A comparison is made between the VHF backscatter radar data at Jicamarca and the HF vertical ionosonde data at Huancayo during the spread-F conditions together with the multi-station and multi-satellite VHF radio scintillations data. One of the mechanisms for the generation of spread-F is the cross-field instability mechanism due to the interaction of eastward electric field on the sharp vertical plasma density gradient at the base of the F-layer shortly after sunset. This mechanism of spread-F development can be unmistakably identified on the sequence of HF ionosonde records, and is associated with the westward progression of the first starting of VHF scintillations due to the westward movement of the solar terminator. The other mechanisms of spread-F occurrence are the movement of these irregularities upwards due to Rayleigh Taylor instability mechanism and/or eastward movement of the irregularities due to the reversal of the electric field to the nighttime westward direction. This causes the eastward movement of the scintillation producing patches. The latter processes may exist individually or jointly complicating the time development of the spread-F.

1 Introduction

The generation of ionospheric irregularities in the equatorial region during the early part of the night was detected as far back as 1938 by Booker and Wells¹ through the ionospheric records at Huancayo. These irregularities now known as 'Spread-F' have been observed at other equatorial stations, Singapore², Ibadan³, Kodaikanal⁴, Djibouti⁵ and Thumba⁶. The occurrence of spread-F was shown to be closely related with the scintillations of radio stars³. Scintillations of radio beacons on HF, VHF, UHF and even on GHz range are found to be associated with the equatorial spread-F⁷-¹⁰. After detailed comparison of the ionosonde records and the amplitude scintillation records of ATS-6 radio beacons at Huancayo, Rastogi¹¹ has shown that it is the range type of spread-F which caused the VHF scintillations and the frequency spread produced only very weak fluctuations. Rastogi¹² has further shown that almost saturated scintillations of radio waves on HF and VHF bands from geostationary satellite may occur at an equatorial station during the nighttime even in the absence of spread-F. These events were observed when the ionograms showed blanketing type sporadic-E layers simultaneously at different heights.

Farley et al.¹³ showed that irregularities associated with equatorial spread-F can backscatter 50 MHz radio waves with strength 10⁷-10⁸ times the background thermal level. Rastogi and Woodman¹⁴ showed that spread-F which is responsible for the backscattering of VHF radio waves is the range type and not the frequency type. With the inclusion of time varying attenuator in the Jicamarca backscatter receiving system, it became possible to obtain height variation of backscatter power. Repetition of these observations at short intervals of time yields what is known as modified range time intensity (MRTI) records¹⁵. Later improvement of the data processing system has yielded data of digital power of the backscatter echoes against altitude and time¹⁶.

Basu et al.¹⁷ compared the VHF backscatter echo power map with VHF scintillations. They found saturation of VHF scintillations in excess of 20 dB during the times when radar maps showed large intense plume structures rising into the topside ionosphere. At nights when only thin layers of bottomside irregularities were observed, the only moderate-to-weak scintillations were recorded at VHF. Rastogi¹⁸ compared the MRTI records for Jicamarca, with simultaneous vertical incidence ionograms and VHF amplitude scintillation records at Huancayo. The altitude of range type spread-F on ionograms corresponds very well with the altitude of VHF backscatter echoes and was associated with the radio scintillations. In a recent paper Rastogi¹⁹ has compared the VHF backscatter echo power map at Jicamarca during Mar. 1974 with corresponding ionograms and amplitude scintillation records at Huancayo. It was observed that VHF radio scintillations were very strong during the periods when scattering layers were observed simultaneously at different altitudes in the Huancayo ionograms as in
Jicamarca radar maps; the plume structure in radar map was not a necessary condition for the occurrence of radio scintillations.

In view of detailed study of equatorial spread-F irregularities an intensive series of experiments was undertaken by Air Force Geophysics Laboratories, USA in collaboration with the Jicamarca Radio Wave Observatory in Peru during the period 16-30 Oct. 1976 (Ref.20). The main stress of the investigations was the comparison of Jicamarca backscatter power map and the scintillations of VHF radio waves from different satellites. The detailed variations of the scintillations index for all these days were published later by Whitney et al.21

This paper deals with the detailed comparison of VHF backscatter echo power map at Jicamarca (lat., 11.97°S; long., 76.86°W); vertical incidence ionograms at Huancayo with the scintillation of radio waves on 249 MHz from geostationary satellite LES-9 at Huancayo (lat., 11.97°S; long., 75.34°W) and Ancon (lat., 11.7°S; long., 77.15°W) and of Marisat transmission on 257 MHz of ATS-6 on 137 and 360 MHz at Huancayo. The elevation of LES-9 satellite as viewed from Ancon was 44° to 36°, with the ionospheric cross-over region close to 74°W, and as viewed from Huancayo it was at 46° to 38° with the ionospheric cross-over region close to 72°W. The elevation of Marisat from Huancayo was about 21° with the ionospheric cross-over region close to 68°W. The location of ground stations and the ionospheric cross-over regions are shown in Fig.1. The scintillation measurements were available on all days from 16 to 30 October 1976, but the Jicamarca radar operated on only seven nights during this period.

Besides, the multistation satellite scintillation observations, spaced receiver scintillation measurements were also conducted at Ancon by using two independent receiving systems with their antenna located on an east-west base line of 366 mm. The drift speeds of irregularities were computed from the cross-correlation of these scintillation records.

**Fig. 2** shows the VHF backscatter radar echo power map at Jicamarca, LES-9 radio beacon scintillations at Ancon and at Huancayo, and the scintillations of VHF signals from LES-9 received at Ancon and Huancayo on 16 Oct. 1976. The VHF radar power at Jicamarca and the scintillation of LES-9 beacon at Ancon and Huancayo have been described earlier by Arons et al.22 The backscatter echoes were first observed at 1910 hrs LT at an altitude of 300 km. By 1945 hrs LT the minimum altitude of the irregularities had increased to 350 km and an extended structure, commonly referred to as plume, was observed with the irregularities having extended in the altitude range of 400-700 km. The minimum height of the plume structure ended by 2015 hrs LT and the height of a thick irregularity structure continued to decrease to 200 km at 2100 hrs LT and to about 150 km at 2115 hrs LT. There was another plume structure between 2045 and 2115 hrs LT. It is to be noted that strong patches of backscatter echoes were recorded from 1945 to 2045 hrs LT even at times between the occurrence of the two plume structures. Scintillations of LES-9 signals at Ancon were first observed at 2050 hrs LT. Scintillations became stronger with a maximum of about 28 dB at 2130 hrs LT and decreased to a very low value by 2150 hrs LT. The LES-9 signals received at Huancayo showed initial weak scintillations but after 2115 hrs LT an intense scintillation structure similar to that obtained at Ancon was detected. The major scintillation structure

**2 Data**

**2.1 Observations on 16-17 Oct. 1976**

Fig. 2 [(a) and (b)] shows the VHF backscatter radar echo map at Jicamarca, LES-9 radio beacon scintillations at Ancon and at Huancayo, and the ionograms at Huancayo on the evening of 16 Oct. 1976.
RASTOGI: IONOSPHERIC SPREAD-F & EQUATORIAL BACK SCATTERING & SCINTILLATIONS

at Huancayo started at 2116 hrs LT and thus was delayed from the onset of Ancon scintillation by 26 min. As regards the geometry of Fig.1, it corresponds to an eastward drift at the irregularity of 116 m s⁻¹. The duration of scintillation at either station was about 60 min corresponding to E-W dimension of the patch of about 400 km. Thus it seems that the irregularity patch had developed either at or to the west of Jicamarca and drifted eastward at an approximate speed of 100 m s⁻¹ causing scintillations first at Ancon and later at Huancayo. Extrapolating backward in time from the onset of scintillations at Ancon (2050 hrs LT), the scintillation producing irregularities would have occurred over Jicamarca at about 1950 hrs LT which corresponds to the time of the beginning of plume structure. The period of scintillations at Ancon and Huancayo corresponds fairly well with the period in between the two plume structures. Further, only a single peak of scintillation activity was noticed at the two stations when the structure in between the plumes had passed along the propagation path. This 1 hr duration corresponds to lot of structures in the irregularity patch and the scintillations were probably due to the multiple scattering from these mini patches rather than from the plume structures.

Examining the set of ionograms reproduced, one finds that at 1845 hrs LT the ionogram trace was very clean without any spread-F or sporadic-E reflections. At 1915 hrs LT some weak irregularities started at the base of the F-layer (at 300 km), which did not develop into spread-F configuration in later ionograms. At 1945 hrs LT a very strong off-vertical scattering layer without any group retardation effects was noticed at 400 km. At 2015 hrs LT the base of the F-layer increased to 350 km and the oblique trace had merged with the F-layer. At 2045 hrs LT the off-vertical irregularities had been overhead of Huancayo giving rise to number of scattering layers at different heights. The scintillations at Huancayo started about half an hour later at 2115 hrs LT when the irregularity had moved east of Huancayo. The ionogram at 2130 hrs LT shows the absence of scattering irregularities, when the scintillations at Huancayo continued up to 2215 hrs LT. Thus on 16 Oct. 1976 the irregularity structure with lot of smaller patches within itself had developed

![Fig. 3—(a) VHF backscatter radar echo power map at Jicamarca on 19 Oct. 1976 compared with the variations of the scintillation index of VHF signals from LES-9 to Ancon and Huancayo and from Marisat to Huancayo: and (b) vertical incidence ionograms at Huancayo on the evening of 19 Oct. 1976](image-url)
west of Peru and steadily drifted eastward crossing overhead ionosphere at Huancayo and later crossed the propagation paths of LES transmissions to Ancon and Huancayo producing scintillations on the received signals.

2.2 Observations on 19-20 Oct. 1976

The VHF backscatter radar echo power map at Jicamarca and the scintillations of LES-9 transmissions at Ancon and Huancayo and of Marisat transmission at Huancayo on 19 Oct. 1976 are shown in Fig. 3(a). The vertical incidence ionograms at Huancayo on 19 Oct. 1976 are shown in Fig. 3(b).

The VHF backscatter echo power map on this day (similar to that on 16 Oct. 1976) showed two plumes separated in time by about 1 hr. However, the initial echoes unlike on 16 Oct. 1976 showed structure of moderately strong echoes before the initiation of the plume structure. The backscatter echoes also continued at least for 2 hr after the time of second plume. The scintillation records of LES-9 transmissions to Ancon and Huancayo showed four structures. Basu and Arons²⁰ have considered the first structure at Huancayo as composed of two structures. They could not further identify correspondences between these structures in the scintillation records and in backscatter radar map. The scintillations of Marisat transmission at Huancayo indicated the first patch of almost 2.5 hr duration compared to 1 hr long first patch of LES scintillation at Huancayo and less than 1 hr duration patch in LES scintillation at Ancon. The first scintillations started on Marisat to Huancayo at about 1920 hrs LT, on LES to Huancayo at 1930 hrs LT and on LES to Ancon at 1945 hrs LT and the multiple structure of irregularities started at 2015 hrs LT. This sequence is in perfect accordance with the westward progression of solar terminator.

Examining the ionograms at Huancayo on 19 Oct. 1976, it is observed that the spread-F irregularities started at the base of the F-layer (320 km) at 1925 hrs LT. Later as seen in the ionograms at 1940 and 1950 hrs LT the irregularities at the base intensified and extra off-vertical echoes also appeared at an altitude of 400 km. The spread-F echoes weakened around 2000 hrs LT but again range type of scattering echoes were observed at different heights at 2040 hrs LT. Again at 2100 hrs LT spread-F echoes had weakened but grew stronger at 2120 hrs LT. Thus the spread-F structures at Huancayo on 19 Oct. 1976 were due to the
continuation of irregularities generated in situ at the base of the F-region followed by the irregularities moving from off-vertical regions, most probably from region west of Huancayo. The weakening of range spread around 2100, 2230 and 2335 hrs LT corresponded very well with the weakening of scintillation activities at Ancon and Huancayo.

2.3 Observations on 18-19 Oct. 1976

The VHF backscatter echo power map at Jicamarca and the scintillations of LES and Marisat transmissions at Ancon and Huancayo on 18-19 Oct. 1976 are shown in Fig.4(a) while the ionograms at Huancayo for 18 Oct. 1976 are shown in Fig.4(b).

Before describing the VHF radar echo power and scintillation data, let us examine the ionospheric conditions on the evening of 18 Oct. 1976.

The ionogram at 1715 hrs LT shows a retardation type E2-layer developing besides other sporadic-E layers. At 1800 hrs LT the normal E-layer had decreased below the lower frequency end of the recorder but a thin E2-layer with $F_0$ E2 about 2.7 MHz was clearly recorded with four multiple reflections. At 1815 hrs LT, diffuse spread type of irregularities had developed over the region of E2-layer. The development of spread-E echoes has been described by Rastogi. At 1845 hrs LT the low level spread echoes had disappeared and off-vertical satellite echoes were recorded over the normal F-layer trace. At 1905 hrs LT range type of spread-F echoes were recorded at the base of the F-layer. At 1915 hrs LT both overhead echoes at the F-layer base and oblique echoes (as satellites to the main trace) were recorded clearly. At 1940 hrs LT the main F-layer had risen to above 400 km but strong spread-F layer was recorded at 300 km. Later records showed complex structure of the spread echoes. At 2045 hrs LT there was temporary absence of spread echoes which appeared later and continued till after midnight.

Fig.4(a) shows that when the radar operation started at 1930 hrs LT, a weak and thin layer of irregularities had already evolved at the height of 200 km. This type of irregularities in the valley region has been described by Woodman and La Hoz. A plume structure was probably present at around 2100 hrs LT. The plume decayed by 2200 hrs LT but the irregularity region was full of structures between 200 and 400 km of altitude. Basu and Aarons found no correspondence between the radar map and the first scintillation structure observed at Ancon and Huancayo. At initial period there was no definite delay in the occurrence of scintillations of LES transmissions at Huancayo with respect to scintillations of LES transmission at Ancon. Only at later stage there was a definite eastward drift of irregularities.

2.4 Observations on 20-21 Oct. 1976

The backscatter radar echo power map at Jicamarca, scintillations of Marisat transmission at Huancayo and ionograms at Huancayo on 20 Oct. 1976 are shown in Fig.5. The radar at Jicamarca could detect only weak bottomside irregularities in a thin layer at 200 km between 2030 and 2220 hrs LT. On this night, no scintillations were observed either at Ancon or at Huancayo with LES-9 transmission. Marisat
transmission at Huancayo showed scintillations between 1930 and 2030 hrs LT. The ionograms did not show any spread-F echoes. The F-layer traces were quite clean. However, between 2000 and 2100 hrs LT some sporadic-E reflections were observed at different altitudes. Rastogi\textsuperscript{24} has shown that intense nighttime scintillations can be observed in the absence of spread-F but only in the presence of Es layers simultaneously at different heights. It may be that scintillations of Marisat signals transmissions at Huancayo were due to rather localized layers of sporadic-E.

2.5 Observations on 21-22 Oct. 1976

The backscatter radar echo power map at Jicamarca and the scintillations at Ancon and Huancayo are shown in Fig.6(a) while the ionograms are shown in Fig.6(b). The backscatter radar had detected only weak bottomside irregularities and the HF ionosonde recorded only weak frequency type of spreading; the group retardations were clearly seen at all times. No scattering layer was recorded in the ionograms at Huancayo. No significant scintillations were recorded at Ancon, but Huancayo registered moderate scintillations on LES and Marisat transmissions. This is consistent with earlier observations by Rastogi and Woodman\textsuperscript{25} that the range type of spread does not support VHF backscattering.

2.6 Observations on 24 Oct. 1976

On 24 Oct. 1976 the satellite ATS-6 was moving westward and the transmission path of ATS-6 to Huancayo was at the region close to Jicamarca. Thus the scintillation measurements of ATS-6 transmissions to Huancayo offered an opportunity to examine the relationship between different phenomena occurring over the common ionospheric volume.

In Fig.7(a) are shown the radar echo power map at Jicamarca and the scintillation of ATS-6 transmission at Huancayo and LES-6 transmissions at Ancon and Huancayo for 24 Oct. 1976. The ionograms at Huancayo are shown in Fig.7(b).

On this day the radar map showed only weak irregularities between 200 and 300 km heights and there were some substructures within. The ionograms indicated irregularities only at the base of the F-layer. The spread-F irregularities at Huancayo preceded the radar irregularities at Jicamarca which could be interpreted as due to the westward movement of the solar terminator. Once the irregularities are formed at the base, it moves eastward. All the scintillation records indicated two definite events of increased fluctuations. There were no plumes developed on this day. Comparing the time sequence of scintillation of ATS-6 transmissions and the radar map, the first patch was observed when radar map showed structures.
within the patch, and the weakening of scintillations occurred when there were uniformly weak echoes and the second scintillation event occurred when the single patch had broken up into a number of small patches. Thus the scintillation activity does not depend only on the thickness of the irregularity patch but on the presence of the number of substructures from which multiple scatterings could be obtained. The examination of ionograms shows that the spread-F irregularities were locally generated at the base of the F-layer and did not move upwards inside the F-layer. There were no off-vertical echoes.

2.7 Observations on 29-30 Oct. 1976

The radar echo power map at Jicamarca and the scintillations at Ancon and Huancayo on 29 Oct. 1976 are shown in Fig.8(a). The ionograms at Huancayo for the same night are shown in Fig.8(b).

On this night radar irregularities started at the base of the F-layer confined within the height range of 250-300 km, and later strong plume structure was developed with a lot of substructures within. Even though the plume disappeared later, yet the lower irregularity patch continued for over 4 hr. The spread-F in the ionograms started with diffuse echoes at the base but had transformed into number of traces at different heights showing no group retardation effects. This is the period when the scintillation activities were maximum on all the propagation paths.

During the later stage of the development of irregularities, the radar map showed lot of patches of very weak echoes with practically no substructures of stronger echo patches. The resultant ionograms showed only lot of noise patterns but no set pattern of these echoes. The scintillations during these periods were weak. This confirms the earlier conclusion of Rastogi that the spread-F showing uniform amorphous spreading of the echoes cause only moderate scintillations of less than 5 dB in magnitude.

3 Discussion

It is clear that the plasma irregularities in the F-region of the ionosphere can be studied by many ways, like (i) HF ionospheric sounder in vertical as well as oblique propagation, (ii) VHF forward and back scatter radar, (iii) airglow mapping cameras, (iv) radio scintillations on different frequency ranges, (v) top side ionospheric sounder, (vi) in situ rocket-borne experiments and a few other techniques. In order to understand the various features of the generation, development and movement of these irregularities it is necessary to coordinate the results of simultaneous observations under different techniques. The present study is an effort in the above direction.

It has been clearly shown by Rastogi and Woodman that the late night equatorial spread-F is produced following the sudden reversal of the electric fields. The day-to-day variability in the occurrence of...
spread-F during the early hours of the night is more difficult to study due to number of sudden changes in the atmosphere occurring at the sunset terminator region. Comparing the electron drift velocities at Jicamarca with corresponding ionograms Rastogi has shown that on a day-to-day basis the reversal of the electric field before sunset does not produce any spread-F in the evening hours, while the continuation of the daytime electric field for a couple of hours after sunset in normal strength is the most suitable condition for generating spread-F.

The present investigations clearly show that the development of equatorial spread-F at a particular station may be observed in different ways. First, the local generation of irregularities during the post-sunset period but with the eastward electric field first shows diffuse irregularities at the base of the F-layer. These irregularities may extend upwards due to gravitational effects and to the eastward direction due to the reversal of the electric field at nighttime conditions. The longitudinal shift of the spread-F boundary would move westward with the solar terminator but the developed patches would move eastward.

The second phase of first sign of spread-F irregularities may not be locally generated but the patches may be developed west of station and move through clean ionosphere overhead of the station. There, circumstances would produce a clean first and second order phase trace and additional scattering traces with vertical height constant with frequency (not the sometimes called satellite traces). On some days the ionosphere may be more complicated with the presence of locally generated as well as the transported patches of irregularities. A series of excellent quality ionograms are a must for any coordinated studies of the equatorial plasma irregularities.

The scintillation of VHF radio waves from a geostationary satellite does not necessarily require so-called plume structure. Presence of number of scattering centres is necessary condition for generating significantly large scintillations. Further a thick uniform layer of weak irregularities causing the

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Fig. 8—(a) VHF backscatter radar echo power map at Jicamarca compared with the scintillations of VHF signals from geostationary satellites at Ancon and Huancayo on 29 Oct. 1976; and (b) vertical incidence ionograms at Huancayo on 29-30 Oct. 1976.
frequency spread-F configuration does not produce significant scintillation or backscatter of VHF radio waves.

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