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# Sudden phase anomalies during solar flares

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**Abstract.** The solar flares during 1977 September have been analysed in the light of their SPA effects produced in VLF signals over long propagation paths. The analysed data show an apparent linear relation between log (sec $\chi$) and $\Delta h$. Directional effect on the propagation path for VLF signals has been noticed. Observed SPA's data reported by Murubashi *et al.* (1982) have been utilized for estimating the effective recombination coefficient and other related parameters for ionospheric D-region during these flares.

*Key words* : Solar flares—sudden phase anomalies—VLF signals—D-region—recombination coefficient

## 1. Introduction

In the present study we analyse sudden phase anomalies (SPA's) which occurred during 1977 September. Phase variations of GBR 16 kHz Very Low Frequency (VLF) signals were recorded at Naini Tal (29°22′N, 79°27′E) during 1977 September. Only one SPA was detected in the received phase of 16 kHz VLF signal on 1977 September 19. Simultaneous data for other two VLF propagation paths on this date and other SPA's data reported by Murubashi *et al.* (1982) were utilized for present study. The time of occurrence of SPA's on 1977 September 7, 9, 16, 18, and 20, is concerned with solar zenith angles $\chi > 90°$ for propagation path from Rugby (55°22′N, 1°11′W) to Naini Tal. The solar flares of 1977 September of different optical importance classes are responsible for causing SPA's in the reported VLF signals. Data reported by Murubashi *et al.* (1982) comprised of SPA's detected between the VLF propagation paths OMEGA 13.6 kHz, La Reunion (20°58′S, 55°17′E)/OMEGA 13.6 kHz, Haiku (21°24′N, 157°50′W)/GBR, 16 kHz, Rugby (UK)/NPG, 18.6 kHz, Jim Creak (48°12′N, 121°55′W)/NWC, 22.3 kHz, North West Cape (21°49′S, 114°10′E) and Inubo (35°42′N, 140°52′E) Japan. The method of analysis of data and notations used by us have largely been patterned after Chilton *et al.* (1963).

## 2. Method of analysis

All propagation paths have been divided into 95 equal sections. The value of solar zenith angle '$\chi$' at the middle of each section of the path at the time of maximum phase deviation '$\Delta\phi$' were calculated. The average value of sec $\chi$ is obtained by averaging the sec $\chi$ values over all calculated values at middle points for a particular event. Since some of the VLF propagation paths are very long hence only sunlit portions of the paths were taken for getting average sec $\chi$ values. The observed $\Delta\phi$ were converted into the height change $\Delta h$ during the flare according the following expression given by Muraoka *et al.* (1977),

$$\Delta\phi = -360(d/\lambda_w)(1/2a + \lambda_w^2/16h^3)\Delta h,$$

where, $\lambda_w$ is the wavelength of the VLF wave in free space; $c$, the velocity of light; $h$, the height of reflection during day time; $a$, the mean radius of the earth; $\Delta\phi$, the phase change in degrees and $d$, the distance between the transmitter and the receiver. The values of $\Delta\phi$, $\Delta h$, $\overline{\sec\chi}$, $d$ along with optical sighting time and the importance class of the corresponding flares have been given in table 1. The time of optical sighting and importance classes of flares are borrowed from the Solar Geophysical Data (1978).

## 3. Results and discussions

Figure 1 gives a plot of $\Delta h$ versus log $\overline{\sec\chi}$. Each line in the figure corresponds to an individual solar flare. The intercept on the horizontal axis represents the apparent change in the reflection height of the VLF wave that would be observed at the subsolar point (i.e. sec $\chi = 1$).

Following Chilton *et al.* (1963) and utilizing subsolar values of $\Delta h$, the value of $N_r/N_0$, the ratio of electron density necessary for reflecting the VLF signal and maximum value of electron density for sec $\chi = 1$, in the D layer during different flare events were obtained. The effective recombination coefficient at the reflecting layer, $\alpha_r$, was estimated using the relation :

$$I_\infty = (N_r^2 \alpha_r H \exp \tau_r)/\eta\tau_r$$

where $\tau_r$ is the optical depth at the height of reflection ($\chi = 0$); $H$ the scale height, was taken to be 7.5 km, $\eta$ the ionizing efficiency of photons, about one electron/34 eV (Swift 1961), and $N_r$ the mean electron density 433 electrons/cm$^3$, taken from the theoretical model of Chakrabarty & Mitra (1974). Further $I_\infty$ is the solar X-ray flux density outside the atmosphere.

Taking $I_\infty$ values based on SMS-2 data in the 0.5-4 Å band (Williams 1982), we obtained the values of $\alpha_r$ for the flares represented by $c$, $d$, $e$, $f$ and $g$ (figure 1). The estimated values of $\alpha_r$ at the reflection height and other related parameters have been given in table 2. The wavelength ($\lambda$), of X-ray radiation that produces the layer, indicates the effective X-ray region.

The estimated values of $\alpha_r$ for some of the flares are in close agreement with those estimated by Sengupta (1971); Chakrabarty & Mitra (1974); Dubey *et al.* (1977). Although our results are totally based on the observations, but one has to bear in mind that the values of $I_\infty$ adopted for the estimation of $\alpha_r$ are not monochromatic but spread in the 0.5-4 Å band. The interpretation, therefore, depends upon the unknown X-ray spectrum of the incoming solar radiation.

**Table 1.** VLF phase anomalies during solar flares

| VLF propagation path | Date 1977 | Sighting time, UT | Importance class | $\Delta\phi$ degrees | $\Delta h$ km | $\overline{\sec\chi}$ | $d$ km |
|---|---|---|---|---|---|---|---|
| Flare, a | Sep 9 | 0620 | -B | | | | |
| GBR-Inubo | | | | 20.0 | 0.74 | 2.68 | 9550 |
| OMEGA-Inubo | | | | 54.0 | 1.79 | 1.16 | 10970 |
| NWC-Inubo | | | | 39.0 | 1.87 | 1.32 | 6990 |
| Flare, b | Sep 19 | 0004 | -N | | | | |
| GBR-Inubo | | | | 20.0 | 0.74 | 2.83 | 9550 |
| NWC-Inubo | | | | 66.0 | 3.15 | 1.81 | 6990 |
| OMEGA-Inubo | | | | 41.0 | 2.49 | 1.22 | 6100 |
| NPG-Inubo | | | | 24.0 | 1.14 | 1.76 | 7620 |
| Flare, c | Sep 18 | 0019 | 1B | | | | |
| GBR-Inubo | | | | 46.0 | 1.77 | 2.71 | 9550 |
| OMEGA-Inubo | | | | 90.0 | 3.01 | 2.61 | 10970 |
| NWC-Inubo | | | | 110.0 | 5.26 | 1.66 | 6990 |
| OMEGA-Inubo | | | | 93.0 | 5.57 | 1.22 | 6100 |
| NPG-Inubo | | | | 61.0 | 2.85 | 1.78 | 7620 |
| Flare, d | Sep 16 | 2300 | 2B | | | | |
| GBR-Inubo | | | | 27.0 | 1.02 | 3.31 | 9550 |
| NWC-Inubo | | | | 68.0 | 3.27 | 3.05 | 6990 |
| OMEGA-Inubo | | | | 124.0 | 7.48 | 1.32 | 6100 |
| NPG-Inubo | | | | 90.0 | 4.21 | 1.73 | 7620 |
| Flare, e | Sep 20 | 0251 | 3N | | | | |
| GBR-Inubo | | | | 44.0 | 1.67 | 2.33 | 9550 |
| OMEGA-Inubo | | | | 195.0 | 6.52 | 1.51 | 10970 |
| NWC-Inubo | | | | 117.0 | 5.61 | 1.06 | 6990 |
| OMEGA-Inubo | | | | 66.0 | 3.96 | 1.93 | 6100 |
| Flare, f | Sep 7 | 2255 | 1N | | | | |
| GBR-Inubo | | | | 61.0 | 2.33 | 3.22 | 9550 |
| OMEGA-Inubo | | | | 56.0 | 1.87 | 3.17 | 10970 |
| NWC-Inubo | | | | 119.0 | 5.73 | 2.97 | 6990 |
| OMEGA-Inubo | | | | 163.0 | 9.82 | 1.27 | 6100 |
| NPG-Inubo | | | | 146.0 | 6.84 | 1.61 | 7620 |
| Flare, g | Sep 19 | 1006 | 3B | | | | |
| GBR-Inubo | | | | 56.0 | 2.14 | 3.00 | 9550 |
| OMEGA-Inubo | | | | 178.0 | 5.95 | 2.21 | 10970 |
| GBR-Naini Tal | | | | 196.0 | 10.44 | 1.64 | 6854 |

The effect of direction of the VLF propagation is evident from figure 1, where some of the plotted points for the propagation path NWC-Inubo (denoted by an arrow mark), show too much scatter in their apparent linear relation as compared with other plotted points for their propagation paths. The reason for such a scatter may be that the NWC-Inubo path lies in the N-S direction. The path of propagation in this direction will be sunlit more or less simultaneously during the rotation of the earth. Consequently, the values of sec $\chi$ over the path do not suffer appreciable variation around the average value. However, further evidence is needed to support this conjecture.

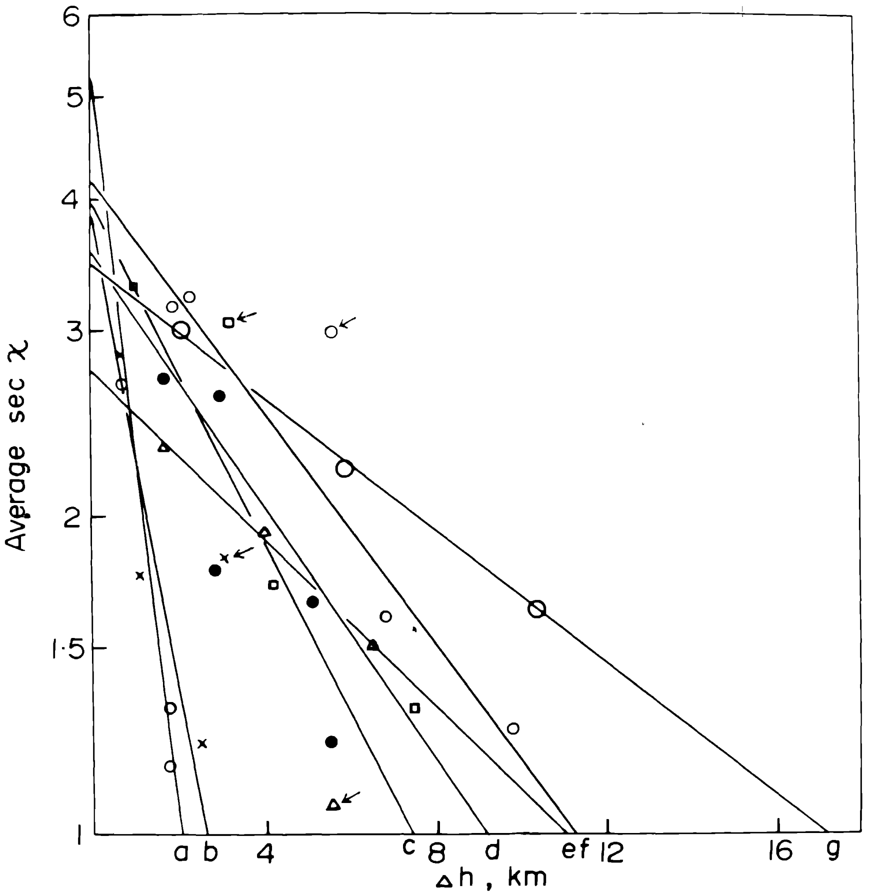

**Figure 1.** Estimated values of average sec $\chi$ versus VLF reflection height change, ($\Delta h$), for the solar flares of 1977 September.

**Table 2.** Result of various parameters obtained from SPA's for solar flares during 1977 September

| Value | Flare, f | Flare, d | Flare, c | Flare, g | Flare, e |
|---|---|---|---|---|---|
| Date, 1977 | Sep 7 | Sep 16 | Sep 18 | Sep 19 | Sep 20 |
| Time, UT | 2245 | 2300 | 0048 | 1045 | 0359 |
| $N/N_0$ | 0.36 | 0.33 | 0.24 | 0.48 | 0.47 |
| $\tau_r$ | 4.51 | 4.75 | 5.65 | 3.79 | 3.79 |
| $\lambda$, Å | 1.80 | 2.15 | 2 15 | 1.40 | 2.00 |
| $E$, keV | 6.89 | 5.77 | 5.77 | 8.86 | 6.20 |
| $\Delta h$, km | 11.4 | 9.2 | 7.4 | 17.2 | 11.1 |
| $h_0$, km | 69.9 | 72.5 | 75.6 | 62.8 | 68.9 |
| $h_r$, km | 58.6 | 60.8 | 62.6 | 52.8 | 58.9 |
| $I_\infty$ ergs cm$^{-2}$ sec$^{-1}$ | 5.0×10$^{-2}$ | 1.3×10$^{-2}$ | 4.3×10$^{-3}$ | 5.2×10$^{-2}$ | 4.5×10$^{-3}$ |
| $\alpha_r$ cm$^3$ sec$^{-1}$ | 3.23×10$^{-4}$ | 6.97×10$^{-5}$ | 1.11×10$^{-5}$ | 5.81×10$^{-4}$ | 5.03×10$^{-5}$ |

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