in turn produce the WLS.

#### 4. Summary

In this study the amplitude and phase of VLF navigational transmitter signal (19.8 kHz) from NWC, Australia, recorded at Allahabad, have been analyzed, to detect the WLS. On the control day WLS with periods 40-180 minutes are present during day/night and night/day transition times which are probably generated due to passage of dusk and dawn terminator. The WLS observed during flare days with periods varying 90-200 minutes show remarkable difference in their period, occurrence duration/time and intensity. WLS are mostly observed during morning and evening periods when D-region ionosphere is in developing stage. The observed WLS are probably caused by the internal gravity waves associated with solar flares in the lower ionosphere and solar flares associated changes or gradients in the temperature, electron density and plasma conductivity. The further analysis of VLF signals using large no of solar flare events is required for the better understanding of generation mechanisms of WLS under solar flare conditions.

#### 7. References

1. A. G. Emslie, H. Kucharek, B. R. Dennis, N. Gopalswamy, G. D. Holman, G. H. Share, A. Vourlidas, T. G. Forbes, P. T. Gallagher, G. M. Mason, T. R. Metcalf, R. A. Mewaldt, R. J. Murphy, R. A. Schwartz, T. H. Zurbuchen, "Energy partition in two solar flare/CME events", *J. Geophys. Res.*, 109, 2004, A10104, doi: 10.1029/2004JA010571.
2. A. P. Mitra, *Ionospheric Effects of Solar Flares*, Reidel Publishing Company, Dordrecht-Holland., 1974.
3. B. T. Tsurutani, O. P. Verkhoglyadova, A. J. Mannucci, G. S. Lakhina, G. Li, and G. P. Zank, "A brief review of "solar flare effects" on the ionosphere", *Radio Sci.*, 44, RS0A17, 2009, doi:10.1029/2008RS004029.
4. D. P. Grubor, D. M. S`ulic', and V. Zigman, "Classification of X-ray solar flares regarding their effects on the lower ionosphere electron density profile", *Ann. Geophys.*, 26, 2008, pp. 1731-1740.
5. J. K. Hargreaves, *The Solar-Terrestrial Environment*, Cambridge University Press, New York., 2003.
6. N. R. Thomson, and M. A. Clilverd, "Solar flare induced ionospheric D-region enhancements from VLF amplitude observations", *J. Atmos. Solar Terr. Phys.*, 63(16), 2001, pp. 1729-1737.
7. R. Singh, B. Veenadhari, M. B. Cohen, P. Pant, A. K. Singh, A.K. Maurya, P. Vohat, and U. S. Inan, "Initial results from AWESOME VLF receivers: set up in low latitude Indian regions under IHY2007/UNBSSI", *Current Science*, 98 (3), 2010, pp. 398-405.
8. A. Grossmann, J. Morlet, "Decomposition of Hardy functions into square integrable wavelet constant shape", *SIAM Journal on Mathematical Analysis*, 15, 1984, pp. 723-736
9. L. F. Chernogor, Ye. I. Grigorenko, V. I. Taran, and O. F. Tyrnov, "Ionosphere Wave-Like Disturbances (WLD) Following the September 23, 1998 Solar Flare from Kharkiv Incoherent Scatter Radar Observations," in (Proceedings of XXVIIth General Assembly URSI, Programme, Poster Presentations Maastricht Exhibition and Congress Centre (MECC), Maastricht, 2002a, p. 2278.