

Early Phase of Equatorial Spread-F Seen by HF Ionosonde & VHF Backscatter Radar

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Comparing the VHF backscatter radar echo power maps at Jicamarca and the vertical incidence ionograms at Huancayo, it has been shown that the post-sunset spread echoes start at the base of the F-layer, if no blanketing, sporadic or uniform layer is left in the E-region after sunset. In cases, when a blanketing sporadic-E or any uniform intermediate layer in this E-region persists after sunset, then the spread echoes appear to form first at this E-layer and later at the base of the F-layer, the two irregularity regions remaining unconnected. It is suggested that the first seeding of the spread irregularities at the equatorial ionosphere in the evening hours occurs due to gradient drift instability at any height between the E- and F-layers wherever a large vertical plasma density gradient exists. Later the irregularities may extend upwards throughout the F-region due to the buoyancy effects through Rayleigh-Taylor instability mechanism provided proper conditions are present for the bubbles to attain reasonably upward velocities.

1. Introduction

Various techniques have been utilized to study the spread-F irregularities in the ionosphere. Spread-F was discovered through HF ionospheric soundings by Booker and Wells¹ at Huancayo. Extensive network of ionosonde established during IGY has revealed two regions of high occurrence of spread-F, one at high latitudes and another over a belt of $\pm 20^\circ$ over the magnetic equator²⁻⁵. It was also shown that the latitudinal variations of spread-F occurrence is better when plotted against dip latitude rather than against dipole or geographic latitudes indicating strong control of local magnetic inclination (dip) on the generation of the spread-F irregularities.

Equatorial spread-F has been studied by direct examination of ionograms from equatorial stations, viz. Singapore⁶, Kodaikanal⁷, Ibadan⁸ and Thumba⁹. The occurrences of equatorial spread are preceded by a very rapid rise of the F-region, accompanied by the occurrence of very high multiple echoes¹⁰. Osborne⁶ found positive correlation between the mean monthly rate of post-sunset increase of $h'F$ and the occurrence of spread-F at Singapore. Chandra and Rastogi⁹ showed that the equatorial spread-F is basically of the following two types. (i) Range type when the scatter is at lower frequencies only with f_oF_2 quite clearly defined; and (ii) frequency type when the scatter is increasing with frequency and f_oF_2 normally not discernible. The spread-F associated with the post-sunset rise of $h'F$ has been shown to be the range type¹¹.

Cohen and Bowles¹² studied the equatorial spread-F through the VHF forward scatter across the

magnetic equator employing a 2580-km transmitter-receiver separation with mid-point near Huancayo. The VHF propagation was usually identifiable with the lowest height of the associated spread-F on the ionograms. They concluded that the spread-F arises from scattering by a relatively thin sheet of irregularities in electron density when it occurs at the bottom of the F-layer or as much as 100 km lower.

The incoherent backscatter radar at Jicamarca has provided another unique technique of studying the equatorial spread-F¹³. They found that the irregularities of wavelength of 3 m can be generated anywhere in the F-region and suggested a minimum threshold altitude that the bottom of the F-layer must be above before the irregularities are first generated. The incorporation of range-time-intensity (RTI) technique to the radar made it more suitable to study the irregularities and with the digital power mapping technique the Jicamarca radar became the most powerful tool to study the spread-F irregularities over the magnetic equator on a regular basis. Woodman and La Hoz¹⁴ have described the radar power maps obtained by this technique. Unlike the conventional HF ionosondes, the echoes are obtained at Jicamarca by the scattering of 3-m irregularities and as such one can map the irregularities in the region above the peak electron density level of the F-layer. The very narrow width of the beam enables the defining of the region of irregularity far more accurately than what is possible from HF ionosondes. Due to wide-band and wide-beam width antenna used with the ionosondes and due to larger wavelength of radio waves used, the ionograms incorporate both the vertical as well as off-

vertical echoes simultaneously recorded. However, the ionosondes do indicate the overall condition of the ionosphere and the general height distribution of the electron density. The large amount of information on spread-F obtained through ionosondes should be compared with the highly sophisticated VHF incoherent radar and this paper is an attempt in this direction. Radar power maps at Jicamarca are compared with the vertical incidence ionograms at Huancayo.

2. Results

In Fig. 1 are reproduced the backscatter echo power map at Jicamarca on 10 Dec. 1975, after Basu *et al.*¹⁵, and the corresponding ionograms at Huancayo.

The ionogram at 1830 hrs LT indicated clearly defined f_oF_2 and f_xF_2 , and the group retardations at the beginning of the F trace. It is to be noted that the sporadic-E reflections were very weak. Due to the decay of lower level ionizations following sunset the group retardation in the F-layer trace at lower frequencies disappeared and no E-region trace was seen. At 1945 hrs LT some satellite traces parallel to

the $1 \times F$ trace were seen indicating oblique reflections due to sharp discontinuity in the iso-electron contours in the F-layer. At 2000 hrs LT spread-F echoes were seen. Some of the traces being even in virtual height, lower than the $h'F$ indicating irregularities about 30 km below the base of the F-region. The radar map indicated backscatter echoes at 2010 hrs LT from a height of about 230 km, whereas the base of the F-layer was at about 275 km. In the subsequent ionograms the spread echoes appeared to remain strong but the higher frequency end of the $h'f$ trace and the critical frequencies were easily discernible. The radar echoes confined to levels 240-300 km and no echoes at lower height were observed. It is seen that when no E traces are left after sunset, the spread-F develops at about 20-30 km below the base of the F-region.

In Fig. 2 are reproduced the echo power map of 50 MHz radar at Jicamarca after Basu and Kelley¹⁶ as

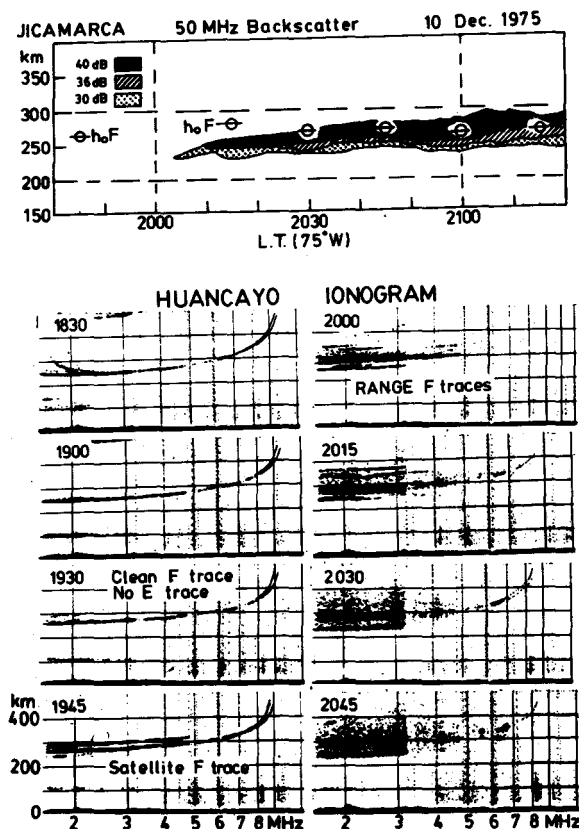


Fig. 1—Backscatter-echo power map of 50 MHz Jicamarca radar on the evening of 10 Dec. 1975 (after Basu *et al.*¹⁵), compared with corresponding ionograms at Huancayo (Note clean F-traces without any sporadic-E after sunset preceding the development of range spread-F at the base of the F-layer, with the upper portion of the F-layer being clear of the spread.)

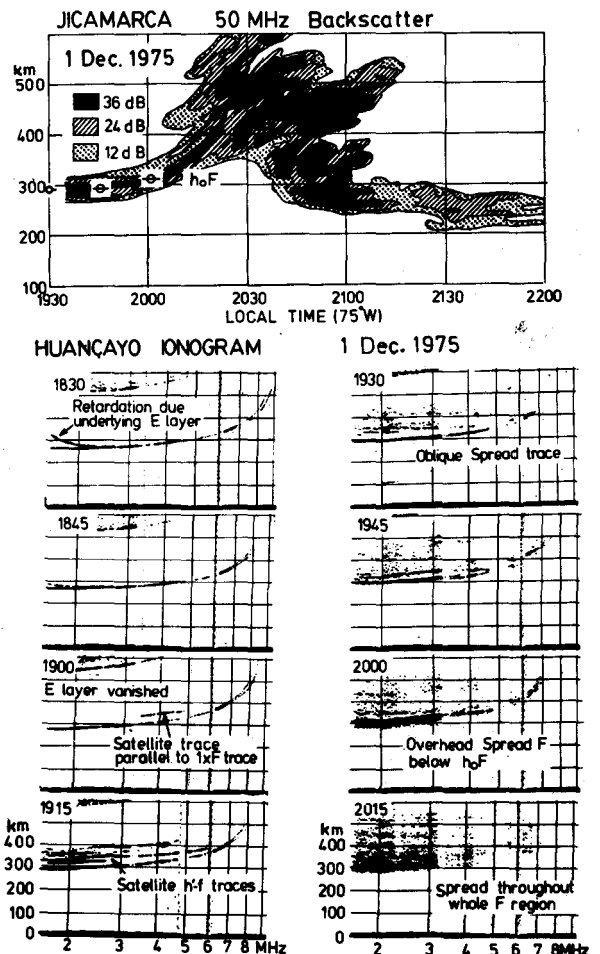


Fig. 2—Backscatter-echo power map of 50 MHz Jicamarca radar on the evening of 1 Dec. 1975 (after Basu and Kelley¹⁶) compared with corresponding ionograms at Huancayo (Note clean F trace without any sporadic or normal E-layer after sunset and that the spread irregularities were generated near the base of the F-region. At 2015 hrs LT both HF ionogram as well as the VHF radar showed irregularities throughout the whole F-region.)

well as the corresponding ionograms at Huancayo. In this case an extremely clean F-layer was left after sunset and absolutely no reflections were seen on the ionograms below the F-layer. The first sign of irregularities were seen through a satellite trace at 1900 hrs LT and a number of satellite traces at 1915 hrs LT. At 2000 hrs LT the spread-F had developed quite strongly on the ionograms although the critical frequencies were discernible. At 2015 hrs LT the spread-F had extended throughout the F-region.

The VHF radar map did not indicate any irregularities in the E-region. The irregularities developed at the base of the F-layer and had extended throughout the F-region by 2015 hrs LT. It is again confirmed that in the absence of strong layers in the E-region after sunset, the spread-F irregularities on the HF ionograms as well as on VHF radar map are seen only near and above the base of the F-region.

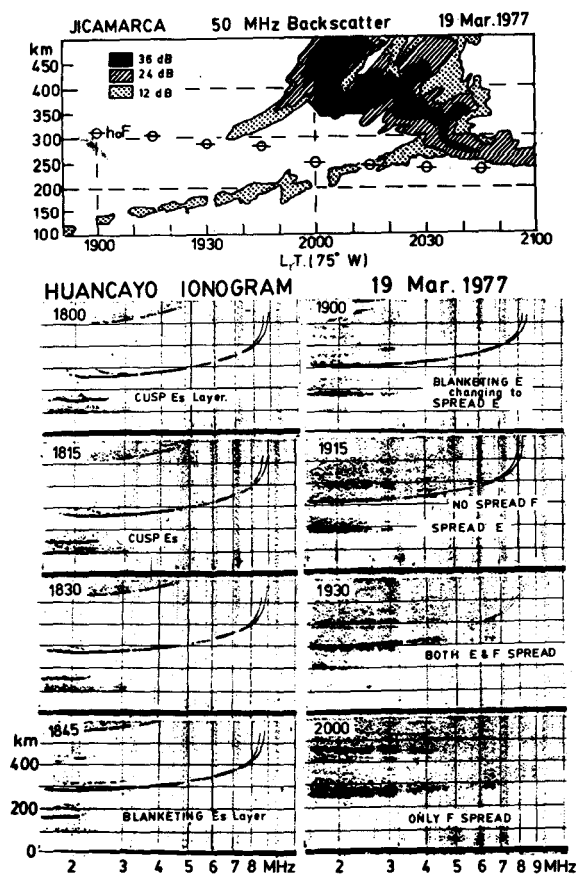


Fig. 3—Jicamarca 50 MHz backscatter echo power map on 19 Mar. 1977 (after Basu *et al.*¹⁷) compared with the corresponding ionograms at Huancayo (Note the cusp type of sporadic-E layer which continued after sunset, and that the spread echoes first developed at this sporadic-E layer and later at the base of the F-region. Radar map showed upwelling of the irregularities after 1945 hrs LT and the ionograms showed correspondingly obliteration of the F-layer $h'f$ trace.)

Now we compare the VHF radar map for 19 Mar. 1977 (after Basu *et al.*¹⁷) with corresponding ionograms at Huancayo in Fig. 3. The ionogram for 1800 hrs LT showed strong cusp type of sporadic-E layer which continued to exist for a period of about 1 hr transforming itself into a strong sporadic-E layer at 180 km by 1900 hrs LT. At 1915 hrs LT strong spread echoes developed at 180 km on the previously existing Es region; the F-region trace was very clear from the lowest frequencies up to the critical frequencies. At 1930 hrs LT spread echoes developed at F-region too and at 2000 hrs LT only F-region spread remained.

The radar map indicated first the irregularities in the E-region and about half an hour later at the base of the F-layer. At 2000 hrs LT the radar irregularities extended up to 500 km and the ionogram indicated spread echoes throughout the F-region.

In Fig. 4, we reproduce the echo power map at Jicamarca for the evening of 20 Mar. 1974 (after Woodman and La Hoz¹⁴) and compare it with the ionograms at Huancayo for the same period. The ionograms at 1800 hrs LT indicated a layer breaking out of the base of the F-layer which transformed into a

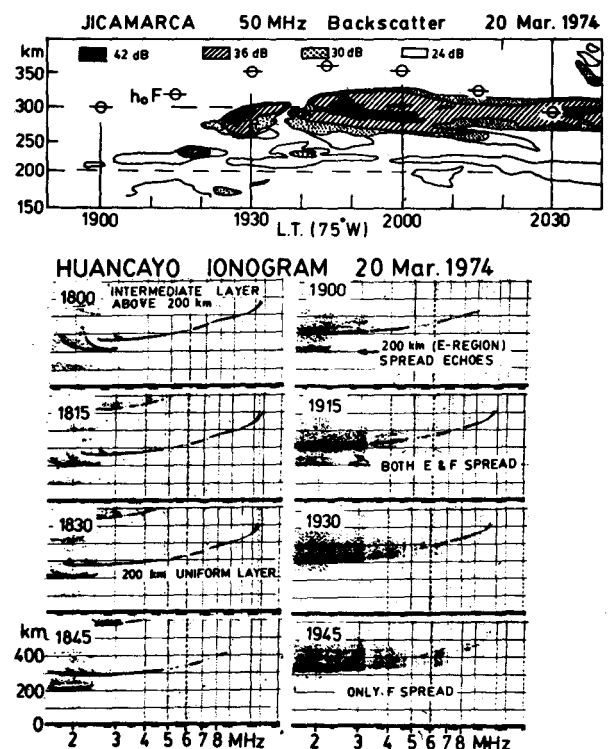


Fig. 4—Jicamarca 50 MHz backscatter echo power map on 20 Mar. 1974 (after Woodman and LaHoz¹⁴) compared with corresponding ionograms at Huancayo (Note the post-sunset uniform layer with group retardation at 200 km which transformed into spread E-layer. The VHF radar indicated strong backscatter echoes from regions much below the F-layer.)

thin uniform, retarding layer at 200 km at 1830 hrs LT. At 1845 hrs LT spread echoes appeared at the base of the intermediate layer at 200 km and at 1900 hrs LT strong spread-E echoes were recorded on the ionogram. At 1915 hrs LT both E- and F-region spreads were distinct with a clear region in between. At 1930 hrs LT the E-spread had disappeared and only F-spread was seen. The radar map showed echoes first from 200 km level and later from the F-region.

3. Discussion

The discovery of spread-F irregularities in the upper portions of the ionosphere and the plumes by Jicamarca radar maps by Woodman and La Hoz¹⁴ had revolutionized the ideas on the equatorial spread-F and generated a spurt of theoretical investigations on the equatorial F-region irregularities. The Rayleigh-Taylor instability as the cause of spread-F was first suggested by Dungey¹⁸. The report on the theory of spread-F by Haerendel¹⁹ provoked extensive theoretical investigations on the characteristics of the equatorial spread-F specially as observed by the VHF backscatter radar²⁰⁻²⁵. Besides the nonlinear processes, Ossakow and Chaturvedi²⁶ and Ott²⁷ included the electric field in the ion-momentum equations. Ossakow *et al.*²⁸ performed numerical simulations of the Rayleigh-Taylor instabilities for equatorial spread-F using realistic altitude profiles for ion-neutral collision frequency, recombination rates and background electron density. They showed that the higher altitude of the F peak and/or steep bottomside electron density gradient are favourable for the development of irregularities. These plasma density depletions rise nonlinearly to the topside by polarization $E \times B$ motion. Thus the present theories of Rayleigh-Taylor instabilities in the equatorial F-region satisfactorily describe the features of the spread-F in the F-region as well as on the topside of the ionosphere.

The only comparison of the same sample of ionosphere by HF ionosonde and VHF radar available in literature is for 20 Mar. 1974, the evening of the launching of Equion rocket from Punta Lobos rocket range in Peru²⁹. They have shown that the regions of rapidly fluctuating electron density and their gradients as observed by rocket-borne Langmuir probe coincided exactly with the radar backscatter power map. They also noted thin bottomside irregularities seen with the radar which did not produce scintillations at 137 MHz nor the spread-F on the ionograms. Similar radar echoes have been previously attributed by Balsley and Farley³⁰ to partially coherent reflections from a steep gradient in electron density. This thin layer was later followed by spread-F on the ionogram and simultaneous strong echoes from

the lower portion of the F-layer. During the period of rocket flight the strongest echoes were observed from the altitude region of largest plasma gradient. It is after these features that the upper portions of the F-region showed irregularities generally described as plumes.

Reid³¹ was first to suggest the $E \times B$ gradient drift instability mechanism for the spread-F and Cunnold³² extended the above idea proposing that small irregularities existing in the 130-km altitude may be amplified by this instability. Farley *et al.*¹³ pointed that the coupling between E- and F-region as required by Reid's theory can only be effective for wavelengths of the order of a kilometre or more and thus does not explain the 3-m irregularities seen by Jicamarca backscatter radar.

With the context of the results of Equion Rocket Launching and the evidence presented in this paper it is suggested that the initial seeding of the spread-F irregularities occur at the base of the F-layer or in the E-region much below the F-layer due to the gradient-drift instability at the regions of large plasma gradients provided there exists a suitable electric field (eastward). These irregularities would be later intensified by the Rayleigh-Taylor mechanism and would be transported upwards into the F-layer as well as would produce shorter wavelength irregularities responsible for the VHF radar echoes on 3-m wavelength and the scintillations of VHF and even UHF radio waves.

This idea of two-step development of equatorial spread-F by the combined gradient drift and Rayleigh-Taylor instability mechanisms has been shown to explain satisfactorily the seasonal and the longitudinal variations of the equatorial spread-F as well as the abnormal regeneration of the equatorial spread-F during post-midnight hours³³.

4. Conclusions

- (i) The spread-F irregularities in the equatorial ionosphere develop at about 15-30 km below the F-region base (as seen from the ionograms) in the cases when the lower E-region is free from any sporadic or uniform retarding type of layer following the sunset.
- (ii) In the case of retarding or blanketing type of sporadic-E layer persisting after sunset the first spread irregularities develop at the level of sporadic-E and 15-30 min later at the base of F-region. The spread-E layer vanishes rapidly and the spread-F regions may develop in strength later on, but the two spread layers remain separate whenever they coexist.
- (iii) The spread-F may show upwelling on some occasions leading to the plumes extending to topside of the F-layer but on some occasions the spread-F region may remain confined to the lower portion of the F-layer.

- (iv) When the radar irregularities are confined to lower regions of the F-layer the ionograms show range spread with clear critical frequencies.
- (v) When the radar maps indicate upwelling or plumes, the ionograms show complete spread-F with no indication of $h'f$ trace or critical frequencies.
- (vi) The level of intense echoes of range type spread-F on ionograms compare fairly well with the peak scatter levels of radar echoes of MRTI records.
- (vii) The equatorial spread-F is generated in a two-step process of gradient drift instability produced at or below the base of the F-region and the upward extension of the plasma irregularities through Rayleigh-Taylor instability mechanism.

References

- 1 Booker H G & Wells H W, *Terr Magn & Atmos Electr (USA)*, **43** (1938) 249.
- 2 Shimazaki T, *J Rad Res Lab (Japan)*, **6** (1959) 669.
- 3 Wright R W H, *J Geophys Res (USA)*, **64** (1959) 2203.
- 4 Singleton D G, *J Geophys Res (USA)*, **65** (1960) 3615.
- 5 Lyon A J, Skinner N J & Wright R W, *J Atmos & Terr Phys (GB)*, **19** (1960) 145.
- 6 Osborne B W, *J Atmos & Terr Phys (GB)*, **2** (1952) 66.
- 7 Bhargava B N, *Indian J Meteorol Geophys*, **9** (1958) 35.
- 8 Lyon A J, Skinner N J & Wright R W, *J Atmos & Terr Phys (GB)*, **21** (1961) 100.
- 9 Chandra H & Rastogi R G, *Ann Geophys (France)*, **28** (1972) 37.
- 10 Rastogi R G, *Proc Indian Acad Sci Sect A*, **85** (1977) 230.
- 11 Rastogi R G, *Proc Indian Acad Sci Sect A*, **87** (1978) 115.
- 12 Cohen R & Bowles K L, *J Geophys Res (USA)*, **66** (1961) 1081.
- 13 Farley D T, Balsley B B, Woodman R W & McClure J P, *J Geophys Res (USA)*, **75** (1970) 7199.
- 14 Woodman R F & La Hoz C, *J Geophys Res (USA)*, **81** (1976) 5447.
- 15 Basu S, Arons J, McClure J P, La Hoz C, Bushby A & Woodman R F, *J Atmos & Terr Phys (GB)*, **39** (1977) 1251.
- 16 Basu S & Kelley M C, *J Atmos & Terr Phys (GB)*, **39** (1978) 1229.
- 17 Basu S, Basu S, Arons, McClure J P & Cousins M D, *J Geophys Res (USA)*, **83** (1978) 4219.
- 18 Dungey J W, *J Atmos & Terr Phys (GB)*, **9** (1956) 304.
- 19 Haerendel G, *Theory of equatorial spread-F, Rep., Max-Planck Institut fur Phys und Astrophys, Garching, West Germany*, 1974.
- 20 Hudson M K & Kennel C F, *J Geophys Res (USA)*, **80** (1975) 4581.
- 21 Chaturvedi P K & Kaw P K, *Geophys Res Lett (USA)*, **2** (1975) 381.
- 22 Chaturvedi P K & Kaw P K, *Geophys Res Lett (USA)*, **2** (1975) 499.
- 23 Scannapieco A J & Ossakow S L, *Geophys Res Lett (USA)*, **3** (1976) 451.
- 24 Chaturvedi P K & Ossakow S L, *Geophys Res Lett (USA)*, **4** (1977) 558.
- 25 Jain R K & Das A C, *Proc Indian Acad Sci Sect A*, **87** (1978) 1.
- 26 Ossakow S L & Chaturvedi P K, *J Geophys Res (USA)*, **83** (1978) 2085.
- 27 Ott E, *J Geophys Res (USA)*, **83** (1978) 2066.
- 28 Ossakow S L, Zalesak S T, McDonald B E & Chaturvedi P T, *J Geophys Res (USA)*, **84** (1979) 17.
- 29 Morse F A, Edgar B C, Koons H C, Rice C J, Heikkila W J, Hoffman J H, Tinsley B A, Winningham J D, Cristensen A B, Woodman R F, Pomalaza J & Teixeira N R, *J Geophys Res (USA)*, **82** (1977) 578.
- 30 Balsley B B & Farley D T, *J Geophys Res (USA)*, **80** (1975) 4735.
- 31 Reid G C, *J Geophys Res (USA)*, **73** (1968) 1627.
- 32 Cunnold D M, *J Geophys Res (USA)*, **74** (1969) 5709.
- 33 Rastogi R G, *J Geophys Res (USA)*, **85** (1979) 722.