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I-5-5. Solar Flare Effects in the *F*-Region of the Ionosphere

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The large solar flares of November 12 and 15, 1960, were accompanied by prominent *F*-region ionospheric effects at several locations. These flares were also notable in that large sea-level cosmic ray increases were observed shortly after the flare beginning, however, the times of the *F*-region effects agree with the times of the optical flares rather than the arrival of the cosmic rays. Of the eight earlier solar flares associated with sea-level comic ray increases, at least two others also were accompanied by *F*-region effects (November 19, 1949 and February 23, 1956). Evidence is presented that suggests that the height of the *F* layer at the time of the solar event may play a role in determining whether an effect is seen at any given location.

The principal simultaneous effect of a solar flare on the ionosphere occurs in the *D*-region. The large increase in ionization at this low level due to *X*-ray emission from the solar flare results in severe absorption to high frequency radio waves, the so-called short-wave fadeout or sudden ionospheric disturbance. Recently Taubenheim[1] has shown that small increases in *E*-region maximum electron density also occur during most solar flares.

Eleven years ago, Dieminger reported that a large solar flare of November 19, 1949, had a marked effect on the *F*-region over Lindau, Germany[2]. A similar *F*-region effect was observed at Okinawa at the time of the outstanding flare of February 23, 1956[3]. In addition to being very large, these flares were notable in that they were two of the five flares that had occurred up to that time during which increases in sea-level cosmic ray intensity had been observed. Yet, because the *F*-region effect had been detected at so few of the sunlit ionospheric sounding stations, doubt remained as to the correct interpretation of these observations.

Two additional cases of *F*-region effects were observed recently accompanying the two large solar flares that occurred at 1323 UT on November 12, 1960, and at 0207 UT on November 15, 1960[4]. Because these flares were also followed by cosmic-ray increases recorded at sea level, the connection between the relatively few flares that are associated with the emission of these very high energy (relativistic) particles and *F*-region solar flare effects appears to be considerably strengthened.

Fig. 1 shows the variation of *F*-region maximum electron density, as determined from observations of the vertical incidence penetration frequency, at the time of the two November 1960 flares and the two earlier flares discussed above. It can be seen that increases of 20 to 40 percent in maximum electron density occurred during the course of each flare.

Though there now seemed to be little doubt of the reality of the *F*-region solar flare effect, the question remained as to why the effect was observed only at isolated locations rather than universally over the sunlit hemisphere. Fortunately, the November 12 flare occurred during daylight along the rather extensive chain of vertical sounding stations located in the vicinity of the 75°W meridian. Because soundings are made every 15 minutes at these stations, we were able to make a rather careful analysis of possible *F*-region effects. Fifteen minute values of *F2*-layer penetration frequency (*foF2*) around the time of the November 12 flare are shown on Fig. 2 for six sunlit sounding stations. The stations are arranged in order of increasing h_{max}, the height of maximum electron density in the *F2*-layer, as determined by a manual ten-point method. The flare beginning time is shown by an arrow on the time scale. Considering pre-flare and post-flare trends, it seems clear that a flare-associated

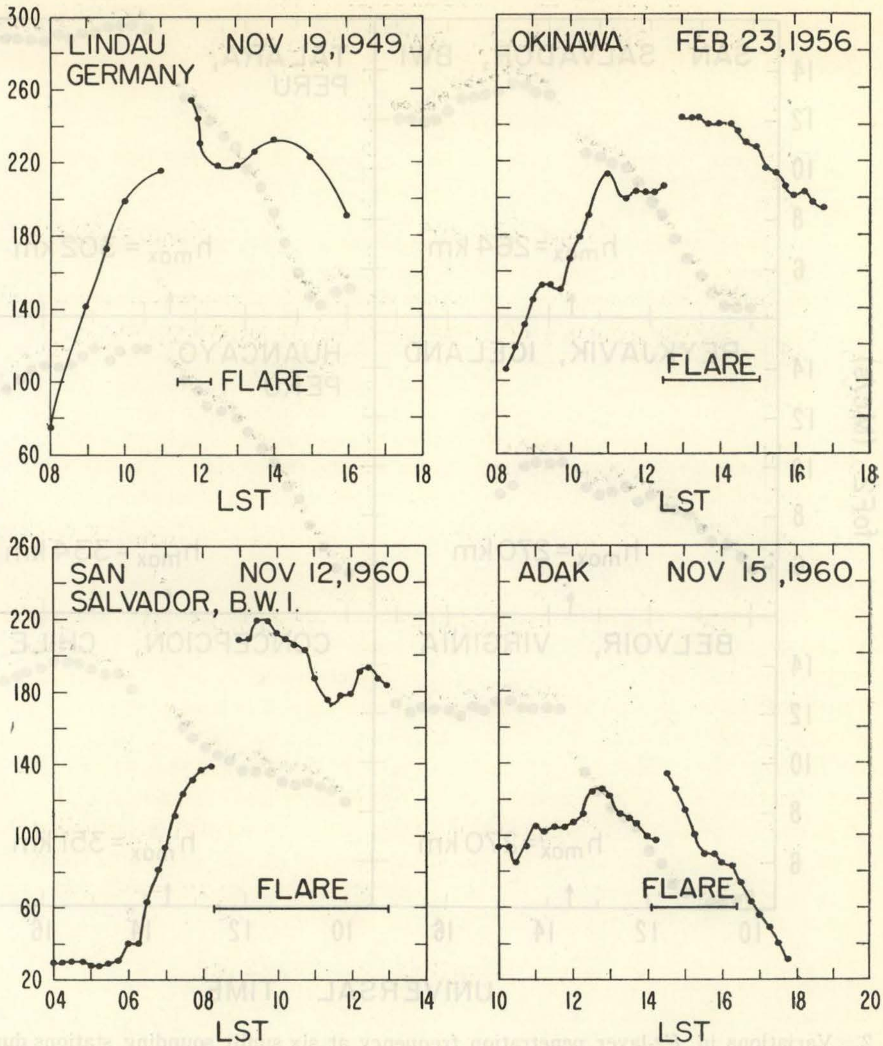


Fig. 1. Variations in *F2*-layer maximum electron density during four solar flares that were associated with sea-level increases in cosmic ray intensity.

increase in penetration frequency, which is directly related to the maximum electron density, occurred at at least four of the stations (San Salvador, Reykjavik, Belvoir and Talara). Flare-associated increases probably did not occur at Huancayo and Concepcion. Note that the magnitude of the flare effect discontinuity seems to vary inversely with h_{max}. This is what might be expected on a simple picture where the flare radiation has a peak ionization rate at a level significantly below the *F2*-layer, the rate falling off exponentially with increasing height above this level.

The magnitude of the estimated *foF2* discontinuity at a number of sunlit sounding stations during the November 12 event as well as three other events is shown on Fig. 3. A solar flare associated with a polar cap absorption event, October 20, 1957, 1638 UT, is also shown on the curve along with the three recent relativistic particle events. In the February 23, November 12 and November 15 events, there is a clear cut tendency seen for a significant *foF2* discontinuity to occur at those locations where the pre-flare height of the *F2* maximum is about 310 km or less. It can be seen that an *F*-region effect is not nearly as clear cut in the case of the PCA flare.

The question of the timing of the *F*-layer effect was then examined. It is interesting to inquire whether the effect occurs simul-

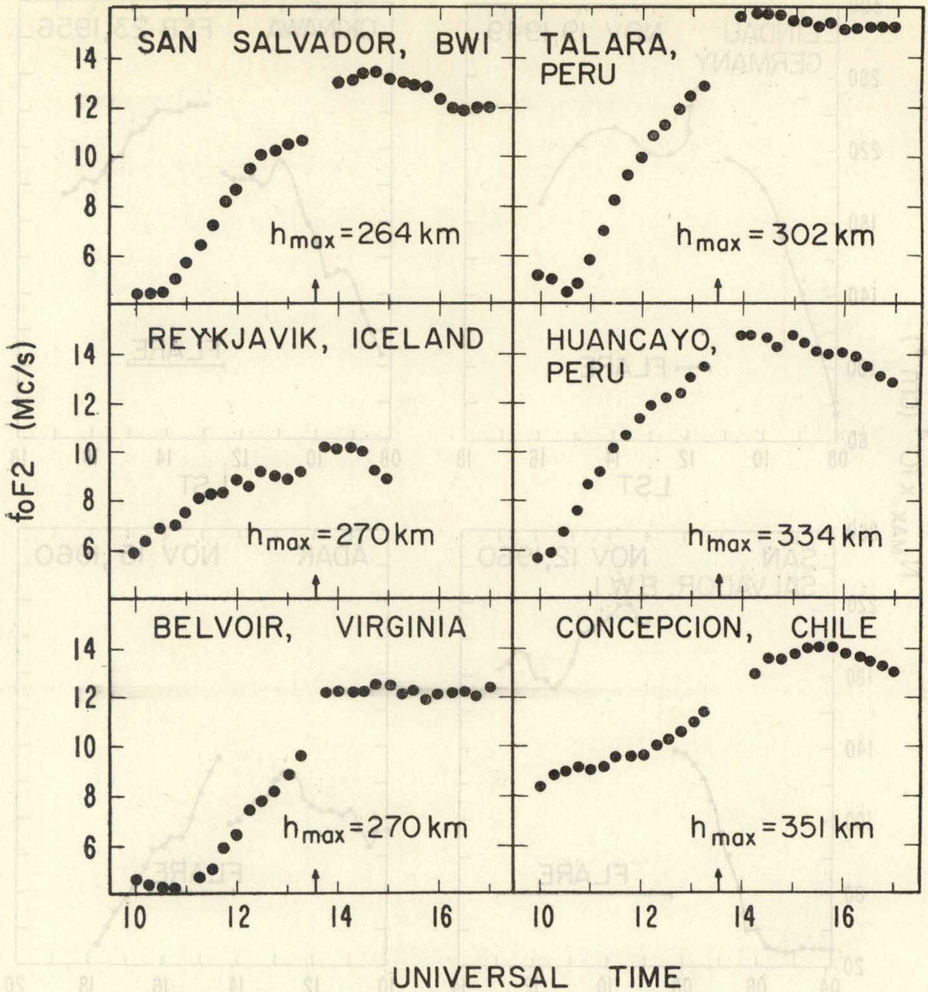


Fig. 2. Variations in *F2*-layer penetration frequency at six sunlit sounding stations during the large solar flare of November 12, 1960. Arrow marks flare beginning.

taneously with optical flare emission or if it is directly related to the arrival of the high energy particles on the earth. The question of timing was examined for both the November 12 and 15 events. Fig. 4 shows the variations in the frequency of WWV 20 Mc/s signal as recorded at Boulder, Colorado during the November 12 flare event[4]. The effect shown, which can be seen to begin within a few minutes of the beginning of the flare, can be interpreted as a 20 kilometer lowering of the reflection height at the midpoint of the path. The change in height of the reflection level is directly related to the area under the frequency change curve. It can be seen that the maximum *F*-layer effect (i.e., the reflection level reaching its lowest height) occurred at about the same time as the maximum in flare intensity (0630 LST). After about 0635 the effect observed can be interpreted as a gradual recovery as the reflection level returns to its pre-flare height. The sea-level cosmic ray increase at Deep River, Ontario did not begin until at least 0642, a time well after the principal *F*-region effect has taken place. The November 15 event is shown in Fig. 5. In the upper part of the figure it can be seen that the *foF2* increase began sometime between the 0215 and 0230 observations. The middle figure shows that the large increase in optical flare intensity occurred between 0218 and 0221 with the flare maximum occurring at or shortly after 0221. Sea-level cosmic ray intensity, on the other

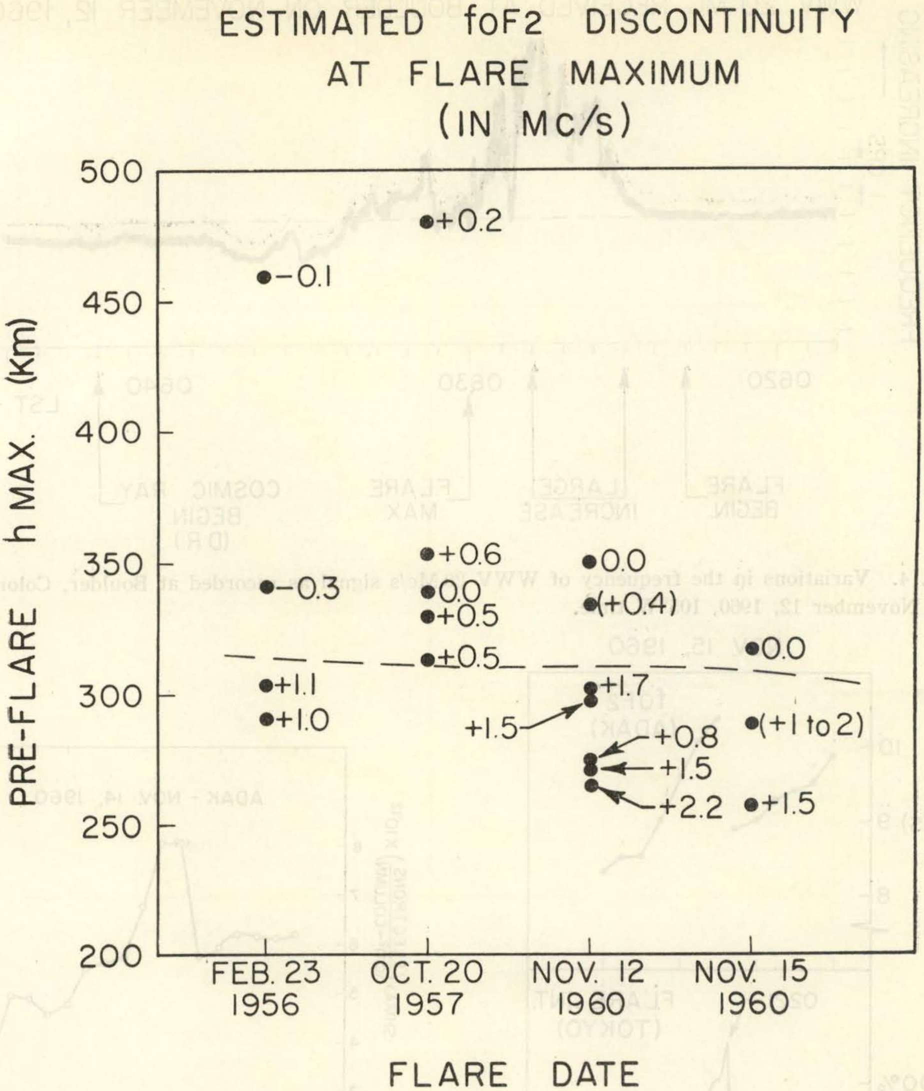


Fig. 3. Estimated discontinuity in *F2*-layer penetration frequency (in megacycles) at a number of sunlit sounding stations at the time of four solar flares.

hand, did not begin to increase at Deep River until 0242, or about twelve minutes after the *foF2* increase was first observed. Clearly, both of the November 1960 events suggest that the *F*-layer effects are directly related to the optical flare and not the high-energy particle radiation.

Solar flare effects in the *F*-region could come about in two ways; either through a real increase in the amount of ionization present due to an increase in the production of ionization, or by a re-distribution of pre-existing *F*-region ionization caused by electrodynamic drift forces associated with the increased *D*-region conductivity. Fortunately, because of the remarkably short duration of *D*-region absorption during the November 15 event at Adak (November 14, 180°W time), essentially complete *h'F* profiles were obtained throughout almost all of the flare event. These profiles have been analysed for sub-peak electron content and the results are shown in Fig. 6. The total number of electrons in a centimeter-square column between the bottom of the *E*-region and the height of the *F2* maximum is shown (*Shmax*). It appears that an increase of about 25 percent in sub-peak electron content occurs as a re-

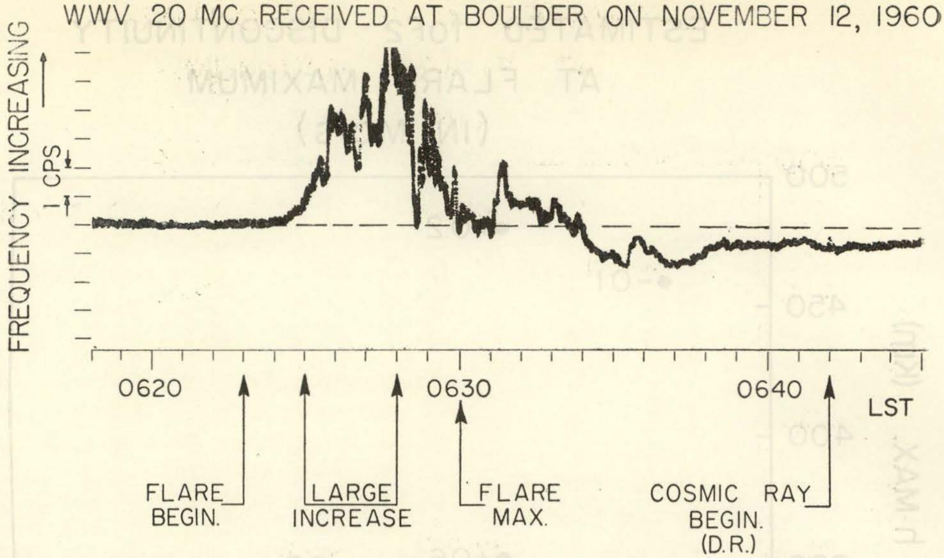
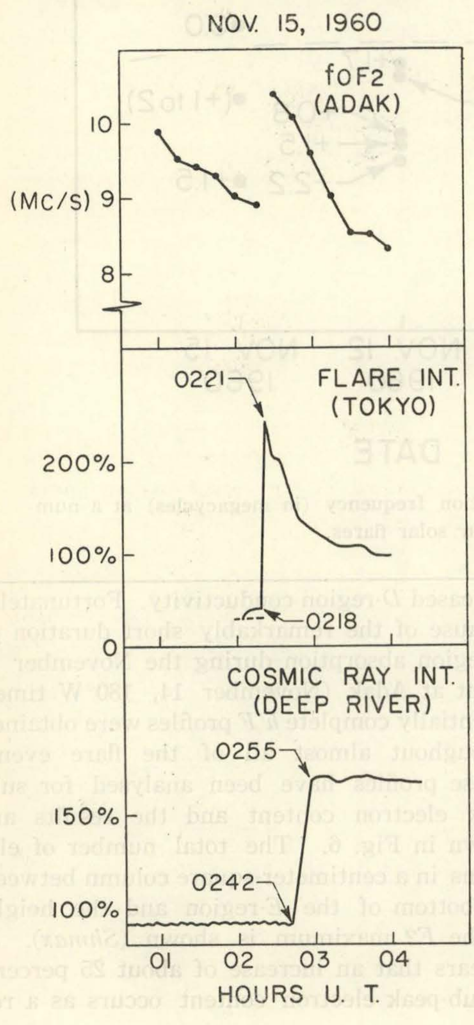


Fig. 4. Variations in the frequency of WWV 20 Mc/s signal as recorded at Boulder, Colorado, November 12, 1960, 105°W time.



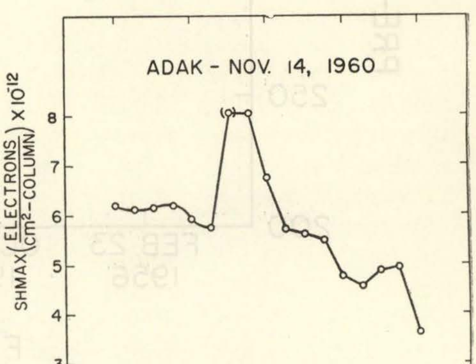


Fig. 6. Sub-peak electron content at Adak during November 15 flare event.

Fig. 5. Variations in *F2*-layer penetration frequency, *foF2*, (Adak, Alaska), flare intensity (Tokyo), and sea-level cosmic ray intensity (Deep River, Ontario) during the November 15 flare event.

sult of the solar flare. This finding supports the view that a real increase in photoionization rate occurred as a result of the solar flare. However, a re-distribution mechanism cannot be ruled out entirely, until more is learned about the electron content and distribution in the topside of the *F*-layer.

A last point concerns whether or not *F*-region effects are ever seen accompanying large flares that are not associated with sea-level cosmic ray increases. Ionospheric observations taken during the twelve largest PCA flare events in the 1957–1959 period have been examined. For only one, the October 20, 1957 event, shown in Fig. 3, was there any indication of *F*-region effect. Considering large flares (importance 2 or greater) without either sea-level cosmic ray increases or PCA events associated with them, only one, March 9, 1958, had a possible small *F*-region effect. Based on the work done to date one would have to conclude that *F*-region flare effects are predominantly a feature of those flares also having associated with them emission of the relativistic particles responsible for increases in sea-level cosmic ray intensity. This suggests that these flares are in some way unusual in their photon radiation as well as in their high energy particle emission.

References

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Discussion

Ratcliffe, J. A.: Colud not these phenomena be caused by movement of the *F*-layer, consequent upon the currents and charges produced in the *D*- and *E*-regions during SIDs? In this context it is noticeable that, apparently, very special conditions both in time and space, have to be satisfied before the effect occurs. Moreover the time constant of recovery after the SID effect in the *F* region seems, on a cursory examination, to be more rapid than would be expected from the normal rate of change in the evening.

Knecht, R. W.: A re-distribution of pre-existing *F*-region ionization caused by electrodynamic effects associated with the *D*- and *E*-region flare effects is certainly a possibility. The fact that the sub-peak electron content showed a very marked increase during the Nov. 15 1960 flare at Adak has led us to favor the hypothesis that a real increase in the production of *F*-region occurred. Regarding the recovery time constant of the *F*-region effects, if the higher photochemical rates proposed by Van Zandt are used, recovery in an hour or less would be expected.

Maeda, K.: In connection to the discussion made by Mr. Ratcliffe, I like to present a comment. You showed in a slide that the rate of inrease of *foF2* is rather small at levels higher than a certain height, say 250 km, while the rate is very large at heights lower than that. I think that this discontinuity is difficult to be explained, by mere vertical drift of the layer.