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A synoptic study of VLF sudden phase anomalies recorded at Visakhapatnam

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A synoptic survey of Sudden Phase Anomalies (SPAs) observed in the phase variation measurements of 16 kHz VLF transmissions from Rugby (England) made at Visakhapatnam (India) has been carried out. These Sudden Ionospheric Disturbances caused during solar flares are examined in relation to flare time enhancements of X-ray radiation fluxes. It is found that nearly 81% of SPAs recorded have accompanying X-ray enhancements and in 80% of the cases $H\alpha$ flares and microwave bursts also occur concurrently. Using SPA magnitudes and flare time X-ray flux values, the threshold level of X-ray flux to induce an SPA has been estimated as 1.5×10^{-3} ergs/cm^2/s. In majority of the events, the change in reflection height during the flare is observed to be less than 4 kms. Other SPA characteristics like onset times, growth and relaxation times etc. have also been studied. These results are consistent with those obtained for other propagation paths.

Key words: Lower ionosphere; sudden Phase Anomalies; VLF propagation.

1. Introduction

In recent times there has been an increasing concern over the deleterious consequences of disturbances in space weather on high technology satellite based communication, navigation and exploration. The severe space weather conditions caused by Coronal Mass Ejections (CMEs) constituting the solar wind modify the earth's magnetic field and manifesting as magnetic storms can impact a wide range of these services as well as ground based power lines and gas pipe lines (Allen and Wilkinson, 1993; Kappenman, 2001). The precursors of these CMEs and associated magnetic storms are solar flares occurring in the vicinity of sun spot groups. Solar flares are a complex phenomena involving catastrophic emission of highly energetic particles and enhancements in the radiation intensity of the entire electromagnetic spectrum. While the geomagnetic storm effects are a little delayed (Post Storm Effects or PSEs) and may persist for one to three days and except in rare cases considered to be a high and mid latitude phenomena (Lastovicka, 2002), the short lived disturbances due to enhanced electromagnetic radiation accompanying a flare occurs almost immediately in the sunlit ionosphere. These sudden ionospheric disturbances commonly known as SIDs can severely degrade or disrupt radio communication and navigational aids. Hence, monitoring of the solar flares is imperative and recording of SIDs becomes one of the major aspects of flare monitoring.

Although the effects of enhanced XUV radiation during a flare are seen throughout the ionosphere, particularly the D-region is sensitive to radiations less than 10 Å and responds dramatically. The study of the behavior of the D-region during solar flares is very important because the low and very low frequency navigational signals and HF/MF radio communication and broadcast signals are severely affected. Therefore, recording of SIDs generally facilitate not only flare patrol but also the determination of the magnitudes of ionization enhancements as well as the mechanisms of recovery in the region. Of the many techniques of recording the SIDs, Sudden Cosmic Noise Absorption (SCNA), VLF Sudden Phase Anomalies (SPA) and Sudden Frequency Deviation (SFD) recordings are best suited for this purpose (Mitra, 1974). Of these, again, the SPAs are of particular interest since the propagation of VLF waves takes place entirely in the D-region. It is very well established that these SPAs are a result of excess ionization in the lower ionosphere caused mainly by enhanced X-ray emissions below 10 Å. Ever since Kreplin *et al.* (1962) have reported the relationship between flare time X-ray bursts and SPAs, there has been considerable work carried out in the study of flare characteristics and SPA phenomenology (Maeda *et al.*, 1962; Deshpande *et al.*, 1972; Mitra, 1974; Muraoka *et al.*, 1977; Kamada, 1985). But most information for these studies came from measurements made at middle and high latitudes. Such studies from low latitudes especially from Indian zone are few and far between. Paucity of VLF measurements at low latitudes and the availability of phase variation records made at Visakhapatnam, a low latitude station, have prompted us to undertake this work. In this paper the VLF phase variation records of 16 kHz transmissions from Rugby (52.3°N, 1.2°W) England, made at Visakhapatnam (17.7°N, 83.3°E), India between March 1984 and November 1985 have been used to study SPA characteristics and chronicle them. These measurements of relative phase were made by a Tracor 900A receiver using a highly stable Rubidium vapour frequency standard (Hewlett Packard).

2. Regular Phase Variations

VLF wave propagation to great distances is generally explained in terms of wave guide theory of propagation. In this, it is considered that the VLF waves propagate in a large wave guide with the earth's surface and the lower ionosphere, viz. D-region, forming the walls of the guide. The D-region ionization, being solar controlled, undergoes regular and irregular variations which in turn cause phase and amplitude variations of the received VLF signal. Thus, in general during night time the ionospheric reflection height of VLF waves, which is about 85–90 km decreases to around 70 km after sunrise due to increased ionization below the night time reflection level. In such a situation the walls of the wave guide can be visualized as brought closer together and hence the phase velocity increases. In other words, a decrease in the height of reflection causes an increase in phase velocity and also attenuation rates. Hence, the phase velocity of VLF waves in the earth-ionosphere wave guide is greater by day than by night. So, on a normal day a plot of relative phase against time leads to a graph shown in Fig. 1, in which monthly average diurnal phase variations of 16 kHz waves from Rugby received at Visakhapatnam are plotted. It is clear that the transmission time is nearly constant for both all day and all night links between transmitter and receiver and is greater during periods of darkness than it is during day light period. Thus, we see that lowering of the height of reflection, as after sunrise, leads to an increase in phase velocity which results in phase advance in the records. If the height of reflection changes by Δh, the corresponding phase change $\Delta\varphi$ for the first order waveguide mode, which is considered significant for long paths, is given by (Kamada, 1985)

$$\Delta\varphi = \frac{-2\pi d}{\lambda}\left[\frac{h}{2a} + \left(\frac{\lambda}{4h}\right)^2\right]\frac{\Delta h}{h} \qquad \text{(rad)} \qquad (1)$$

where φ is the phase, λ is the wavelength, a the earth's radius, and h the reflection height. From Eq. (1) the diurnal transmission delay Δt can be calculated by

$$\Delta t = \frac{\Delta\varphi}{\omega} \qquad \text{(sec)} \qquad (2)$$

where ω is the angular frequency of the VLF waves.

3. Sudden Phase Anomalies

During a solar flare, due to a sudden increase in the intensity of the ionizing radiation especially in the X-ray band, the electron density is greatly enhanced and ionization is produced below the normal D-region. This results in lowering of the reflection height of VLF waves. As a consequence, the phase records show a sudden and rapid phase advance of the down coming wave. These flare associated disturbances usually have a rapid onset and a slow recovery. The depth of the phase advance is usually an indicator of the intensity of the flare, however depends also on the orientation of the transmission path to the subsolar point.

4. Results

4.1 General types of SPAs

A typical SPA is characterized by a sudden advance of phase followed by a rounded minimum and generally an exponential decay or recovery of phase. In all, 38 well defined phase anomalies have been identified during the period in which the phase variation records are available. Of these 38 events 22 occurred when the entire propagation path was sunlit and the remaining 16 occurred when the path was partially sunlit. Some of the typical SPA's are

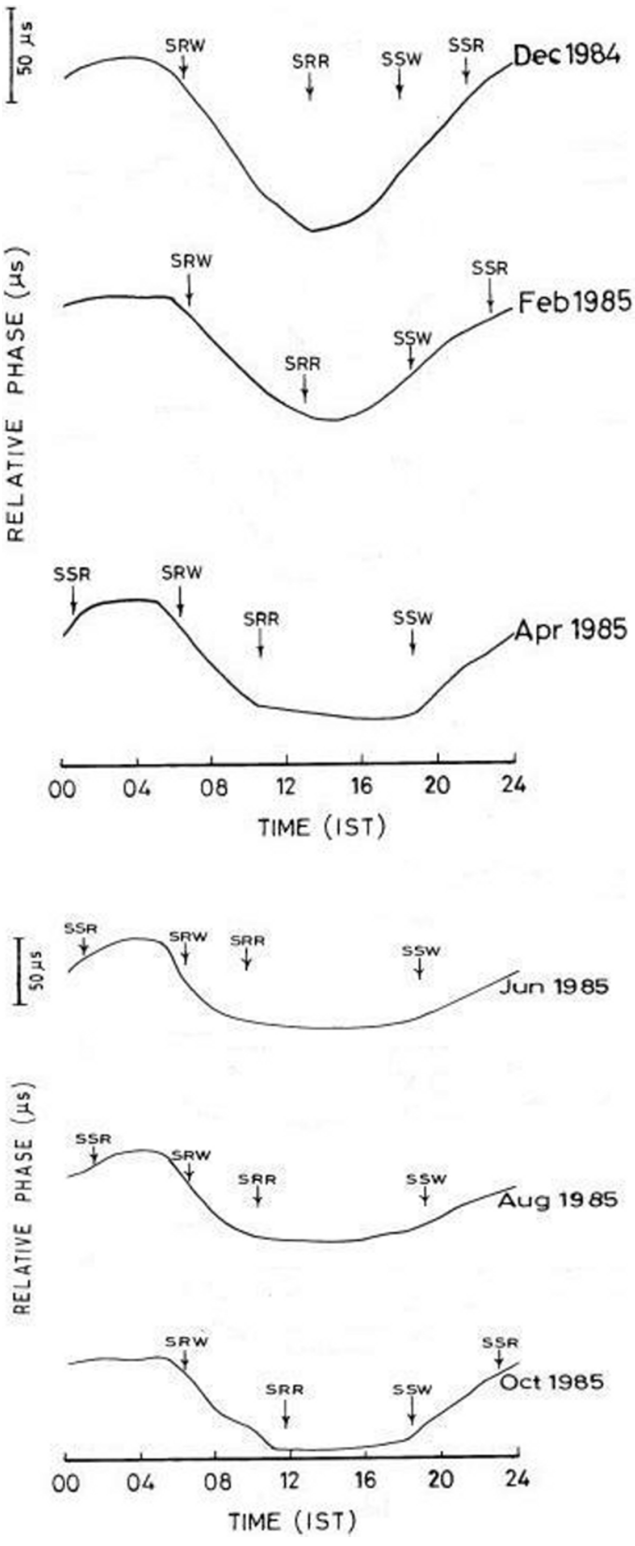

Fig. 1. Monthly mean phase variations of 16 kHz Rugby transmissions received at Visakhapatnam (SRW, SSW, SRR, SSR refer to the sunrise and sunset times at Visakhapatnam and Rugby respectively).

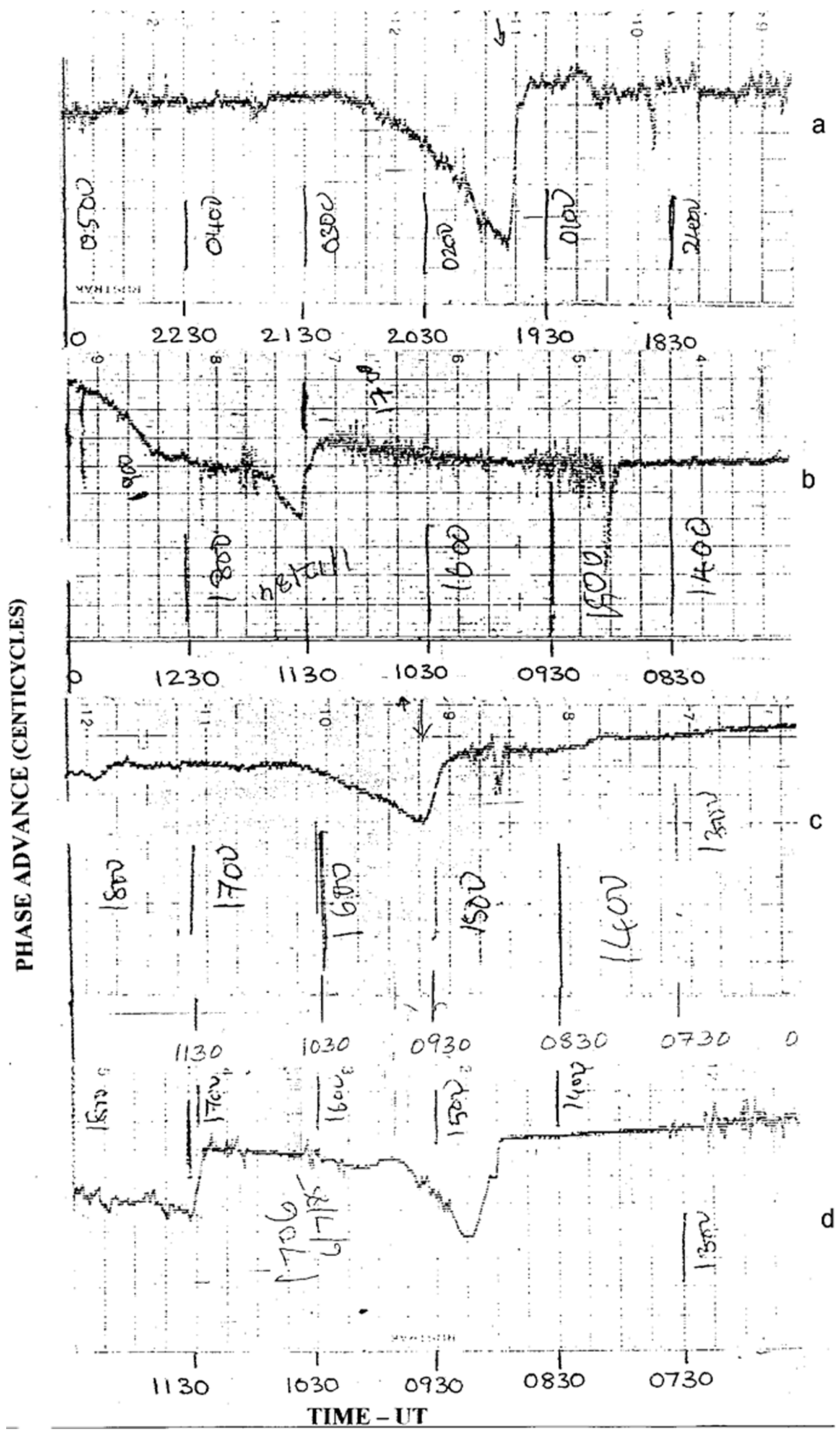

Fig. 2. Typical records of SPAs occurred at (a) 1943 UT on July 17, 1984, (b) 1123 UT on December 1, 1984, (c) 0920 UT on May 13, 1985, (d) 0900 UT on July 6, 1985.

shown in Figs. 2 and 3 (left panels). Although most of the events resemble the simple SPA with characteristics described earlier, some exhibit varying characteristics. For instance, the events shown in Figs. 3(a), 3(b) and 3(c) are typical records with very short onset times. But the SPA in Fig. 2(c) has a gradual onset. A few of the events have either a complex onset time (Fig. 2(d)) or complex phase variation during the event (Figs. 3(b) and 3(c)). These events correspond to the classification as simple (S), gradual (G) and complex (C) types of SPAs made by Kamada (1985) in the SPA events observed at 22.3 kHz (NWC) signal recorded at Toyakawa (Japan). It is interesting to note that a similar behaviour with sudden, slow or gradual onset (with irregular or complex fading) has also been seen in SWF records (Mitra, 1974). One more type of SPA mentioned by Kamada (1985), namely a main event preceded by a short pi-

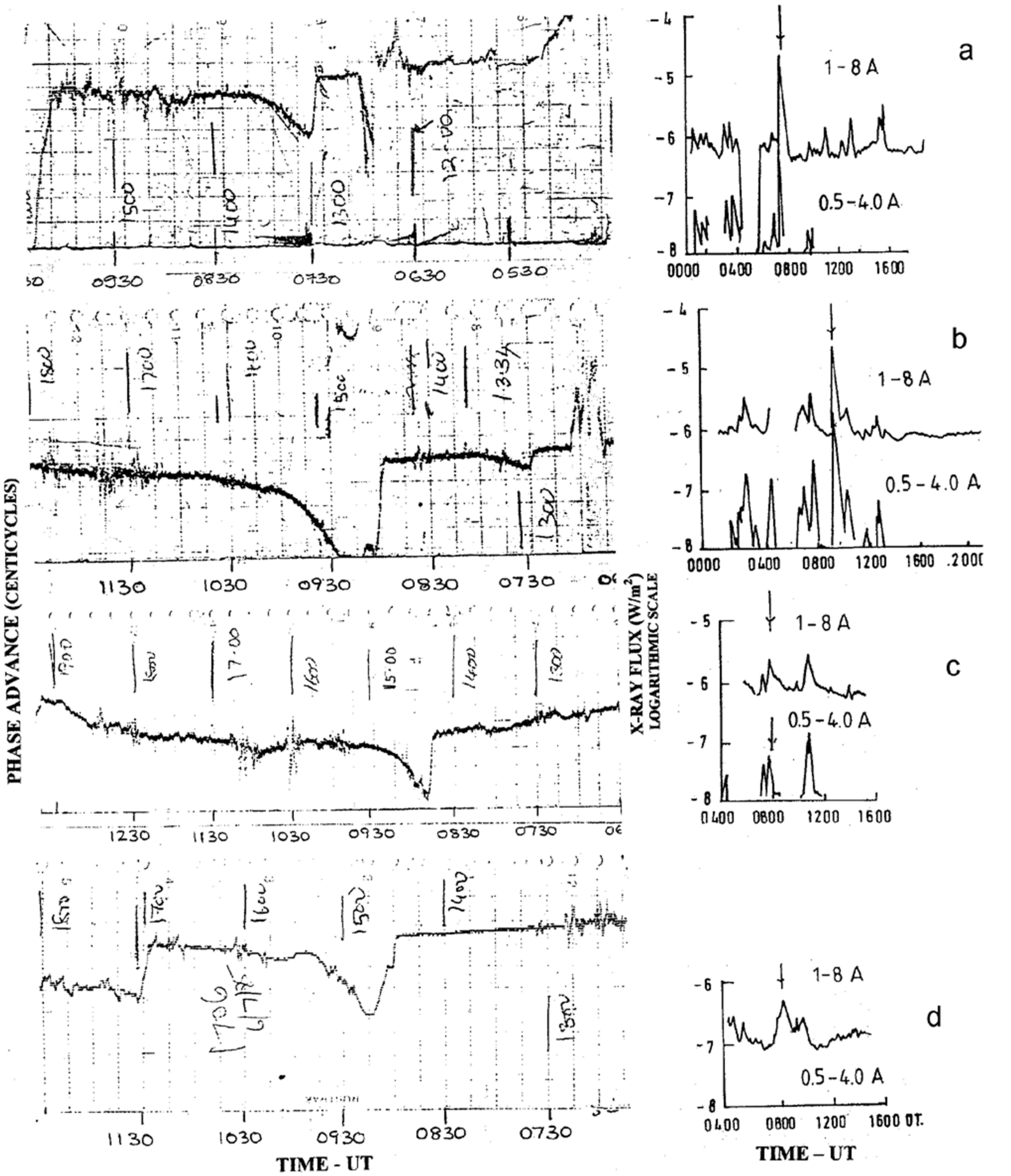

Fig. 3. Representative records of SPAs accompanying X-ray flares. Occurrence times from top (a) 0728 UT on March 13th 1984, (b) 0856 UT on March 16th 1984, (c) 0846 UT on March 22nd 1984, (d) 0900 UT on July 6th 1985.

lot has also been observed here (Fig. 2(a)). But he reported that majority of the events were of G type while we observed that simple or simple—complex type of events are more common.

4.2 Association of SPAs with solar flare events

An examination of the SPA occurrences in conjunction with the solar $H\alpha$ flares, X-ray enhancements and outstanding occurrences of solar radio emission data published in Solar Geophysical Data Bulletins (SGD–WDC) showed that out of the 38 SPA events occurring during sunlit periods of the propagation path, 26 events have one or more accompanying flare events and are considered here. The remaining 12 records with typical SPA characteristics have no accompanying solar flare event and have been discussed elsewhere (Khan *et al.*, 2001). The number of occurrences of SPA events and flare phenomena are given in Table 1. It

Table 1. Number of SPA events and accompanying solar flare events occurred during sunlit period.

Total No. of SPA's	Concurrent Flare Events						
	$H\alpha$ + X-ray + Microwave	$H\alpha$ + X-ray	$H\alpha$ + Microwave	X-ray + Microwave	Only $H\alpha$	Only X-ray	Only Microwave
26	14	4	2	2	2	1	1

Table 2. $H\alpha$ Flare Data Concurrent with SPAs.

S. No.	Date	Station Code	$H\alpha$ Flare Times (UT) Start	Max	End	IMP	SPA times (UT) Start	Max	End	Average —	Δt (μs)	Δh (km)
1	13-3-84	LEAR	0727	0729	0801	IB	0728	0730	0802	50.62	16.86	4.43
2	15-3-84	GOES	0613	0622	0636	—	0621	0625	0645	54.45	3.75	0.98
3	15-3-84	YUNN	0815	0817	0817	SN	0811	0823	0830	49.34	11.25	2.96
4	16-3-84	ATHN	0718	0726	0744	SN	0720	0727	0745	50.45	3.13	0.82
5	16-3-84	WEND	0853	0908	0940	IN	0856	0915	1011	49.8	30.0	7.88
6	17-3-84	LEAR	0607	0608	0640	SN	0609	0611	0642	55.36	13.75	3.6
7	17-3-84	LEAR	0922	0926	0956	IN	0924	0928	1000	50.96	15.63	4.1
8	22-3-84	GOES	0848	0850	0853	—	0848	0852	0920	47.7	21.25	5.58
9	28-3-84	GOES	1104	1109	1114	—	1109	1114	1130	56.86	9.38	2.46
10	29-3-84	GOES	0328	0336	0340	SF	0330	0343	0358	78.49	10.0	2.63
11	30-3-84	YUNN	0458	0458	0513	2B	0459	0501	0515	51.78	12.5	3.28
12	30-3-84	YUNN	0558	0558	0614	1B	0600	0601	0630	51.5	11.25	2.96
13	31-3-84	LEAR	0806	0808	0823	1B	0808	0811	0830	44.34	3.75	0.98
14	16-7-84	RAMY	1930	1931	1945	SF	1933	1933	2030	113.0	32.5	8.5
15	17-7-84	RAMY	1941	1947	1955	SN	1943	1948	2100	113.5	36.25	9.53
16	27-11-84	LEAR	0059	0108	0110	SF	0100	0108	0130	113.79	15.0	3.94
17	23-1-85	LEAR	0725	0734	0827	1N	0726	0735	0830	65.67	18.75	4.93
18	24-4-85	LEAR	0532	0533	0538	SF	0453	0535	0600	55.6	15.6	3.94
19	2-5-85	PEKG	0725	0750	0805	1B,2B	0747	0759	0902	36.0	27.5	7.25
20	13-5-85	WEND	0916	0933	1043	1N	0920	0935	1020	37.7	13.75	3.6
21	7-7-85	PEKG	0527	0529	0535	1B	0528	0531	0545	45.7	3.75	1.0
22	12-7-85	LEAR	0502	0533	0635	SN0	0505	0537	0636	50.0	9.38	2.46

is readily evident that nearly 85% of the events have accompanying $H\alpha$ flares. The relevant $H\alpha$ flare data are given in Table 2.

4.3 Correlation with X-ray enhancements

Universal Time (UT) variation curves of X-ray fluxes in the 0.5–4 Å and 1–8 Å bands measured by GOES 6 satellite and published for each day of the month in the monthly bulletins of SGD are used to study the correlation between X-ray flux enhancements and SPA occurrences. It is found that 21 out of 26 SPAs or nearly 81% have accompanying X-ray enhancements in one or both wavelength bands. Among these, except on one occasion, the rest of the events have accompanying $H\alpha$ and microwave bursts. This is in agreement with Deshpande *et al.* (1972) who while examining every X-ray enhancement capable of producing the SID is a major solar event, found that in 80% of the cases $H\alpha$ flares and microwave bursts occur concurrently. The SPA and concurrent X-ray enhancement times and peak fluxes are given in Table 3. The correlation between the observed SPAs and X-ray flux enhancements is brought out clearly in Fig. 3 in which some of the events are reproduced.

5. SPA Characteristics

5.1 Onset time

Different SIDs are known to exhibit different time developments. So also, the SPAs show varied temporal development depending on the time histories of the flare events. The onset time is generally defined as time difference between beginning of the flare and start of SPA. In Fig. 4, the SPA onset time difference from the corresponding flare ones are plotted against percentage of occurrence in all SPAs which accompanied $H\alpha$ flares. It can be clearly seen that

Table 3. Particulars of X-Ray Enhancements concurrent with SPAs.

S. No.	Date	X-ray Enhancements 1–8 Å Start	Max UT	End	Flux W/m^2	X-ray Enhancements 0.5–4 Å Start	Max UT	End	Flux W/m^2	SPA Times Start	Max UT	End	Average —	Δt (μs)	Δh (km)
1	13-3-84	0726	0728	0812	1.4 (−5)	0719	0726	0738	2.4 (−6)	0728	0730	0802	50.62	16.86	4.43
2	15-3-84	0621	0631	0710	4.5 (−6)	0617	0625	0648	3.9 (−7)	0621	0625	0645	54.45	3.75	0.98
3	15-3-84	0807	0812	0825	4.0 (−6)	0807	0815	0820	1.8 (−7)	0811	0823	0830	49.34	11.25	2.96
4	16-3-84	0720	0725	0745	1.7 (−5)	0720	0725	0745	2.6 (−6)	0720	0727	0745	50.45	3.13	0.82
5	16-3-84	0855	0910	1020	2.5 (−5)	0855	0910	1000	5.0 (−6)	0856	0915	1011	49.8	30.0	7.88
6	17-3-84	0607	0621	0648	4.9 (−6)	0609	0622	0638	4.5 (−7)	0609	0611	0642	55.36	13.75	3.6
7	17-3-84	0924	0928	1038	1.7 (−5)	0919	0928	1020	2.1 (−6)	0924	0928	1000	50.96	15.63	4.1
8	22-3-84	0847	0852	0920	1.0 (−5)	0836	0850	0929	1.0 (−6)	0848	0852	0920	47.7	21.25	5.58
9	28-3-84	1109	1117	1138	7.5 (−6)	1112	1122	1138	8.0 (−7)	1109	1114	1130	56.86	9.38	2.46
10	29-3-84	0327	0337	0353	7.7 (−6)	0327	0335	0348	1.3 (−6)	0330	0343	0358	78.49	10.0	
11	30-3-84	0600	0604	0630	8.0 (−6)	0600	0614	0621	7.0 (−7)	0600	0601	0630	51.5	11025	2.96
12	31-3-84	0807	0811	0830	3.0 (−6)	0810	0821	0843	2.0 (−8)	0808	0811	0830	44.34	3.75	0.98
13	27-11-84	0100	0120	0220	1.0 (−6)	0100	0112	0145	7.0 (−7)	0100	0108	0130	113.79	15.0	
14	1-12-84	1122	1129	1150	8.0 (−7)	1119	1127	1153	3.0 (−8)	1123	1131	1145	78.31	17.5	4.6
15	24-4-85	0450	0520	0720	9.0 (−6)	0450	0535	0620	7.0 (−7)	0453	0536	0600	55.6	15.0	3.94
16	24-4-85	0910	1020	1500	1.0 (−4)	0910	1020	1520	3.0 (−5)	0918	0937	1015	41.0	37.5	9.85
17	2-5-85	0738	0756	1800	3.0 (−5)	0738	0756	1400	3.0 (−6)	0747	0759	0902	36.0	27.5	7.21
18	13-5-85	0900	0935	1020	1.0 (−5)	0920	0935	1020	1.0 (−6)	0920	0935	1020	37.7	13.75	3.6
19	7-7-85	0523	0523	0545	1.5 (−6)	0523	0523	0525	1.5 (−7)	0528	0531	0545	45.7	3.75	0.98
20	8-7-85	0935	1000	1040	4.0 (−6)	0950	1000	1020	3.0 (−7)	0945	1000	1030	36.6	5.0	1.3
21	12-7-85	0500	0535	0600	5.0 (−6)	0510	0530	0600	5.0 (−7)	0505	0537	0636	50.6	9.38	2.46

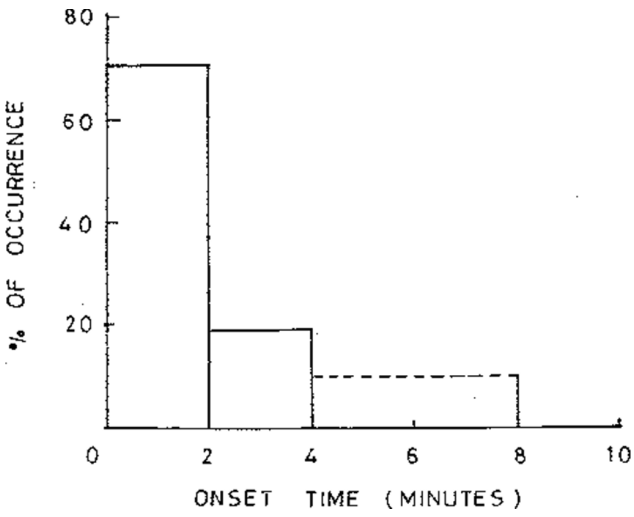

Fig. 4. Percentage occurrence of SPA onset times.

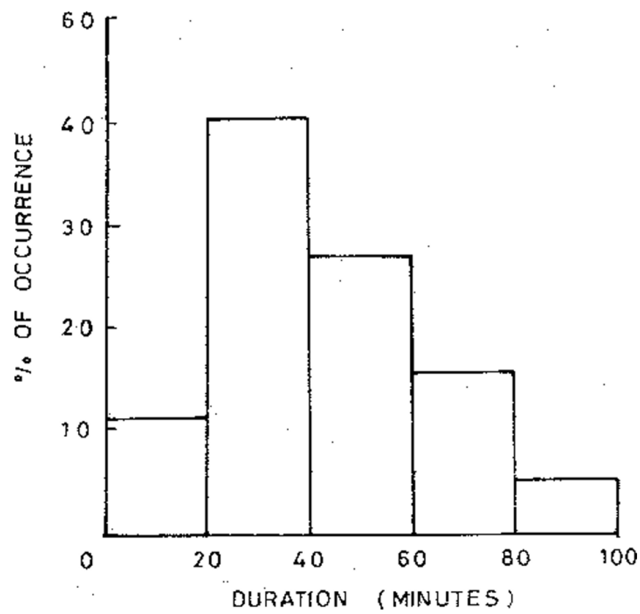

Fig. 5. Percentage occurrence of SPA durations.

in 71% of the cases, the SPA began within two minutes of start of the flare. When X-ray enhancements are considered (Table 3), it is found that in 70% of the cases, the SPAs began within four minutes of the start of the flare event. This is in conformity with Deshpande *et al.* (1972) who found a delay of 3–4 minutes between beginnings of X-ray and SPA events.

5.2 Times of growth and relaxation

The time taken from the beginning of the event to reach the maximum is normally denoted as the time of growth of SPA and flare events and the time difference between the maximum of the flare event ($H\alpha$ or X-ray) and the maximum of SPA, the relaxation time. Estimated from the onset and maximum times of SPAs and the flare events, the average time of growth is found to be 11 minutes for SPA, 7 minutes for $H\alpha$, 12 and 10 minutes for X-rays in 1–8 Å and 0.5–4 Å bands respectively. This result is in good agreement with that of Deshpande *et al.* (1972) who reported the times of growth of 9 minutes for SPA and 10 and 8 minutes for 0–8 Å and 0–3 Å X-ray bands respectively. The average relaxation times calculated are 3 minutes for $H\alpha$, 4 minutes for both the X-ray bands while Deshpande *et al.* (1972) reported 2 and 3 minutes of relaxation times for 0–8 Å and 0–3 Å X-ray bands respectively.

5.3 Duration of SPA events

The duration of SPA event, i.e., the time from the beginning of the event to recovery normally varies from 30 minutes to 2–3 hours (Chilton *et al.*, 1963). In the present investigation, though the duration varied from 16 minutes to 100 minutes, it is observed that over 65% of the SPAs lasted between half an hour to one hour as seen in Fig. 5. Kamada (1985) also observed that the duration of SPA events were within 1 hour for majority of events.

5.4 SPA Decay or Phase Recovery

As can be seen in the typical SPA records shown in Figs. 2(a) to (d), the recovery part of the phase anomaly is very nearly exponential in conformity with earlier observations of Chilton *et al.* (1964) and Albee and Bates (1965). During the decay phase, the phase variation can approximately be expressed as

$$\Delta t = \exp(-\alpha t') \tag{3}$$

where Δt is the change in phase in microseconds and t' is the time from the maximum. The decay coefficient α calculated using Eq. (3) ranges from 0.008 to 0.05 which is in general agreement with Albee and Bates (1965) who reported the coefficients ranging from 0.01 to 0.04 calculated using the same relation for different flare events observed on 10.2 kHz NBA signal recorded at College, Alaska.

5.5 Threshold level of X-ray flux

It is known that not all X-ray enhancements below 20 Å during a flare result in SID effect. Sometimes, no SPA is found even though the propagation path is sunlit and the solar X-ray flux is enhanced. These events termed as no SPA or null SPA effects result if the enhancement in X-ray flux is small and/or the effective solar zenith angle is large (Mitra, 1974). However, high percentage of occurrence was found to exist with SPA for X-ray flares in 10–50 kev range (Mitra, 1974). The capability of an X-ray enhancement to produce an SID effect depends on the flux level. The minimum flux level of X-rays in the 1–8 Å band needed to cause a perceptible SID is termed as threshold level. Using SPA magnitudes and the flare time X-ray flux values it is possible to estimate the threshold level. In the calculation of the X-ray flux threshold level we have adopted the formula given by Muraoka *et al.* (1977), that can be applied to various VLF propagation paths, which is of the form

$$\ln F_\infty = C\Delta t' + \ln F_c \tag{4}$$

where F_∞ is the flare time X-ray flux, $\Delta t'$ is the phase deviation (in microseconds) normalized with respect to zenith angle and F_c gives the threshold value of the flux and C could be taken as a constant whose value is determined by the absorption cross section of the X-rays, the absorbing gas density, wavelength of the VLF wave and propagation

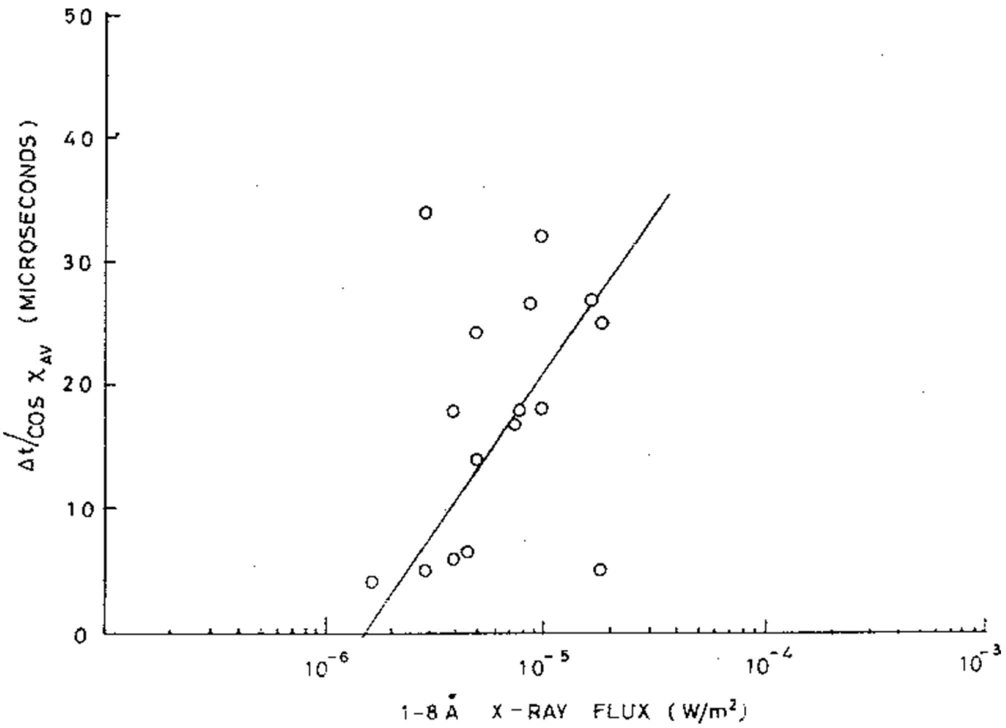

Fig. 6. Variation of normalized phase deviation during SPAs with 1–8 Å X-ray flux.

distance. Thus, a plot between X-ray flux and the normalized phase deviation yields the threshold level. In Fig. 6, the maximum phase deviation during the SPA events normalized with respect to the average zenith angle along the propagation path are plotted against the peak X-ray flux during the events. Although there is some scatter, a linear trend is clearly discernible as most points lie close to the best fit line. From the intercept on the horizontal axis the threshold level is found to be 1.5×10^{-6} W/m^2 or 1.5×10^{-3} erg/cm^2/s. This value compares very well with 1×10^{-3} erg/cm^2/s estimated by Deshpande *et al.* (1972) and 1.5×10^{-3} erg/cm^2/s by Muraoka *et al.* (1977) for the same wave length band.

5.6 Change in reflection height

The change in effective height of reflection (Δh) due to lowering of reflecting layer as phase suddenly advances during a flare has been calculated using the formulas given by Westfall (1961) for estimating the same during flare events. A histogram showing the percentage of occurrence of different Δh values is given in Fig. 7. Although Δh is found to vary from 1 km to 10 kms, in nearly 60% of cases it is less than 4 km. Chilton *et al.* (1963) and Kamada (1985) have also observed wide variability of Δh values from flare to flare. Kamada (1985) gave classification of SPAs based on magnitude of Δh. In this grouping SPAs with Δh below 4 km are said to be of importance 1; with Δh between 4 and 7 kms as of importance 2 etc. Under this classification the majority of SPAs observed in the present investigation can be said to belong to importance 1 group.

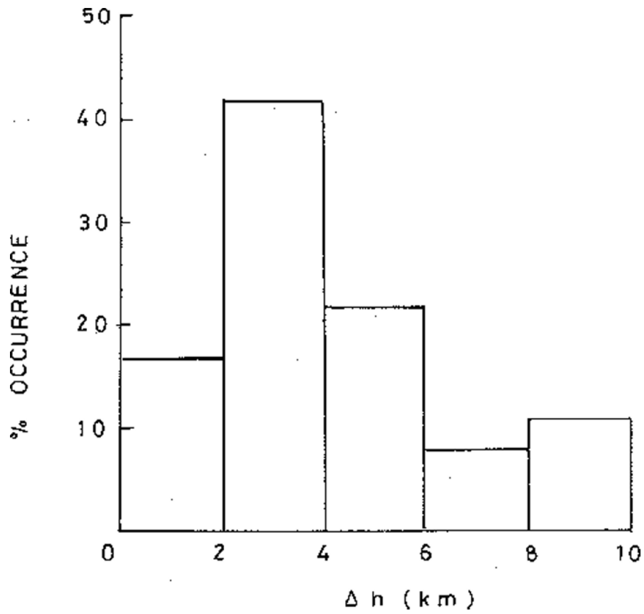

Fig. 7. Percentage occurrence of reflection height decrease during SPAs.

6. Conclusions

There has been a revival of interest in ionosphere in recent times since the ground based radio communication systems are seen as reliable alternatives to satellite based systems whose hardware is very vulnerable to disturbances in space environment. In this context the importance of study of occurrence and characteristics of SIDs need not be overemphasized since these can drastically degrade or disrupt radio signals in the VLF to HF bands which are still the principal bands used in communication and broadcasting. VLF sudden phase anomalies provide us with excellent signatures of solar flares in the ionospheric D-region. Although considerable work has been carried out in this area using measurements from middle and high latitudes, such studies at low latitudes are scarce. In view of this, an attempt has been made at a synoptic study of characteristics of SPAs recorded at Visakhapatnam (India) in 16 kHz transmissions from Rugby (England). The salient results are

1. SPAs occurring during sunlit period of the propagation path between Rugby and Visakhapatnam are in general accompanied by one or more of the solar flare events—$H\alpha$ flare, X-ray and microwave bursts. Nearly 55% of the SPA events observed in the present investigation were accompanied by all the three solar events. In 85% of the cases $H\alpha$ flares and in 81% of the events X-ray enhancements accompanied the SPAs.

2. A study of the time histories of the SPAs showed that in general they begin within 2 minutes (onset) of the beginning of a flare event reaching maximum phase deviation in about 11 minutes (time of growth).

3. The relaxation time of SPA with reference to X-ray flares is found to be about 4 minutes.

4. The duration of the SPA events is observed to lie between 30 minutes and 60 minutes.

5. The threshold level of 1–8 Å X-ray flux above which the flare is capable of inducing an SPA has been estimated as 1.5×10^{-3} erg cm^{-2} s^{-1}.

6. A decrease of 2 to 4 km in the apparent height of reflection is found to be most common during an SPA event.

7. A comparison between the times of occurrence of SPAs and solar radio noise bursts revealed that nearly 73% of the events during sunlit hours of the propagation path between Rugby and Visakapatnam were associated with solar microwave bursts. However, a study of the SPAs in relation to these centimetric wave bursts will be presented elsewhere.

It is seen that the general features of SPAs agree with those on other propagation paths. This shows that the response of the D-region to sudden enhancements in ionizing radiation is same throughout the sunlit hemisphere. SPAs are mainly caused by flare time enhancements in X-ray flux as can be seen from the above results. The concurrent $H\alpha$ flares or microwave bursts indicate that these are major flare-SID events (Deshpande *et al.*, 1972). However, in a few cases it is observed that SPAs did not have accompanying X-ray enhancements but were coincident with $H\alpha$ flares or radio bursts (Table 1). Radio bursts and $H\alpha$ enhancements are only indicators of a flare. In the absence of increase in X-ray flux the reasons for these events needs to be investigated.

The other characteristics of SPAs, namely the times of growth and relaxation, threshold flux level etc. obtained in the present study also agree with those obtained earlier.

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