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" SPRING COLLEGE ON GEOMAGNETISM AND AERONOMY "

(2 - 27 March 1987)

" Spread - F and radio scintillations "

presented by :

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SPREAD - F AND
RADIO SCINTILLATIONS
by
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Fig.-1. shows the first reported scattering of radio waves by Booker and Wells at an equatorial station Huancayo in 1938. Please note two kinds of scattering, one which occurs near the critical frequencies and the second which occurs at lower frequencies

Fig. 2. Next reporting of scattering of radio ~~way~~ waves at low latitudes is due to Osborne in 1952 at Singapore. It was observed that maximum scatter occurred during the months when ~~to~~ the evening rise of the F layer was largest. Maximum scatter occurred slightly after the ~~...~~ time of evening peak of the F region height

Fig. 3. One of the first explanation of F scatter (Spread F) was in terms of the permanent irregularities at higher altitude in the nightside F layer. Spread F was observed on the ionograms when height of F layer was raised above this threshold height -

Fig. 4. Following the Rebers method the temporal variation of spread F at Ahmedabad are shown. During low sunspot years spread F was most common after midnight

during local summer months. During high sunspot years it was maximum during equinoxes ~~...~~ around midnight hours

Fig. 5 At equatorial station Thumba, spread F occurred most frequently before midnight hours

Fig. 6. The ionograms at Brisbane showed multiplicity of traces during spread F conditions and the types RANGE SPREAD and FREQUENCY SPREAD were introduced

Fig. 7. At stations just outside the equatorial belt the spread F was preceded by the satellite echoes. These types of echoes were first described at Ibadan.

Fig. 8 At equatorial station spread F (scatter) are found at frequencies beyond f_oF_2 Hence spread F are not due to reflection condition but due to scattering mode.

Fig. 10. Cohen and Calvert explained the equatorial spread in terms of scattering irregularity at different height and at different distance from the station, the traces observed are due to reflection/scattering by regular layer and the irregularity.

Fig. 11 A comparison between an observed ionogram and a synthesized one.

Fig. 12 The spread F occurrence showed a maximum over the dip equator. The geomagnetic disturbance had a negative effect on the spread F at low latitudes and positive effect at higher latitudes. Disturbance had thus a quenching effect on F region irregularities.

Fig 13. Temporal variations of the F layer parameters during low and high solar activity periods

Spread F occurred more frequently during high than during low solar activity years. The time of peak occurrence was 0000 hrs during low and 2100 hr during high sunspot years.

During high SS years both F region peak height h_mF_2 as well as base height $h'F$ showed a large increase at post sunset hours. No change of thickness (y_mF_2) was noticed during spread F. The maximum electron density in the F region N_mF_2 or the integrated electron content upto h_mF_2 did not show any effect due to the spread F.

Fig. 14 Seasonal variation in spread F at Huancayo showed a distinct maximum around December and a minimum around June months while at Djibouti and Shadan minimum spread F was seen around December. Seasonal variation in spread F was most pronounced in American sector.

Solar cycle variation of spread F at Djibouti, Kodaikanal and Shadan showed increasing spread F with increasing sunspots. A reverse effect was seen at Huancayo.

Fig 15 At any of the stations, spread F is associated with the post evening rise of the height of the F layer, $h'F$. During J months, spread F is a late night phenomenon at any of the stations.

Fig 16. There are two major regions of frequent occurrence of spread F. One around the geomagnetic equator and another in ~~polar~~ auroral regions. At low latitudes spread F occurs during the night hours while at auroral latitudes it occurs at almost at all the hours of the day.

Fig. 17. The Characteristics of spread F at equator (a) small range type of scatter at low frequencies with clear F_2 traces followed

by intense ~~sp~~ range scatter (b) obscuring the critical frequency traces followed by (c) ~~range~~ frequency scatter where scatter is largest near the critical frequencies which are not identifiable. Note range spread traces donot indicate any group retardation effects.

Fig 18. Sequence of spread F at subtropic latitudes consists of (a) weak spread near the critical frequencies followed by (b) strong frequency spread at higher frequencies followed by (c) spread at all frequencies now designated as range spread. Note that spread at last stage appears as ~~superimposition~~ of number of p'-f traces with increasing virtual height and critical frequencies

Fig 19 A development sequence of spread F at subtropic latitude. Note spreading starts at higher ~~latitudes~~ frequencies and extends to lower frequencies with time.

Fig. 20 Some of the discrepancies are cleared when spread F at low latitudes are studied seperately for range and frequency spread. Range spread occurrence shows larger peak ~~due~~ at premidnight hours during sunspot maximum years but spread F occurrence during post midnight hours is more frequent during sunspot minimum years.

The occurrence of frequency spread does not show any significant solar cycle effect. Seasonal occurrence of range spread at Huancayo shows two maxima during February and November with a minor minimum in January but a majors minimum during June months, At all months the maximum occurs at local time 2000 - 2100 hr.
Frequency spread shows a maximum around 0000 hr local during December January months.

Fig. 21 A comparison of the temporal variation of the ionospheric drift speed, height of the F region (h'F) and the spread F at an equatorial station Thumba.

Ionospheric drift was westward during the day and eastward during the night, the reversal occurred 1930 hr.

The height of the F layer started rising few hours before sunset reaching a peak around 1900 hr. local.

~~The~~ Starting of spread F occurred at 1800 hr, before the time of drift reversal and well before the time of h'F peak. Seeding of irregularities occur during eastward electric field

Fig. 22 The occurrence of spread F at Huancayo is very consistently maximum around December solstices and minimum during June solstices. A comparison of the seasonal variation of the time of reversal of electric field and of the ionospheric sunset times indicates that during June solstices, electric field reverses almost at time close to sunset while during December solstices the electric field reverses more than two hours after sunset.

Fig 23 It was suggested that the seeding of spread F irregularities is due to gradient drift (cross field) instability followed by the Rayleigh Taylor instability mechanism

Fig. 24. McNicol and Bowman studied the ionograms at number of stations and observed that the satellite type of spread F occurs most frequently at subtropic latitudes stations Panama, Townsville and Puertorico and is not seen at low latitudes stations at Huancayo and Talara.

Fig 25 (a) Based on the ionogram studies at different stations in India during 1965 the peak occurrence of spread F was found to be earliest (0000 hrs) at the equatorial station Kodaikanal, later at low latitude station

Hyderabad at about 02 hrs and still later at Ahmedabad and Delhi.

(b) Based on the data from a large number of stations in Pacific zone established for time 1962 nuclear test, spread F onset was found to be later at stations farther away from the equator.

(c) The peak latitude of maximum occurrence of range spread coincides roughly with latitude of Appleton Anomaly crest.

(d) The low latitude belt of spread F coincides with the daytime F_2 anomaly belt and not with the equatorial electrojet belt. The development of spread F belt occurs due to a phenomenon similar to the mechanism of daytime F_2 region anomaly belt

A fountain of F region irregularities at similar to the fountain of F region plasma during the daytime was suggested. Irregularities are generated at the base of the F region over the dip equator after sunset during a favourable conditions, lifted up due to buoyancy effects and diffuse along the lines of force to higher latitudes.

Fig 26. ~~[illegible]~~
Comparison of the range-intensity records of VHF backscatter records at Jicamarca with the spread F ionogram at Huancayo. Excellent correlation is seen suggesting spread F at HF range too to be due to scatter and not due to reflections

Fig 27 Range type of equatorial spread do produce VHF backscatter echoes. Frequency spread do not generate. VHF backscatter echoes

Fig 28. Equatorial spread F are known to be associated with radio wave scintillation. It is shown that strong scintillations are seen only during the occurrence of range type of equatorial spread where the ionogram traces do not show any group retardation effects.

Fig. 29. A sequence of spread F and scintillation records at Huancayo during the course of a night.

Fig. 30 Records of radio scintillations on different frequencies from the same satellite recorded at the same station. Scintillations on different frequencies start almost at the

same time on different frequencies not valid with the idea that longer wavelength irregularities are generated first which later generate short wavelength irregularities due to its movement upwards. It seems spread F ~~phenomenon~~ is a rather explosive phenomenon generating irregularities over a wide spectrum of wavelengths almost at the same time.

Fig. 31. Using scintillation data from satellite signals from different locations received at the same ~~region~~ station it is seen that scintillations first start at signals from eastward satellite first and later ~~[illegible]~~ at signals from westward satellite. This suggest westward movement of irregularities at the time of first generation suggesting importance of an eastward electric field generating the irregularities. At later stages the electric field reverses and the irregularities start moving eastward.

Fig 32 Comparison of vertical drift velocities V_z at Jicamarca and the ionograms at Huancayo on 9-10 August 1982. Abnormal reversal of V_z to upward direction around 0100 hr is followed by the generation of strong spread F irregularities in subsequent ionograms

Fig 33 Vertical drift and ionogram comparison on 13–14 May 1975 shows absence of spread F in the evening hours due to counter electrojet but its generation after 2130 hr consequent to the reversal of the vertical drift to upward direction at 2100 hr

Fig 34. Comparison of vertical drift and ionogram on 15–16 May 1974 showing sudden onset of spread F at 0445 hr due to the reversal of electric field to eastward direction

Fig 35. Comparison of power plots of VHF backscatter echoes and ionograms. A thin scattering layer produces weak spread F at small height range, a plume type of scatter echoes produce spread F over a very wide range of height and frequency on the ionograms

Fig 36. Comparison of VHF power plot and ionogram. A very thin scattering layer produces a satellite trace while a plume produces a series of range type spread F traces on the ionogram.

Fig. 37. A E_2 layer configuration before sunset can produce spread E type of irregularities well below the F region

Fig 38 A kink, a discontinuity in $h'-f$ trace within the F layer can generate irregularities at region other than the base of the F layer

Fig 39. A reversal of the Jicamarca drifts and the occurrence of spread F are associated with the reversal of IMF from south to north direction.

Fig. 40. Very strong radar echoes due to spread F are observed from the height range where the rocket borne instruments show largest gradient of plasma density.

Fig. 41 Comparison of Jicamarca E region drifts and spread F. On a day when drift reversed early spread F is not seen but on a day when drift continued to be westward (eastward electric field) spread F was produced

Fig 42. Another example of spread F generation on a day with continued daytime type of drift after sunset and complete absence of spread F in the evening hours on a day of very weak drifts

Fig 43 another example of evening spread F and scintillations associated with eastward electric field

Fig 44. Complete absence of spread F and scintillation on 20 Mar 1975 when V_z became -ve at 1800 hr and strong spread F as well as saturated scintillations on 11 March 1975 when drift continued to be positive after 1800 hr

Fig 45 Effect of geomagnetic disturbance on spread F consists of reduction of occurrence of spread F in premidnight hours and increased occurrence of spread F in postmidnight hours due to geomagnetic disturbance

Fig 46. Effect of geomagnetic disturbance is very similar on scintillations and on the range type of spread F

Fig 47. The geomagnetic ~~eff~~ disturbance effect on range spread F and scintillations are associated with the changes in the height of the F region.

Fig 48 Geomagnetic disturbance effects in h'F at equatorial and subtropical latitude stations. The premidnight effect is typical equatorial phenomenon while post midnight effect is common to both latitudes.

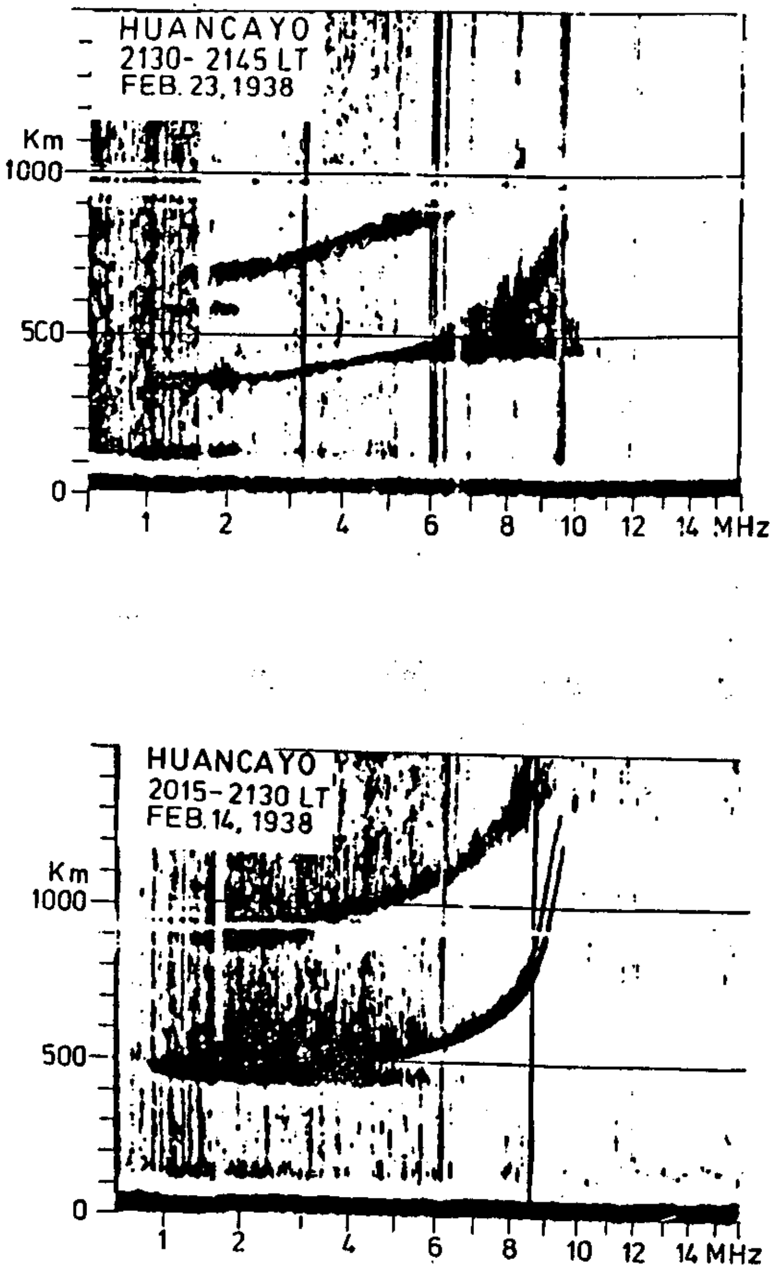
Fig 49. The geomagnetic disturbance effect on the height of the F layer is not a sudden phenomenon but the changes in layer height are a gradual function of the severity of geomagnetic disturbance.

Fig. 50 Changes in layer height as a function of Kp index at equatorial and subtropical stations.

During post sunset hours the height of F region at Huancayo decreases with increasing Kp while no significant changes are seen at tropical latitude station.

During Post-midnight hours increasing Kp causes increasing height of the F layer both at equatorial as well as sub-tropical latitude station

Fig 51 Planning of scintillation recording network by Indian Institute of Geomagnetism in India.



After Booker and Wells (1938)

Fig. 1.

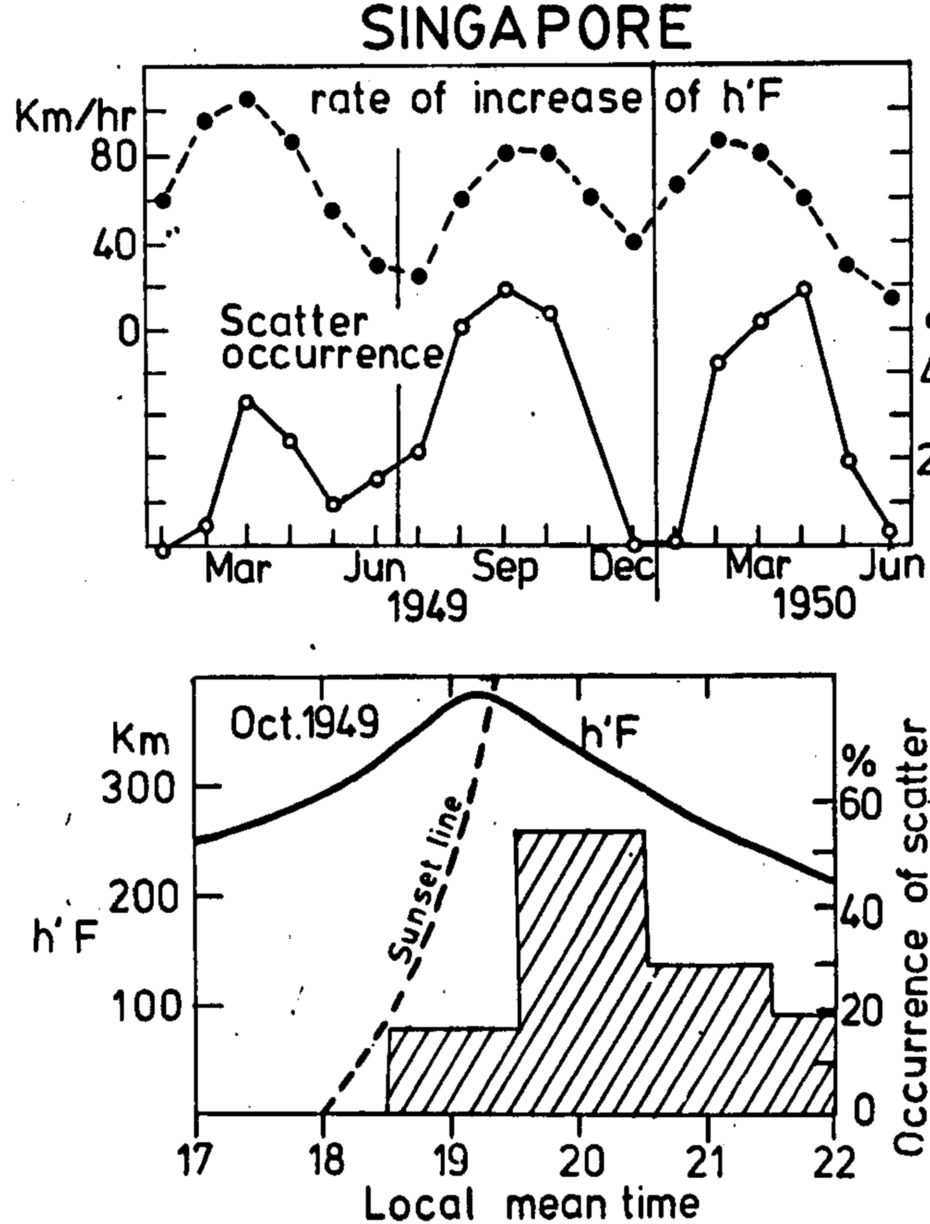
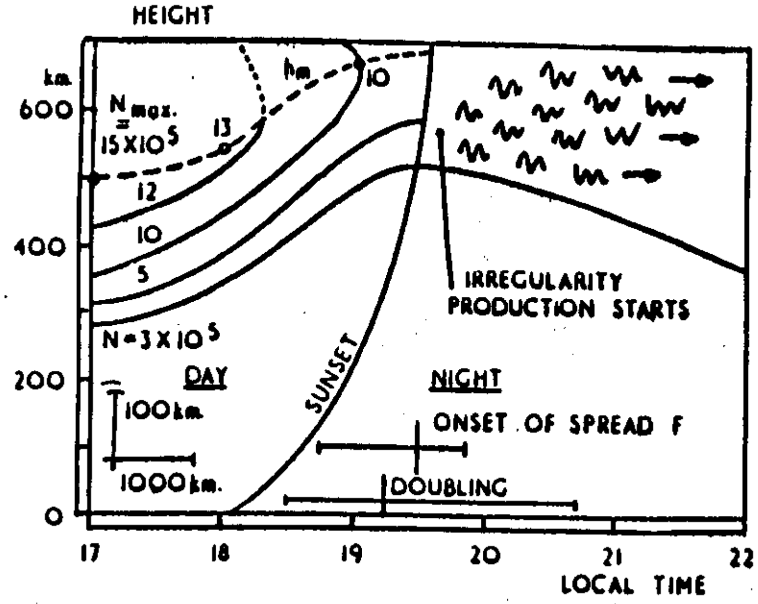
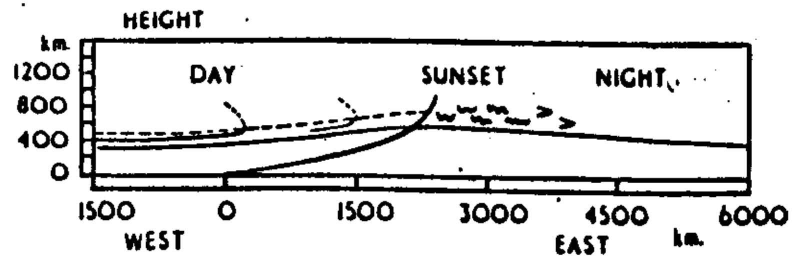


Fig. 2

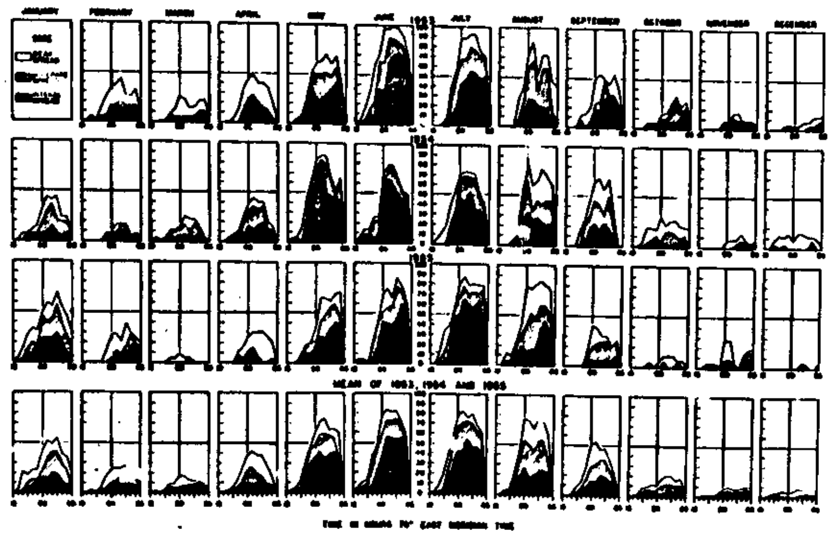


Schematic diagram showing electron density variations in the F region prior to Spread F onset, Ibadan 1957–8. Sunspot maximum data for magnetically quiet days

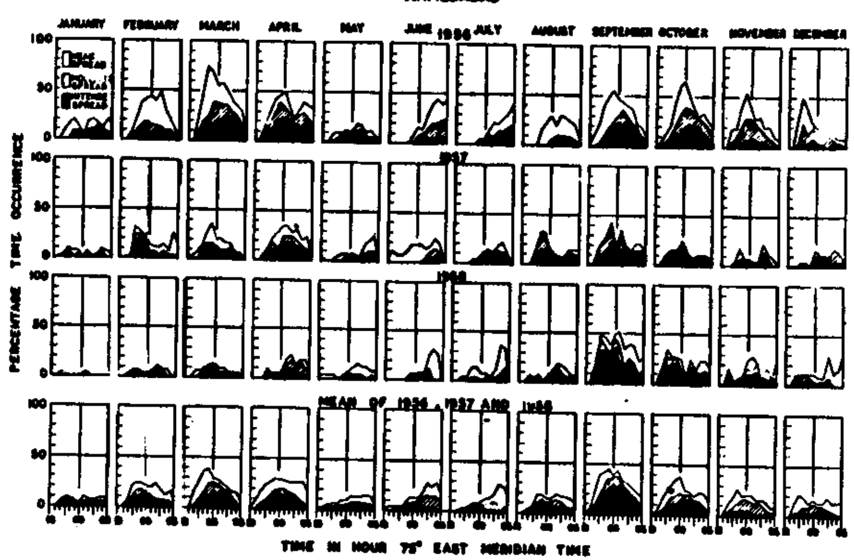


Showing Fig. 1.1.4a redrawn to give an East-West cross-section of electron density with equal horizontal and vertical scales

Fig. 3

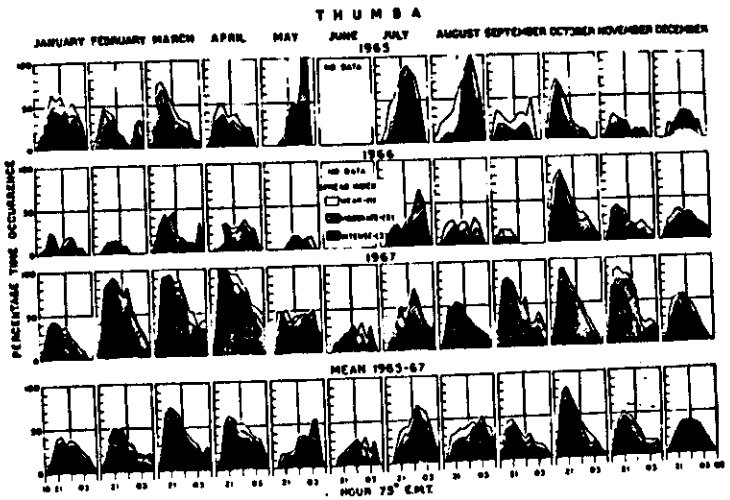


Nocturnal variations of the occurrence of different degree of spread-*F* at Ahmedabad during each months of the low sunspot years 1953-55.



Nocturnal variations of the occurrence of different degree of spread-*F* at Ahmedabad during each month of the high sunspot years 1956-59.

Fig. 4



Nocturnal variations of the occurrence of weak, moderate and intense spread-*F* during each month of the years 1965 to 1967.

Fig 5

BRISBANE 31-MAY. 1948

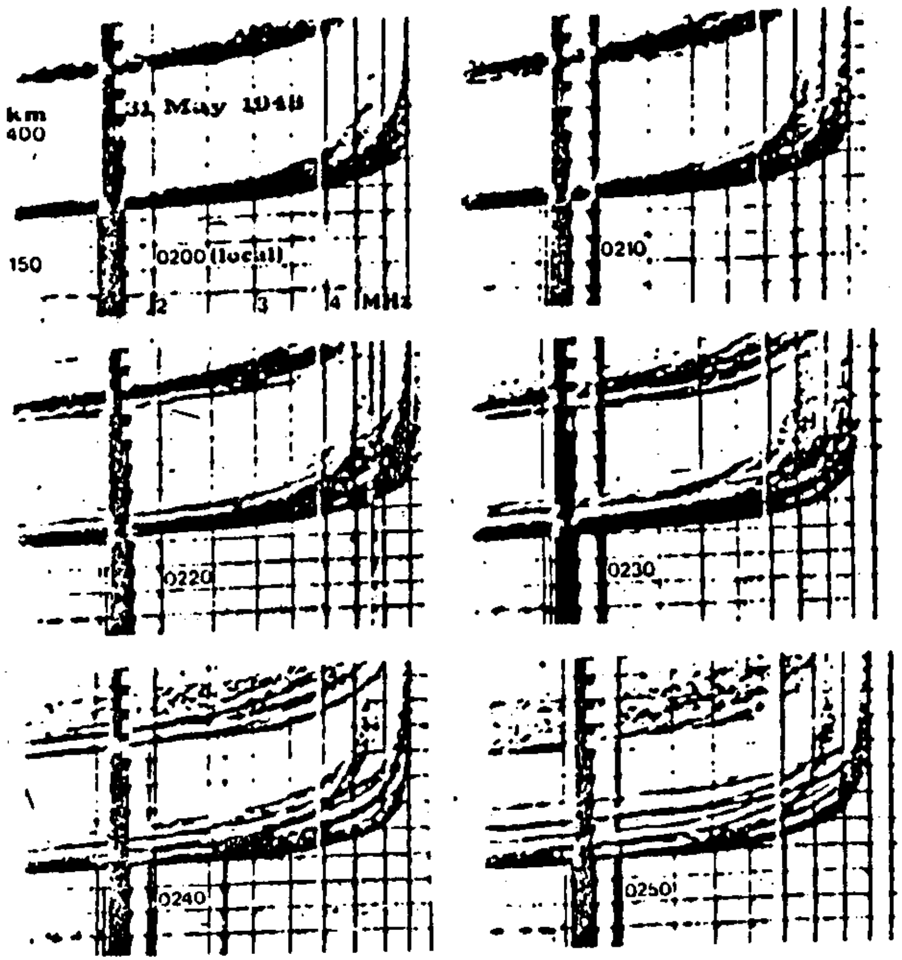
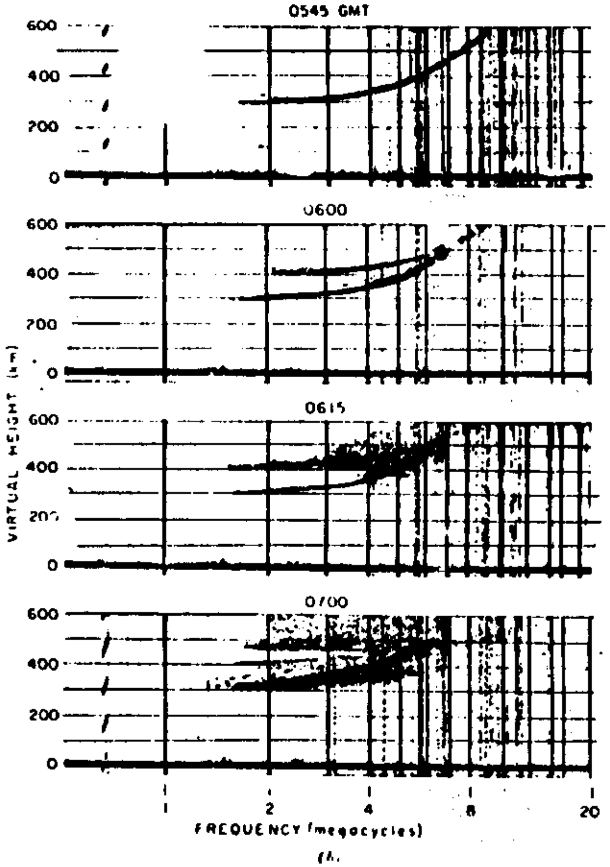


Fig 6



(b) At Canton Island, October 27, 1962; local time for the top ionogram is 1645. Note the onset of spread-F just after sunset.

Fig. 7

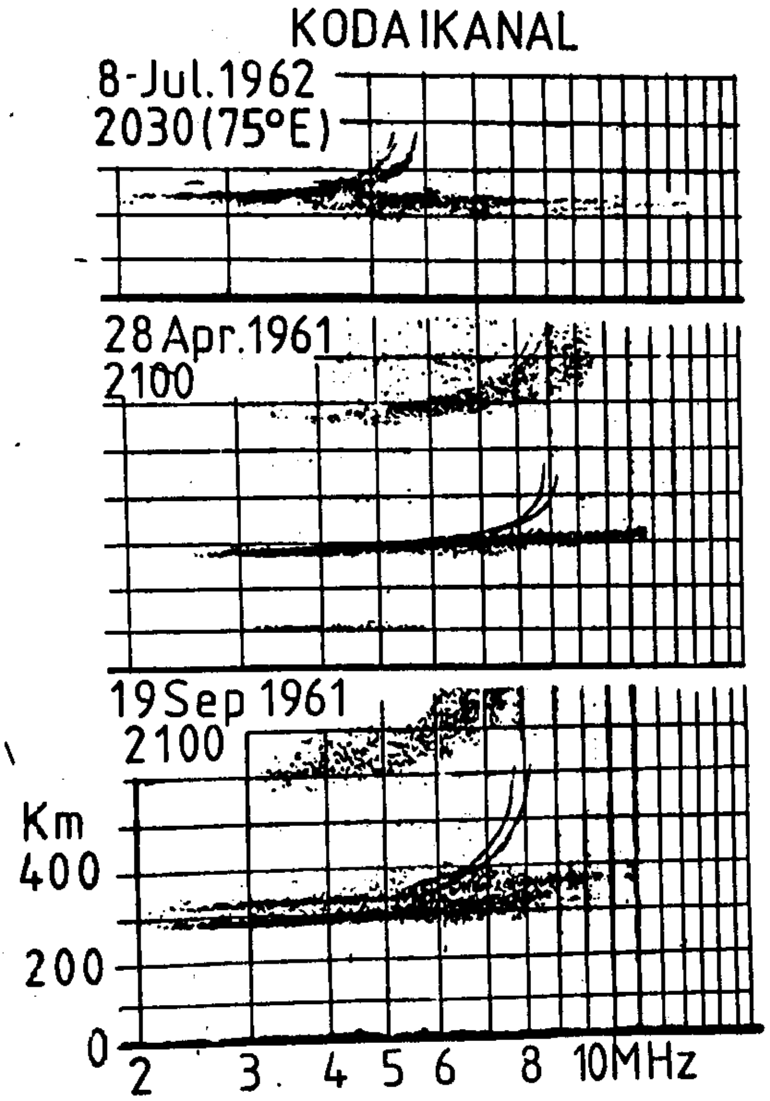
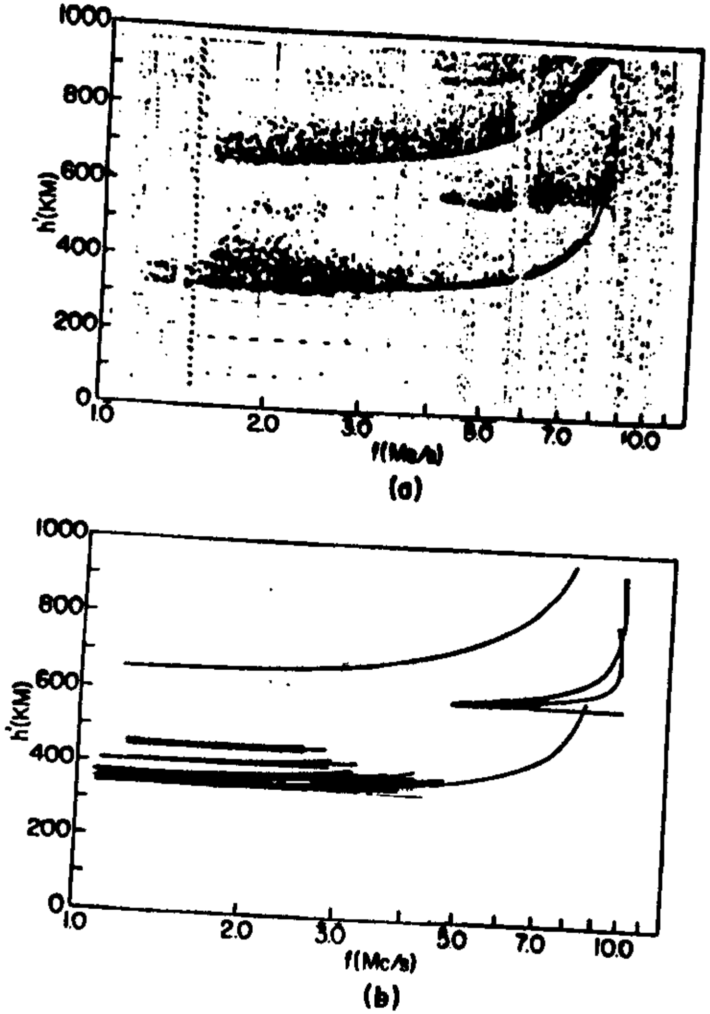


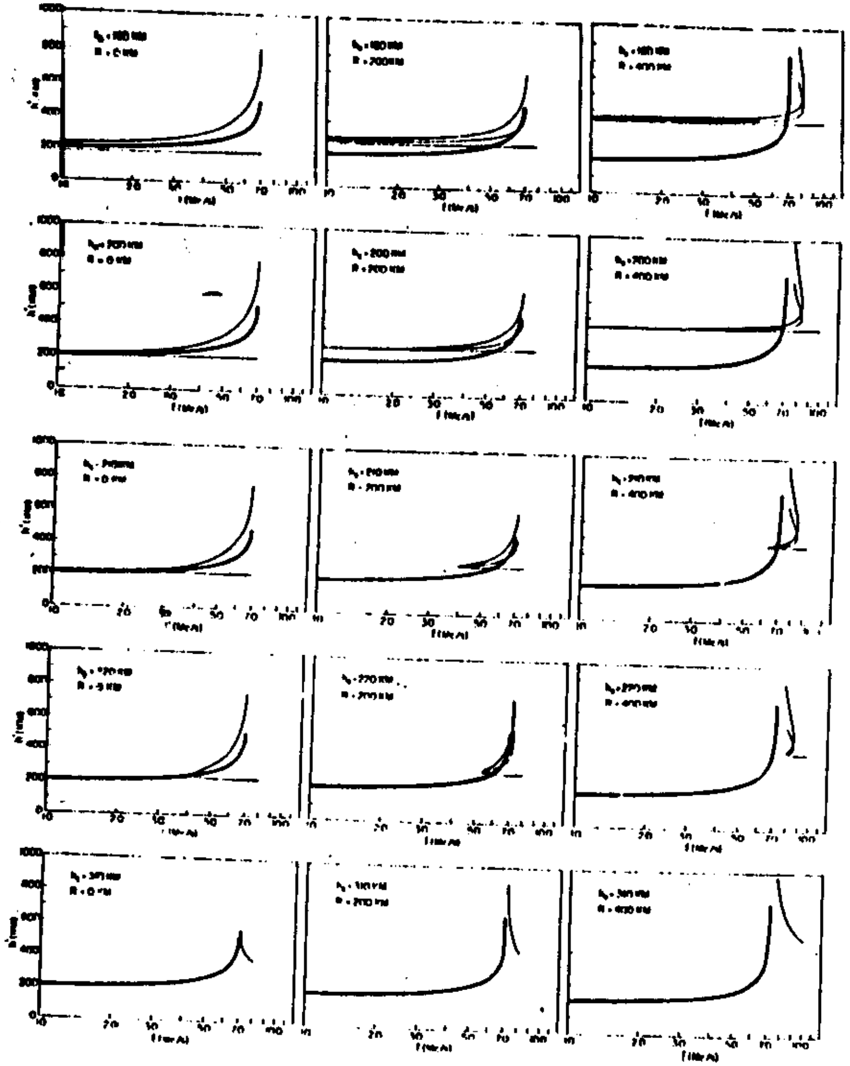
Fig. 8



(a) Huancayo ionogram, recorded at 2031 EST, 21 April 1960, in which two spread-F configurations appear, and

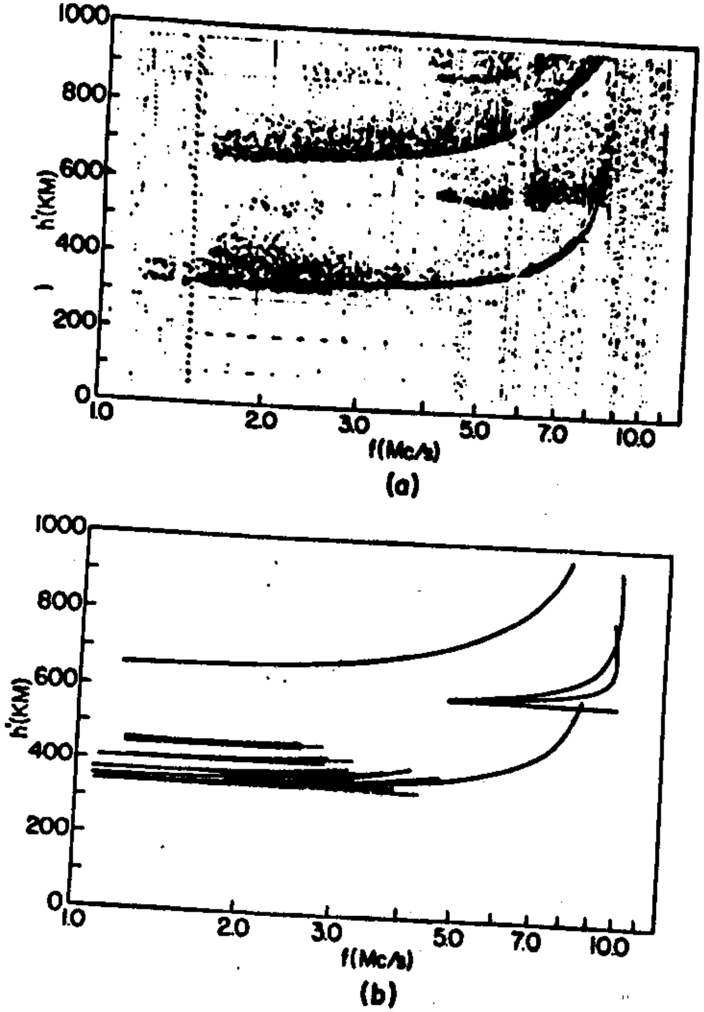
(b) The simulation of this ionogram. (The parabolic F layer used for this calculation has h_o = 328 km, h_m = 450 km, and f_oF = 8.4 Mc/s.)

Fig 9



Predicted 'ionograms' for irregularities at various heights, h_o, and ground distances, R, east or west of an equatorial ionosonde.

Fig. 10



(a) Huancayo ionogram, recorded at 2031 EST, 21 April 1960, in which two spread-F configurations appear, and
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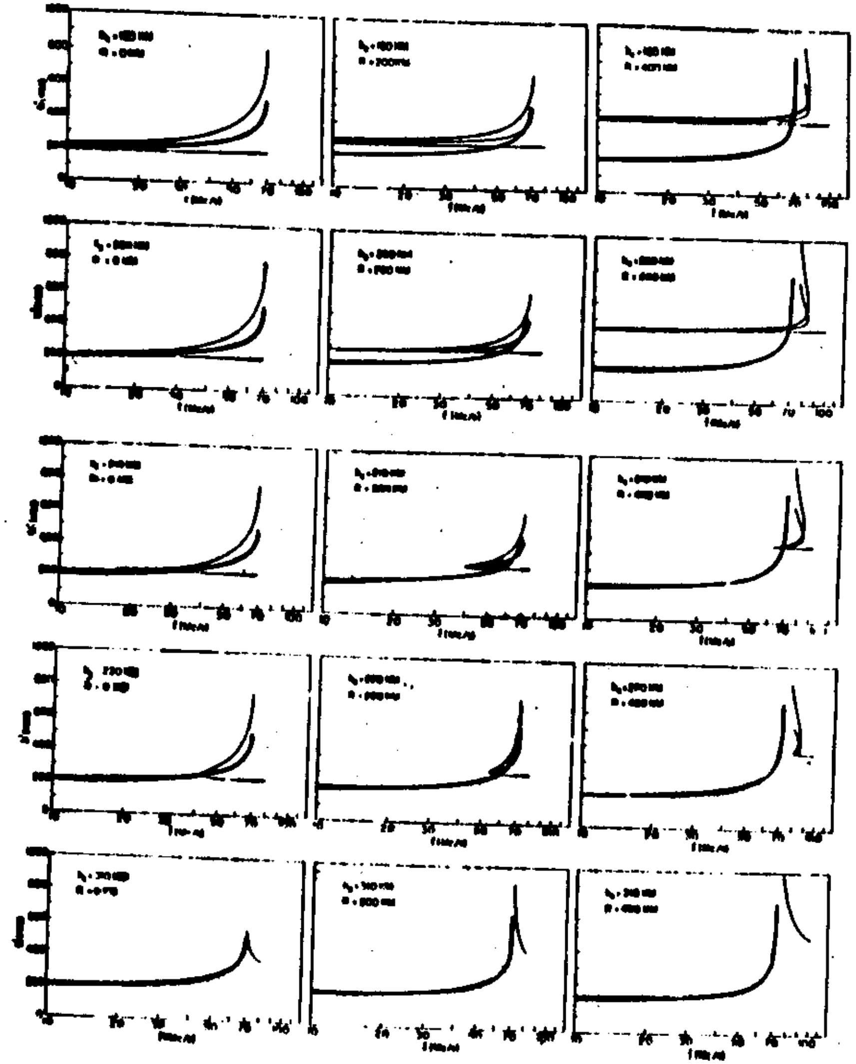
Fig. 11



Predicted 'ionograms' for irregularities at various heights, h_s, and ground distances, R, east or west of an equatorial ionosonde.

A. J. LYON, N. J. SKINNER, R. W. WRIGHT

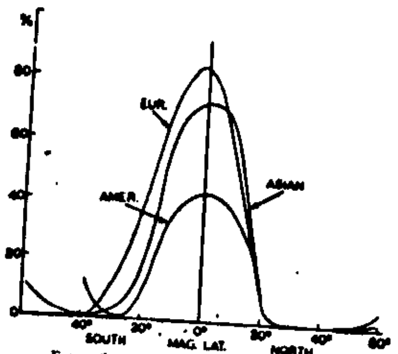


Fig. 4. Spread-F on quiet days – Equinox.

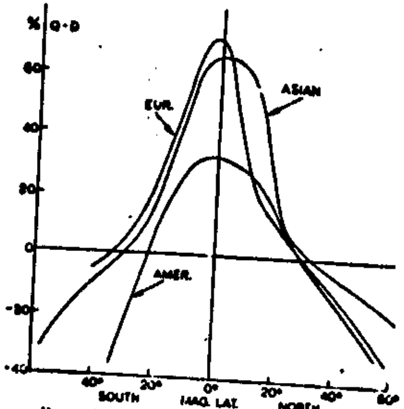


Fig. 5. Spread-F on disturbed days – Equinox.

Fig. 12

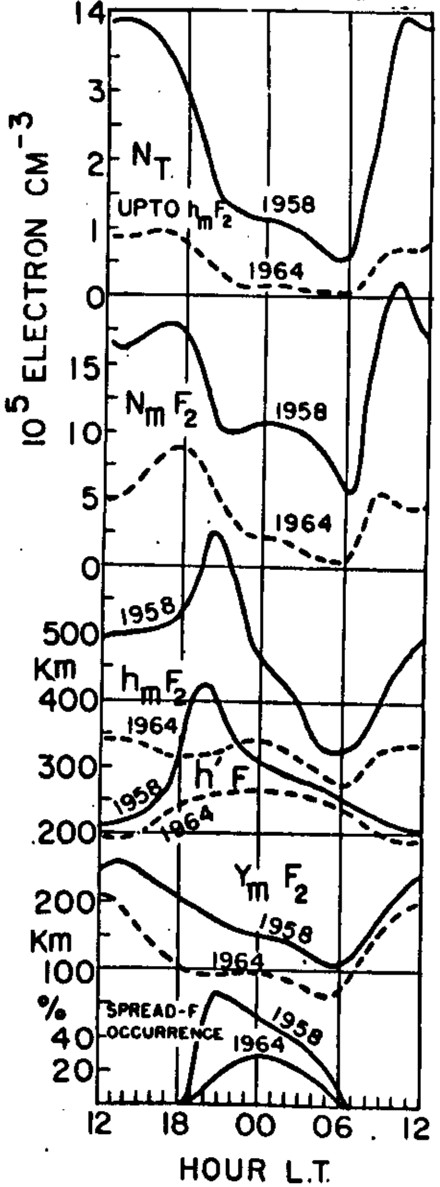


Fig. 13

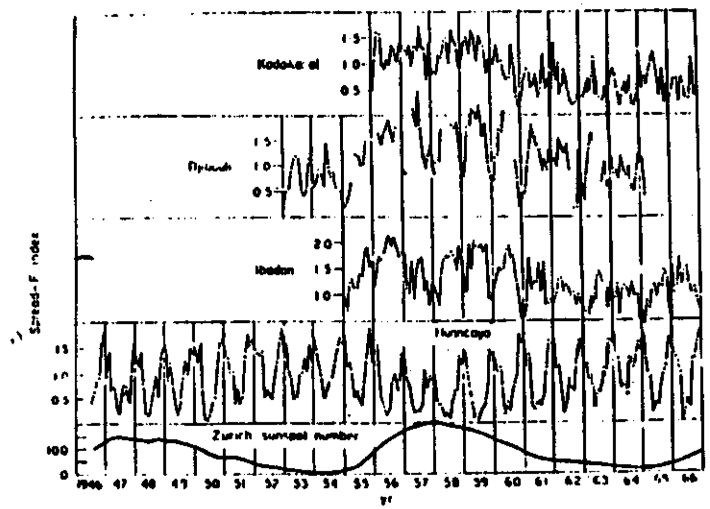


Fig. 1. Month to month variation of mean spread-F index at number of equatorial stations and of the Zurich sunspot number.

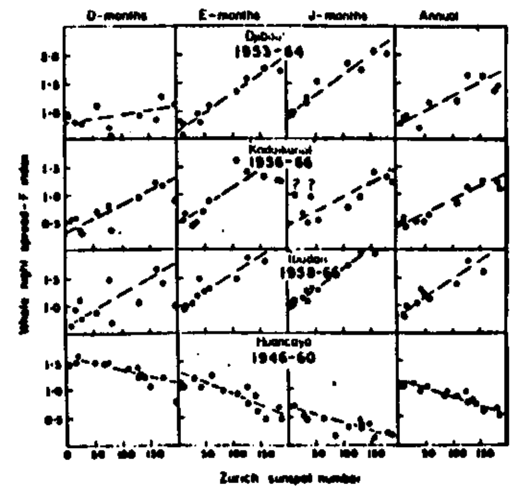


Fig. 2. Plots showing relations between spread-F index at number of equatorial stations and Zurich sunspot numbers for individual seasons.

Fig. 14.

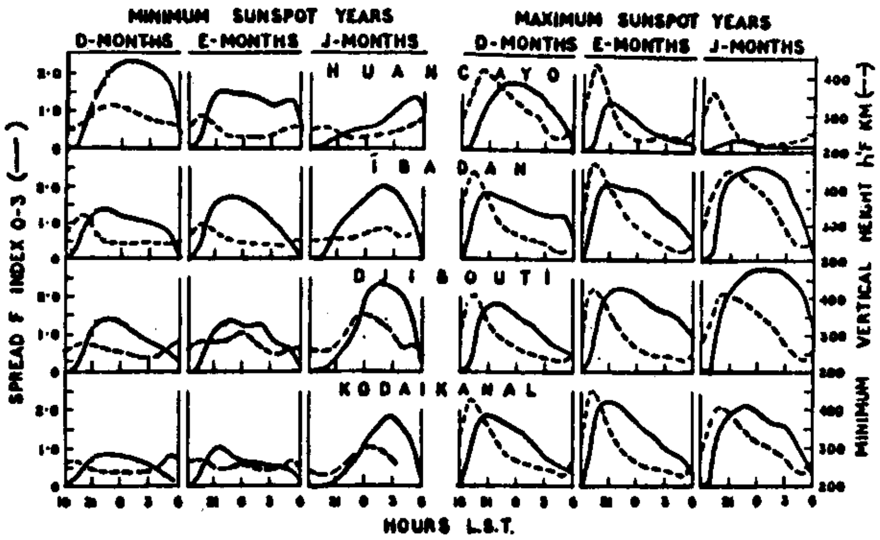
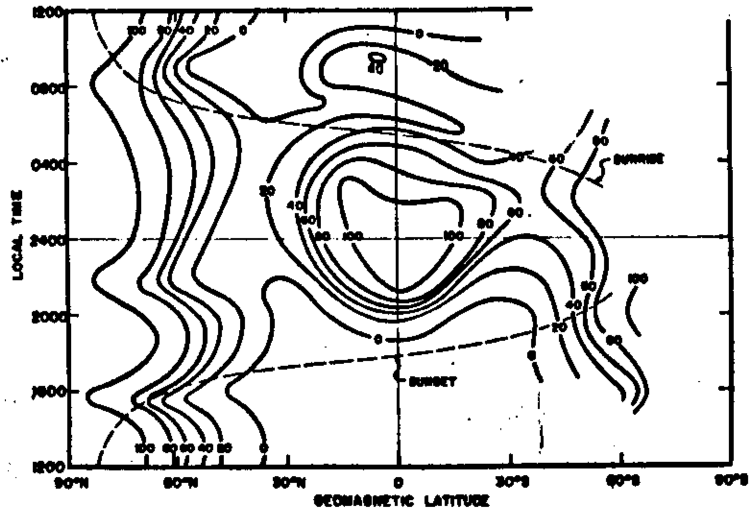


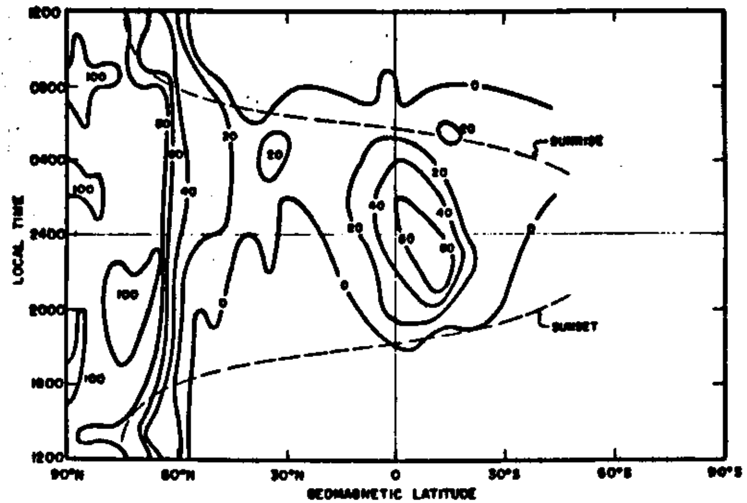
Fig. 3

The nocturnal variation of spread-F and h'F at equatorial stations, Huancayo, Ibadan, Djibouti and Kodaikanal averaged fo each season of the minimum and maximum sunspot years.

Fig. 15



The percentage occurrence of aspect-sensitive scattering observed by the Alouette topside sounder satellite. Ground sunset and sunrise for the middle of the observation period, November 14, is indicated.



The percentage occurrence of frequency spreading observed by ground-based ionosondes during the IGY. This figure has been adapted from *Singleton's* [1960] Figure 2c, preserving his curves for ground sunset and sunrise, at winter solstice.

Fig. 18

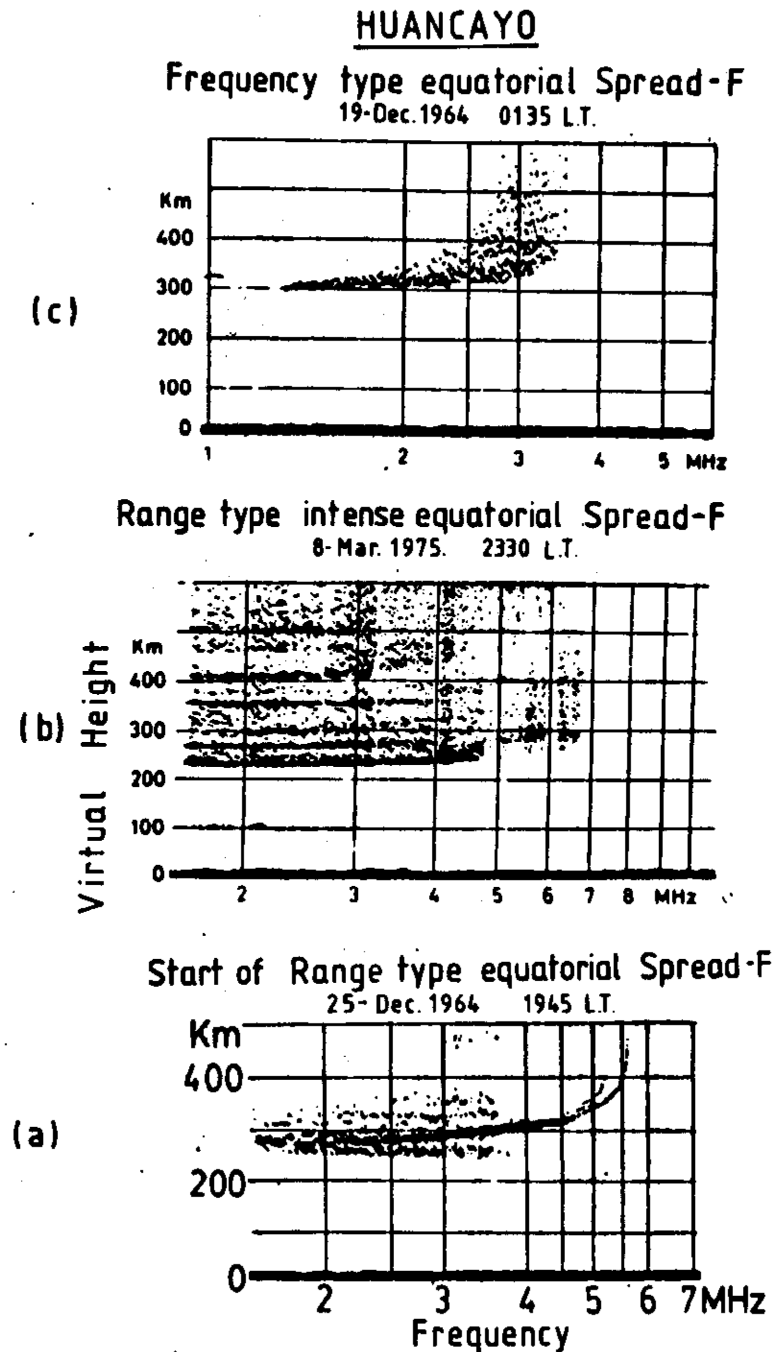
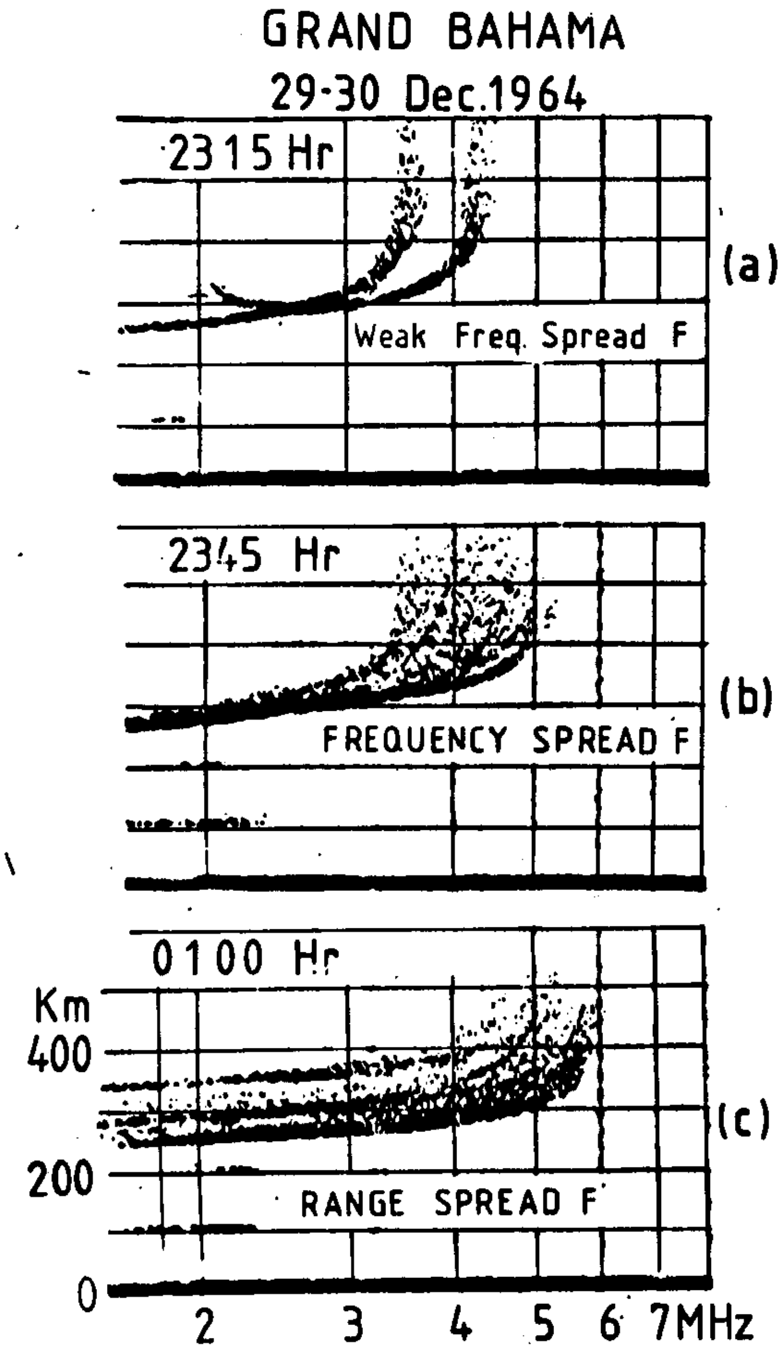
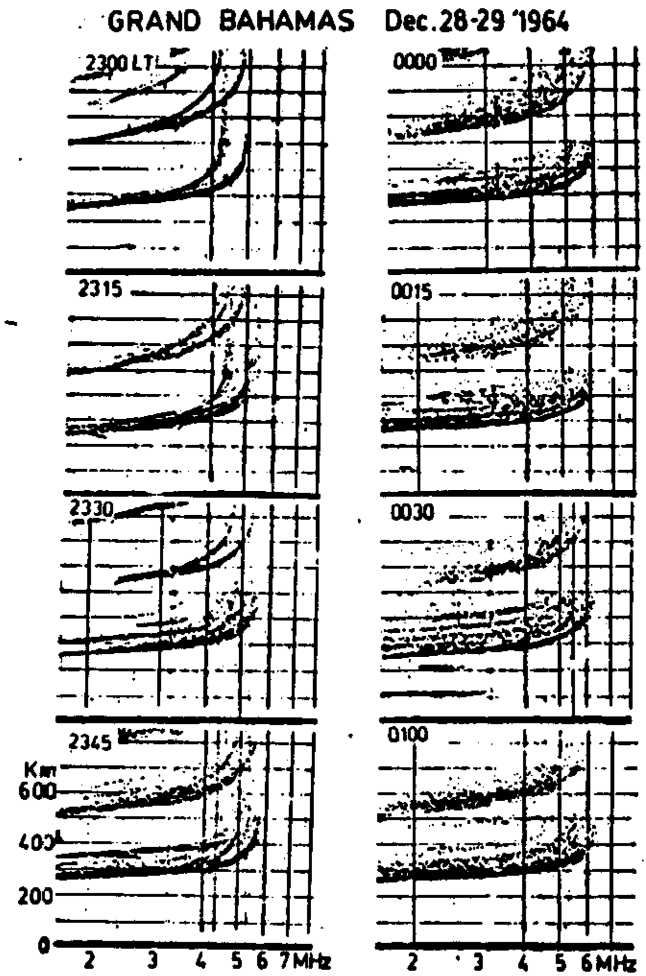


Fig. 17



GRAND BAHAMA
29-30 Dec.1964
2315 Hr
(a)
Weak Freq. Spread F
2345 Hr
(b)
FREQUENCY SPREAD F
0100 Hr
Km
400
(c)
200
RANGE SPREAD F
0
2
3
4
5
6
7MHz

Fig 18



GRAND BAHAMAS Dec.28-29 1964
2300 LT
0000
2315
0015
2330
0030
2345
0100
Km
600
400
200
0
2 3 4 5 6 7MHz
2 3 4 5 6MHz

Fig. 19

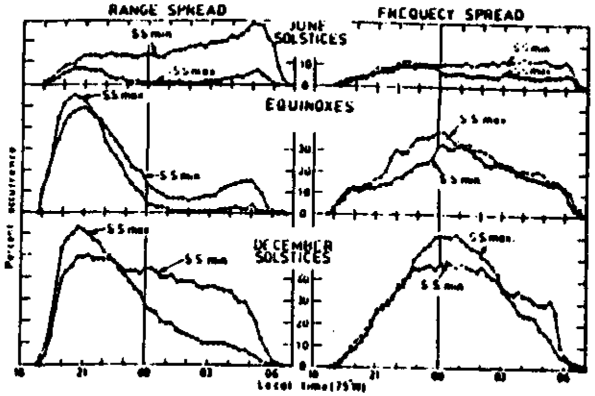


Fig. 3. Average nocturnal variations of the occurrence of range and frequency types of spread-F at Huancayo during different seasons of minimum and maximum sunspot years. Note comparatively more frequent occurrence of range spread during after midnight hours of ss min than ss max years.

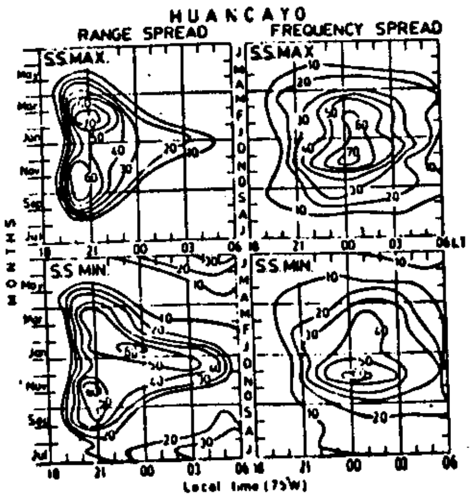


Fig. 4. Contours of constant occurrence probability of range and frequency spread-F at Huancayo during years of minimum and maximum sunspots plotted on a grid of local time and months of the year. Note that contours for frequency spread are similar for the two epochs with maximum occurrence at midnight around Dec.-Jan. months. Range spread during ss max years shows peaks at 2100 LT in February and November months with practically no spread during June, during ss min years changes occur for post midnight spread becoming more frequent and showing another peak around 04-05 LT in June-July.

Fig 20

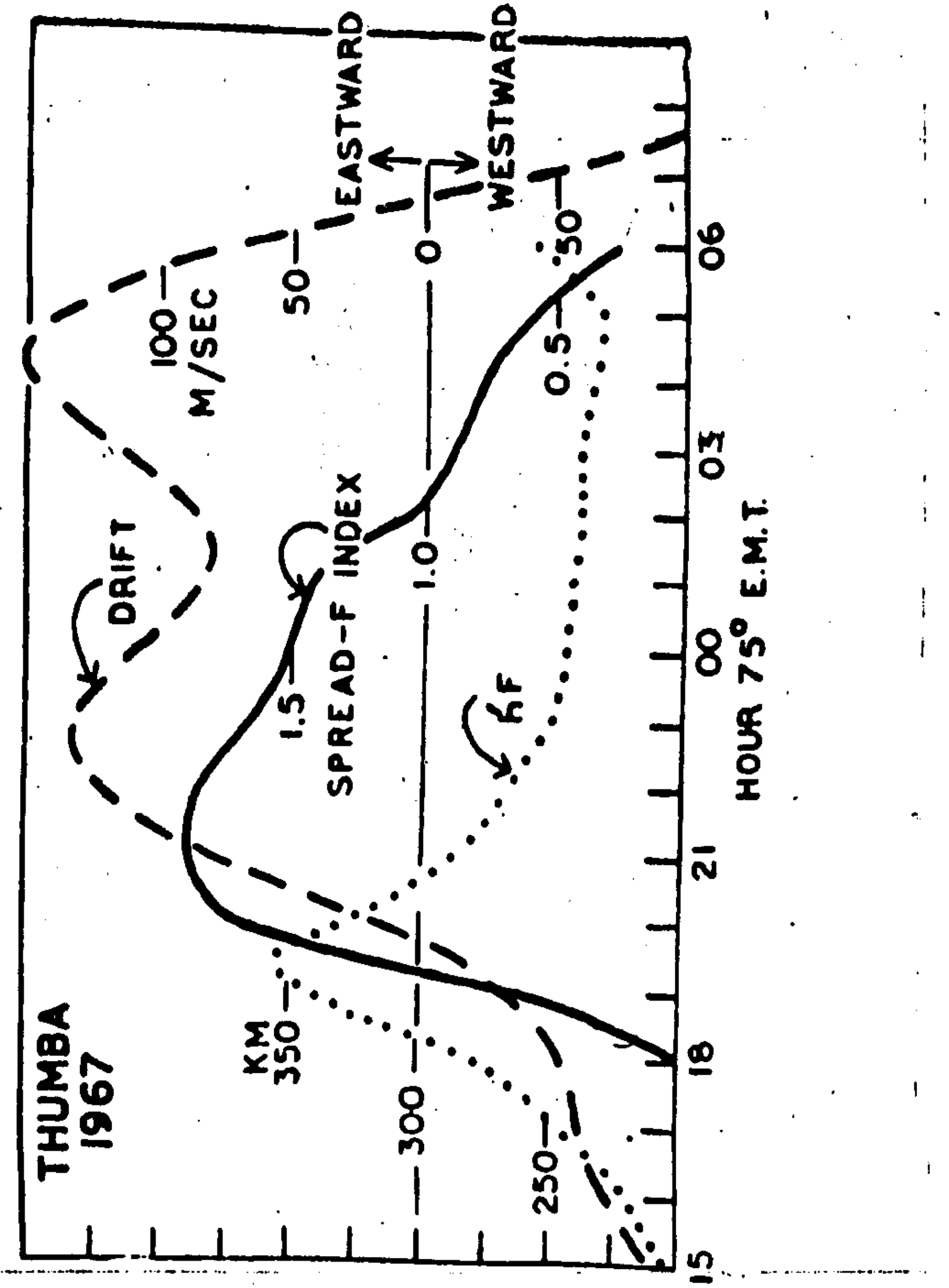


Fig. 21

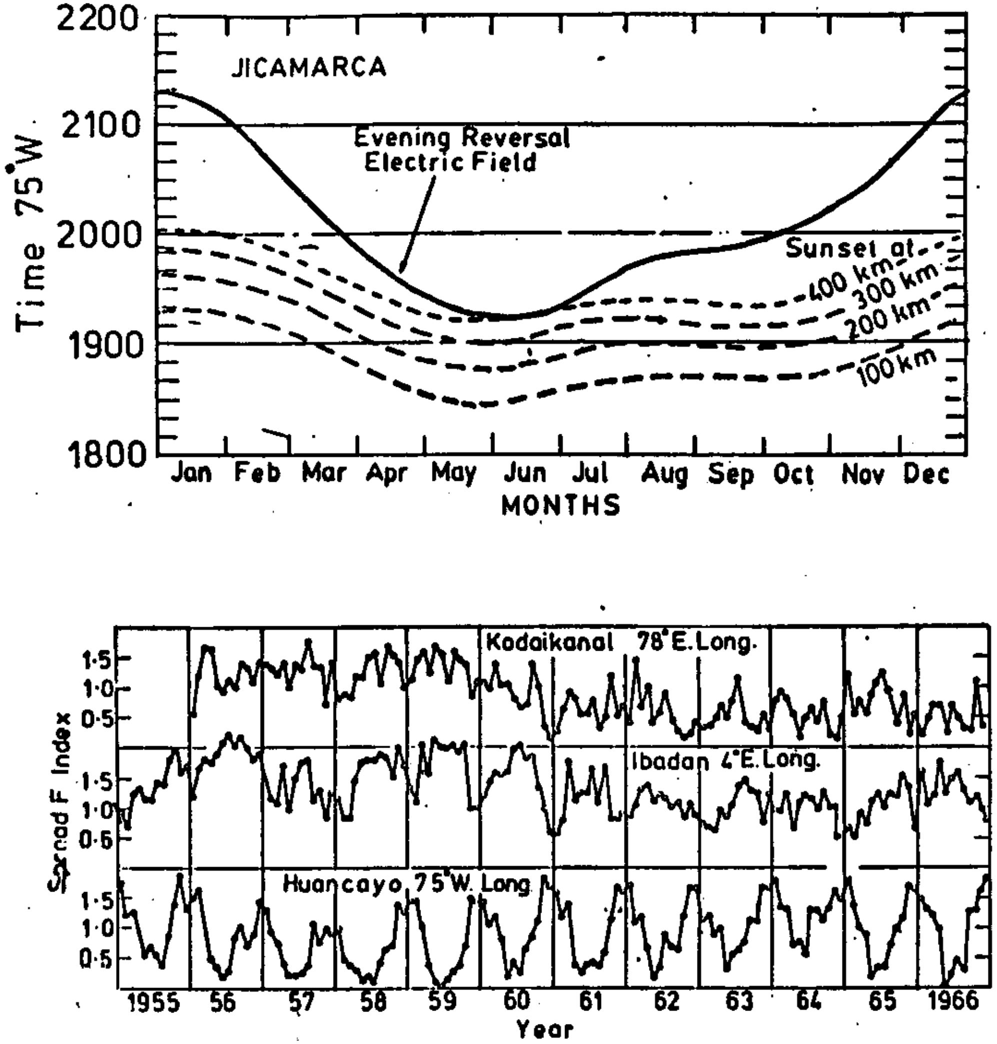


Fig. 22

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 85, NO. A2, PAGES 722-726, FEBRUARY 1, 1980

Seasonal Variation of Equatorial Spread *F* in the American and Indian Zones

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The occurrence of postsunset range type of spread *F* at Huancayo (in the American zone) shows a very consistent and strong seasonal variation with maximum around December and minimum around June solstices during any of the years of solar cycle epoch. The occurrence of range spread *F* at Kodaikanal (in the Indian zone) does not indicate any significant seasonal variation. It is suggested that the range type of equatorial spread *F* is generated by the action of eastward electric field in the ionospheric region with large plasma density gradient present after sunset, provided enough time is available for the development of irregularities before the electric field reverses to the nighttime westward direction. In the American zone the reversal of the electric field during June solstice occurs in general at about the same time as the sunset at the *F* region heights, and the spread *F* irregularities do not get enough time to develop, while during December solstice the electric field reverses more than an hour after the layer sunset, and enough time is provided to the irregularities to develop and produce spread *F* echoes in the ionograms. In the Indian zone the time of the reversal of electric field varies very little with season. The occurrence of spread *F* depends on the day to day variation of the time interval between sunset and the reversal of the electric field. The equinoctial maxima in the occurrence of spread *F* is due to the corresponding maxima in the magnitude of the postsunset peak in the electric field.

CONCLUSIONS

It is suggested that the initial seeding of the irregularities in the equatorial ionosphere during the nighttime hours is due to the gradient drift instability mechanism and in the presence of favorable conditions, as described by *Ossakow et al.* [1979], these irregularities may develop into strong spread *F* configurations throughout the *F* layer by the Rayleigh-Taylor instability mechanism.

The conditions for starting spread *F* over the equator are (1) the nighttime condition in the *F* region, i.e., existence of strong plasma density gradients, (2) continuation of the daytime *Sq* electric field even after the sunset, i.e., the existence of eastward electric field, and (3) the continuation of the above two conditions for a period large enough for the growth of irregularities may be of the order of 1 hour or so.

Fig. 23

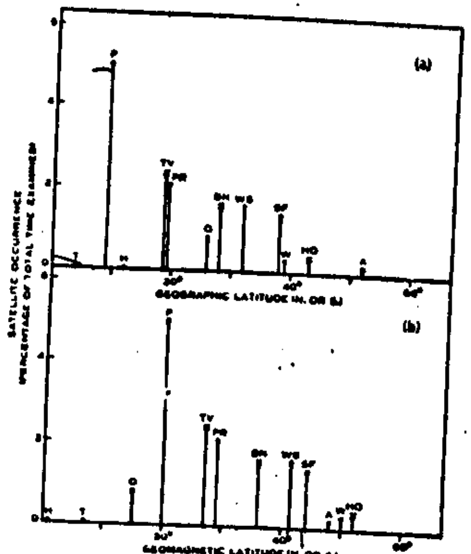
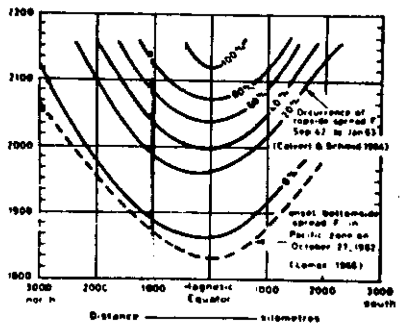


Fig. 1 (a).—Satellite occurrence versus geographic latitude.
Fig. 1 (b).—Satellite occurrence versus geomagnetic latitude.
Stations used: Adak (A), Huancayo (H), Okinawa (O), Panama (P), Puerto Rico (PR), San Francisco (SF), Talara (T), Washington (W), White Sands (WS), Townsville (TV), Brisbane (BN), Hobart (HO).

After McNicol and Bowman

Fig. 24



++ Local time dependence of the onset of bottomside spread-F the percentage occurrence of the topside spread-F with the distance of the station from the magnetic equator

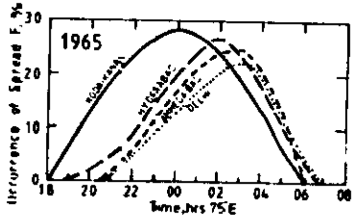
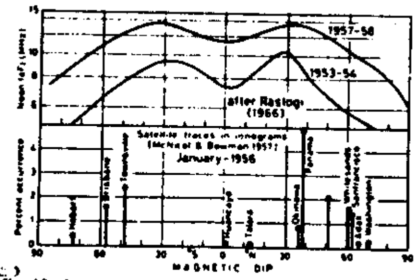


Fig. 13. Nocturnal variation of the present occurrence of spread-F echoes at Indian stations averaged for the year 1965

(a)



(C.)

Fig. 13 Latitudinal variation of the occurrence of range type of non-equatorial spread-F (after McNicol and Bowman) compared with latitudinal variation of midday critical frequency of the F2-layer (after Rastogi)

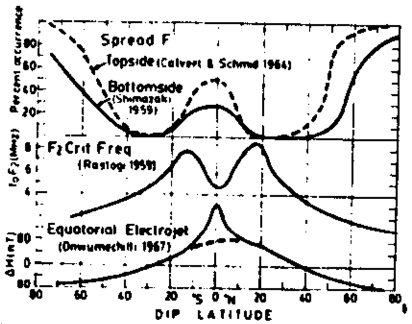
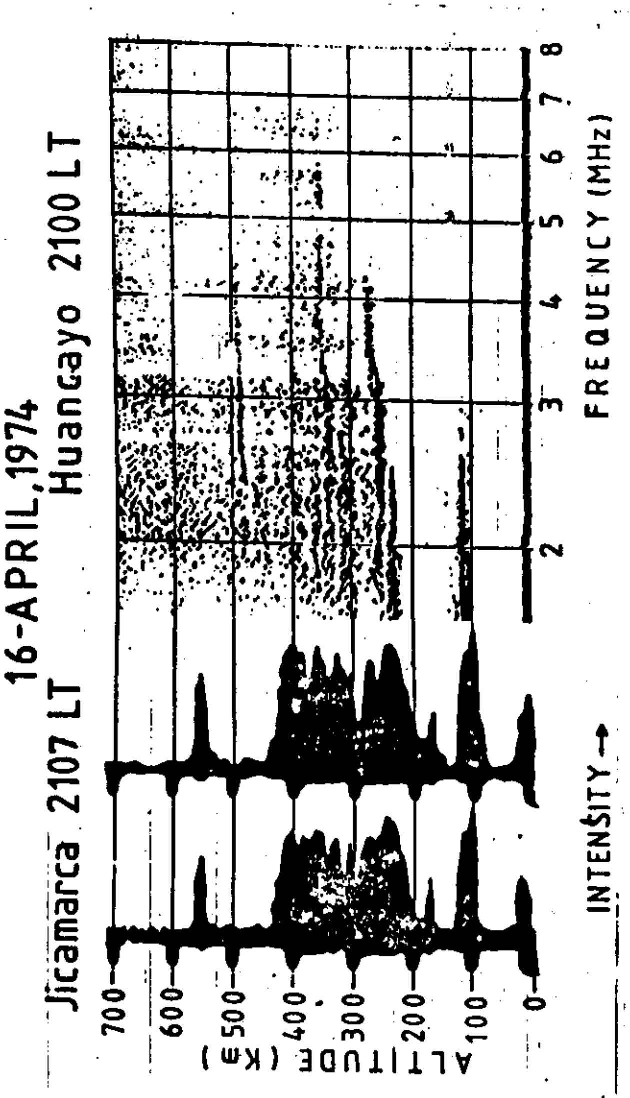


Fig. 14 Latitudinal comparisons of equatorial electrojet (after Onwumechili), critical frequency of the F2-layer of the ionosphere (after Rastogi), occurrence of bottomside spread-F (after Shimazaki) and of topside spread-F (after Calvert and Schmid)

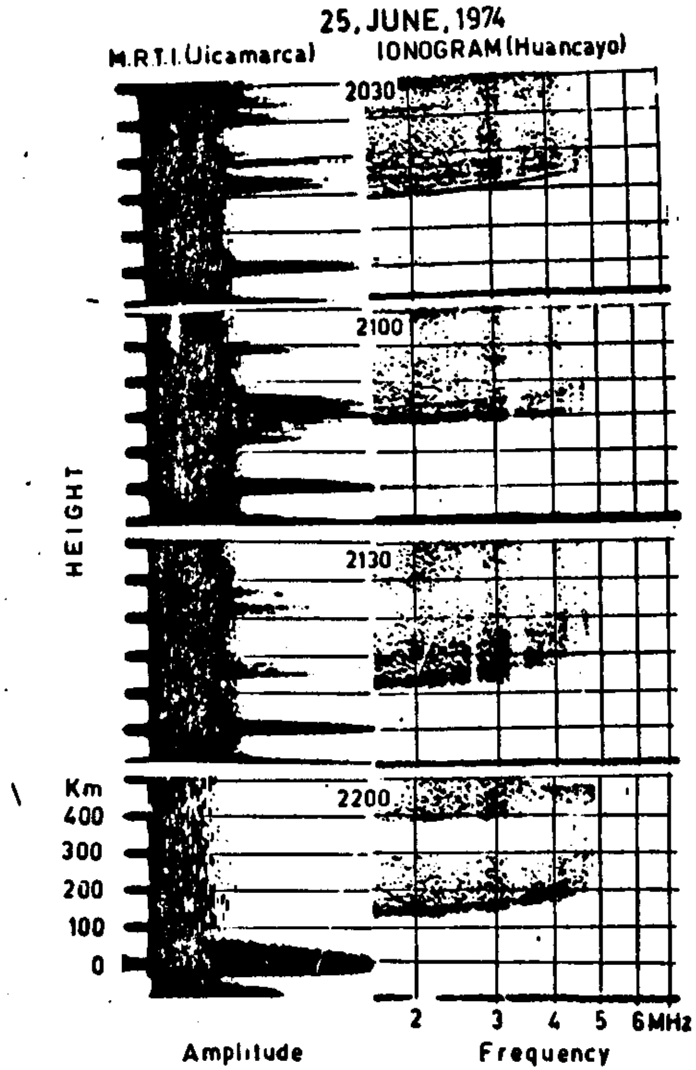
Fig 25

(d)



16-APRIL,1974
Huancayo 2100 LT
Jicamarca 2107 LT
FREQUENCY (MHz)
INTENSITY →
ALTITUDE (Km)

Fig. 26



25, JUNE, 1974
M.R.T.I.(Jicamarca)
IONOGRAM (Huancayo)
2030
2100
2130
2200
HEIGHT
Km
Amplitude
Frequency

Fig. 27

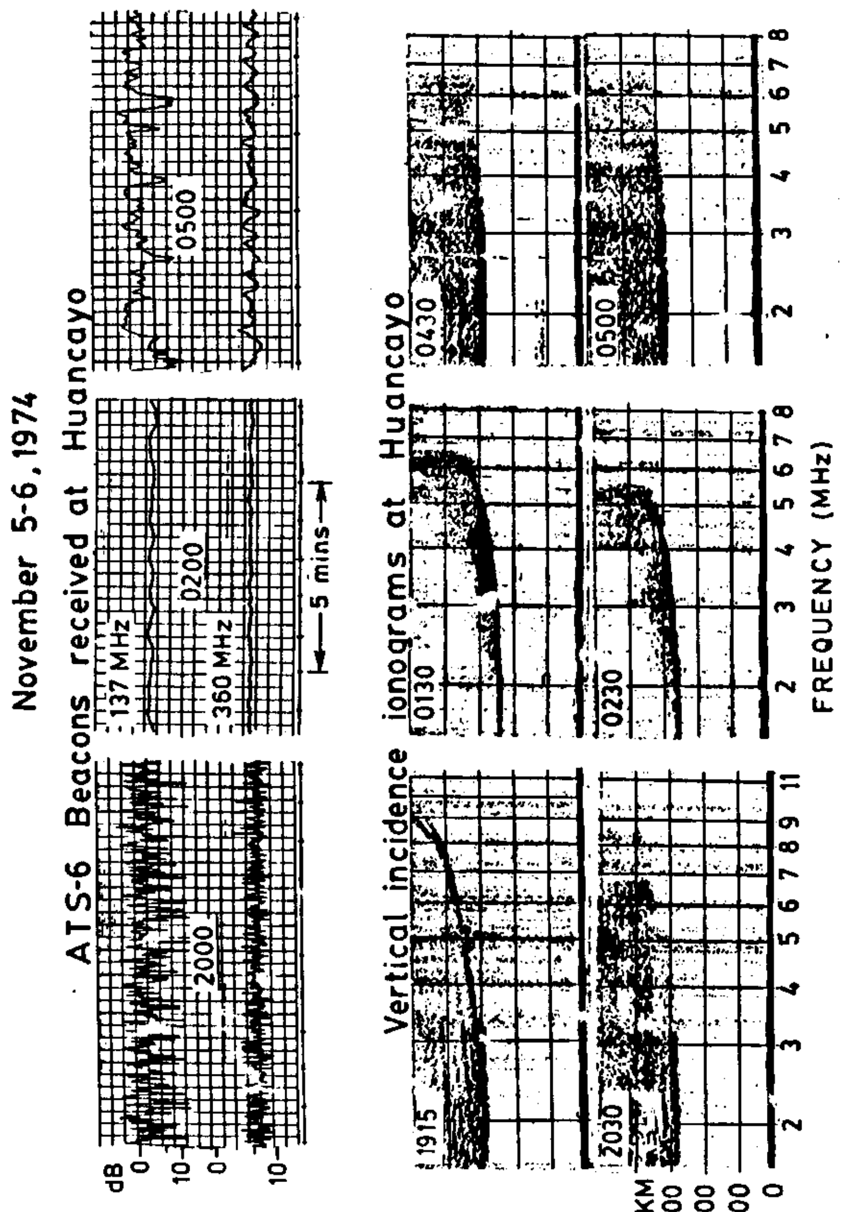

ATS-6 Beacons received at Huancayo
November 5-6, 1974
dB
137 MHz
360 MHz
2000
0200
0500
5 mins
Vertical incidence ionograms at Huancayo
1915
2030
0130
0230
0430
0500
KM
300
200
100
FREQUENCY (MHz)

Fig 28

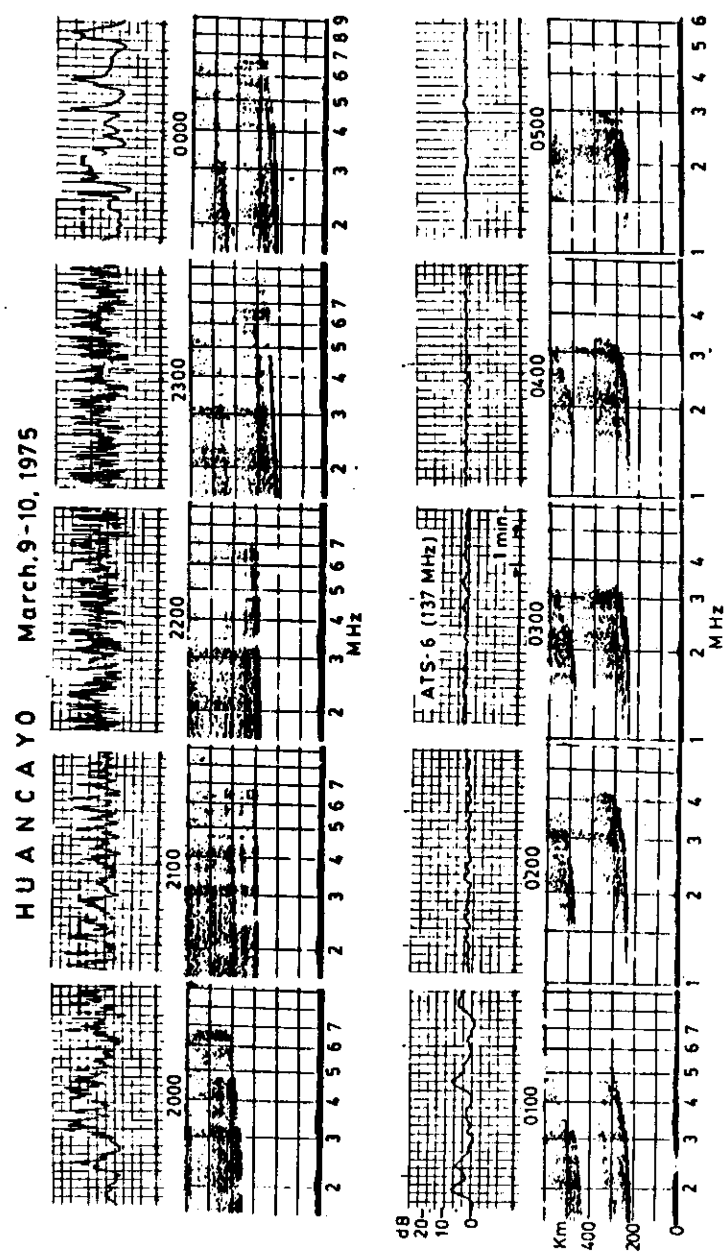
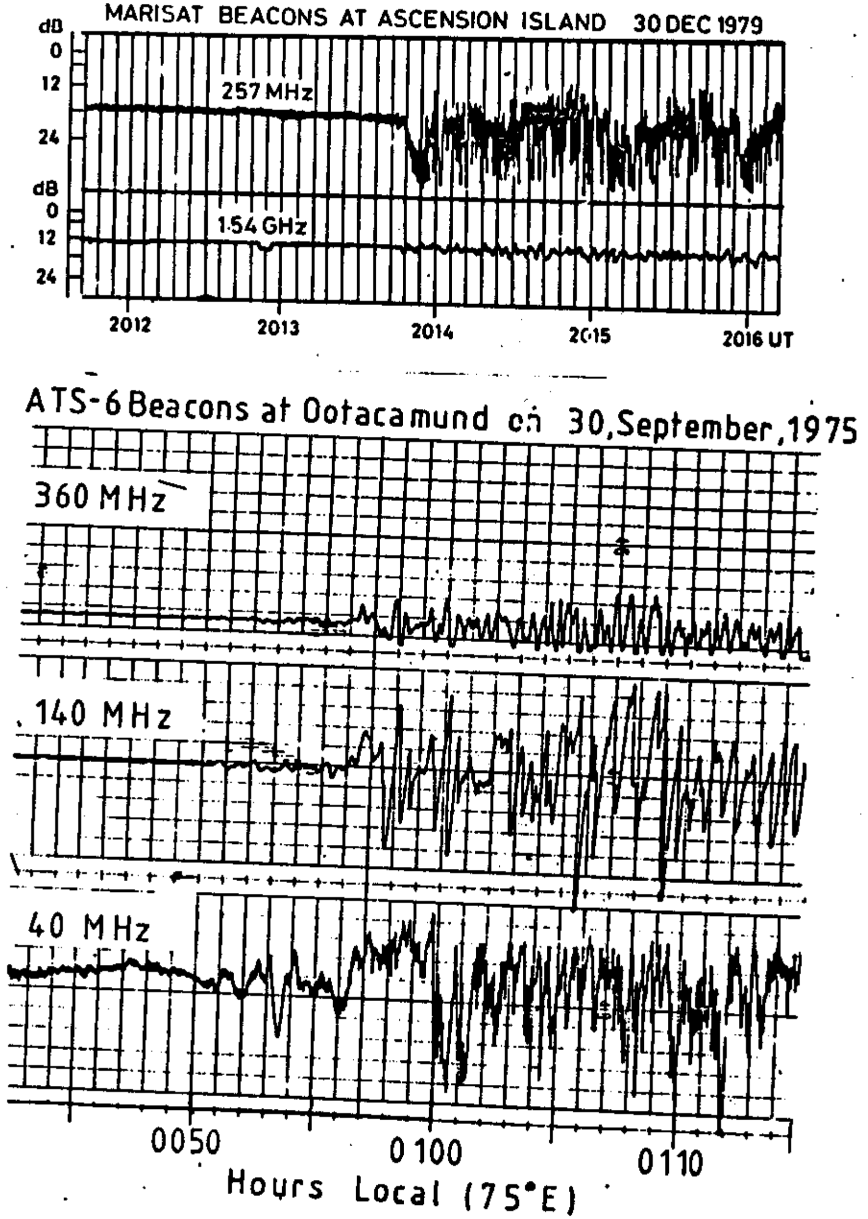

HUANCAYO March, 9-10, 1975
2000
2100
2200
2300
0000
0100
0200
0300
0400
0500
ATS-6 (137 MHz)
1 min
dB
Km
MHz

Fig 29



MARISAT BEACONS AT ASCENSION ISLAND 30 DEC 1979
dB
0
12
24
257 MHz
1.54 GHz
2012
2013
2014
2015
2016 UT
ATS-6 Beacons at Ootacamund on 30, September, 1975
360 MHz
140 MHz
40 MHz
0050
0100
0110
Hours Local (75°E)

Fig. 30

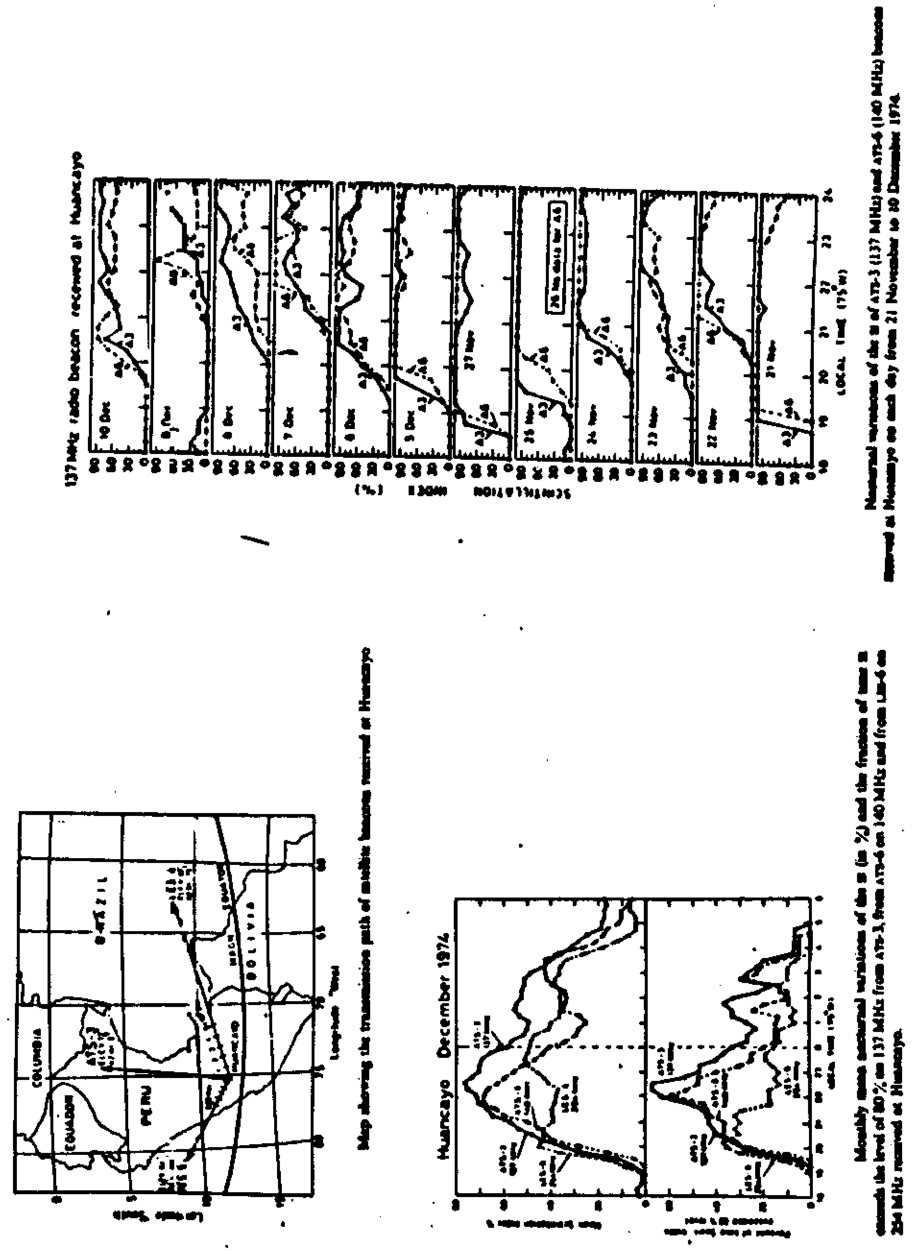
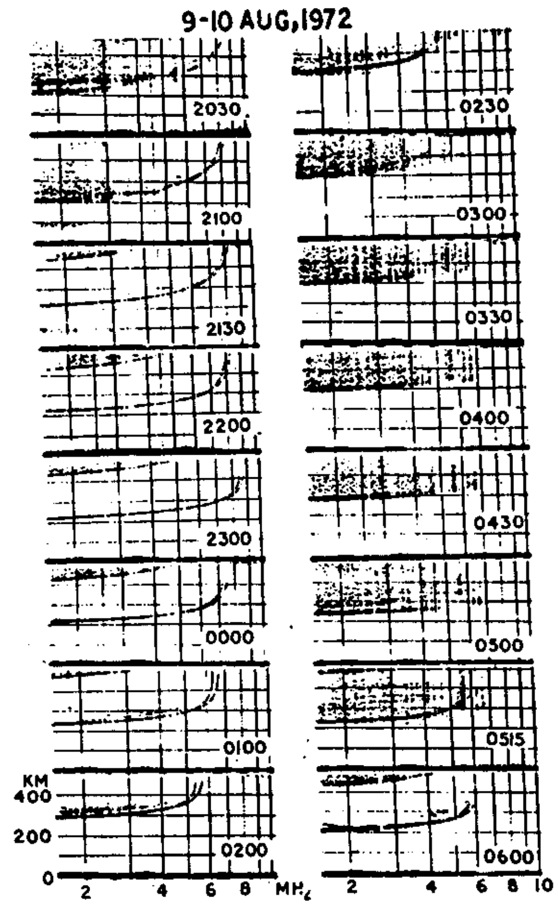


Fig. 31



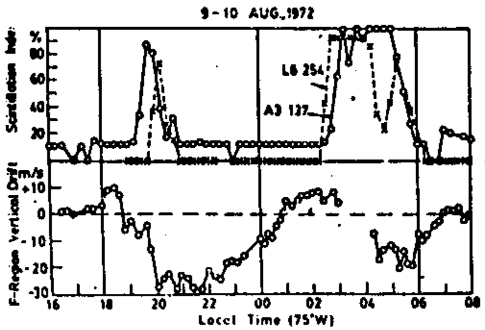
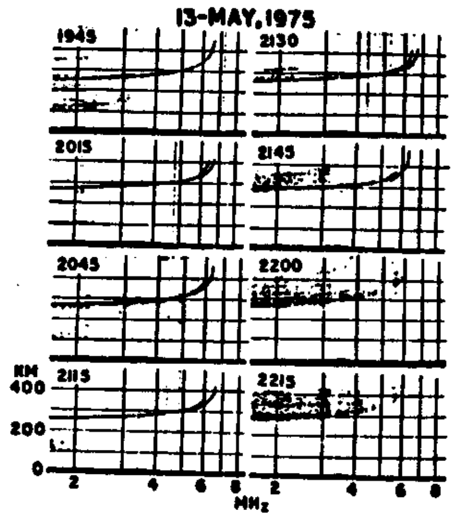


Fig. 5. Comparison of the temporal variations of the F-region vertical drift velocity at Jicamarca and the scintillation index of ATS-3 (137 MHz) and LES-6 (254 MHz) signals at Huancayo on 9-10 August 1972. Note usual evening scintillations around 2000 LT and the unusual appearance of scintillations after midnight at 0200 LT associated with the abnormal upward drifts in the F-region at 0100 LT.

Fig. ~~34~~ 32



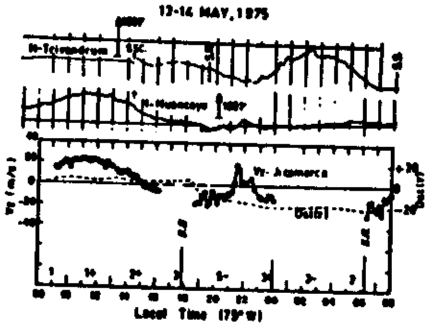


Fig. 33

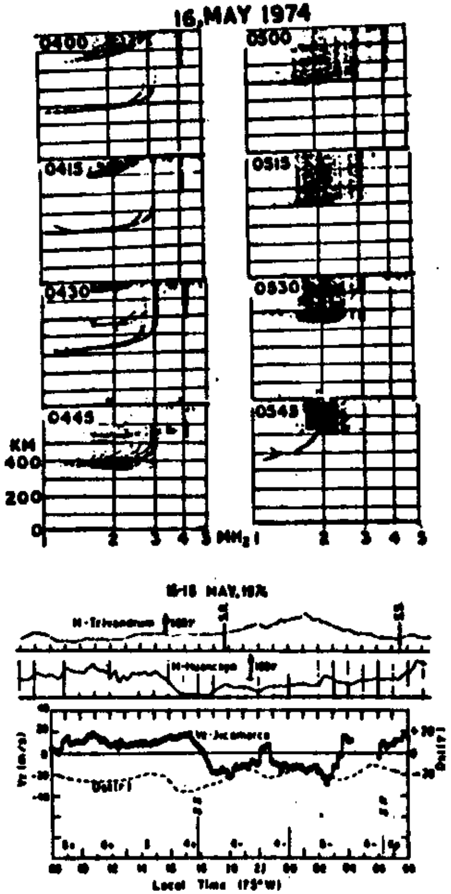

16 MAY 1974
0400
0415
0430
0445
0500
0515
0530
0545
KM
MHz
Local Time (75°W)

Fig 34

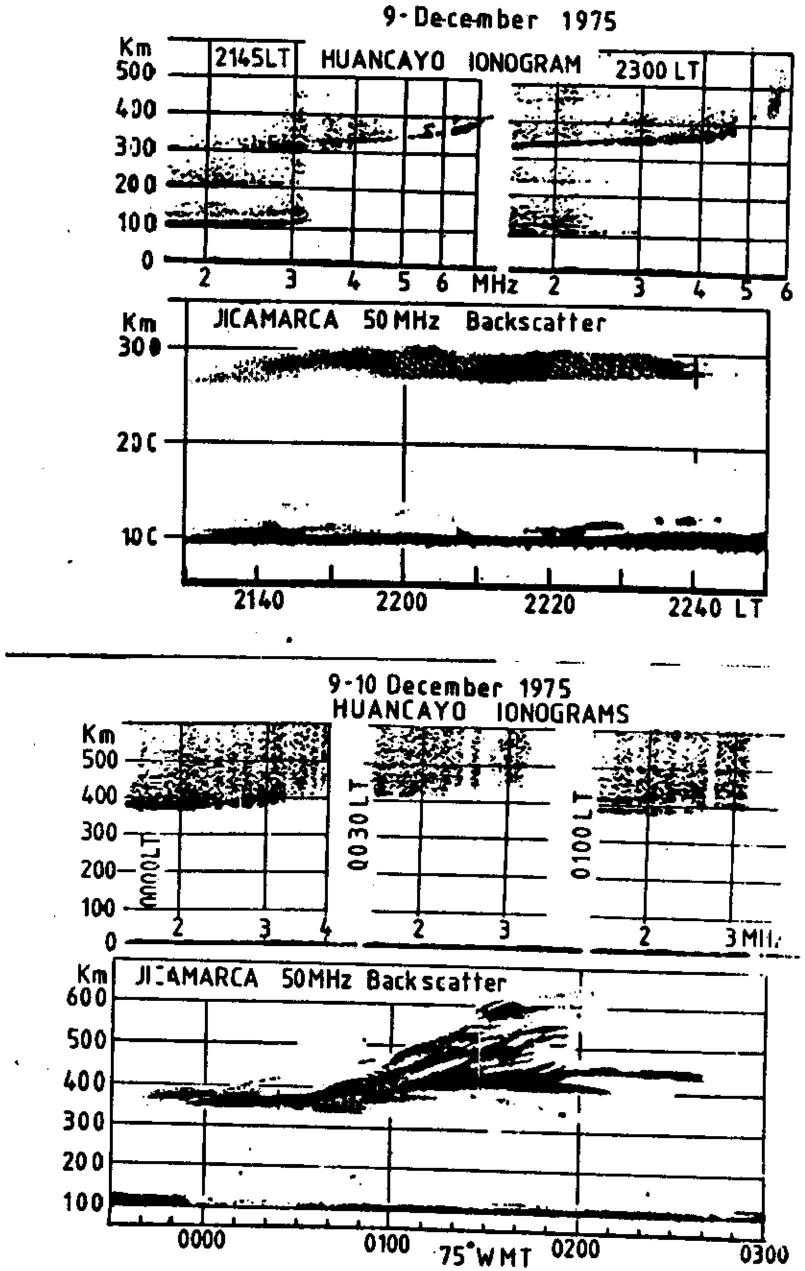

9-December 1975
2145LT
HUANCAYO IONOGRAM
2300 LT
Km
MHz
JICAMARCA 50 MHz Backscatter
LT
9-10 December 1975
HUANCAYO IONOGRAMS
0030 LT
0100 LT
JICAMARCA 50MHz Backscatter
75°WMT

Fig 35

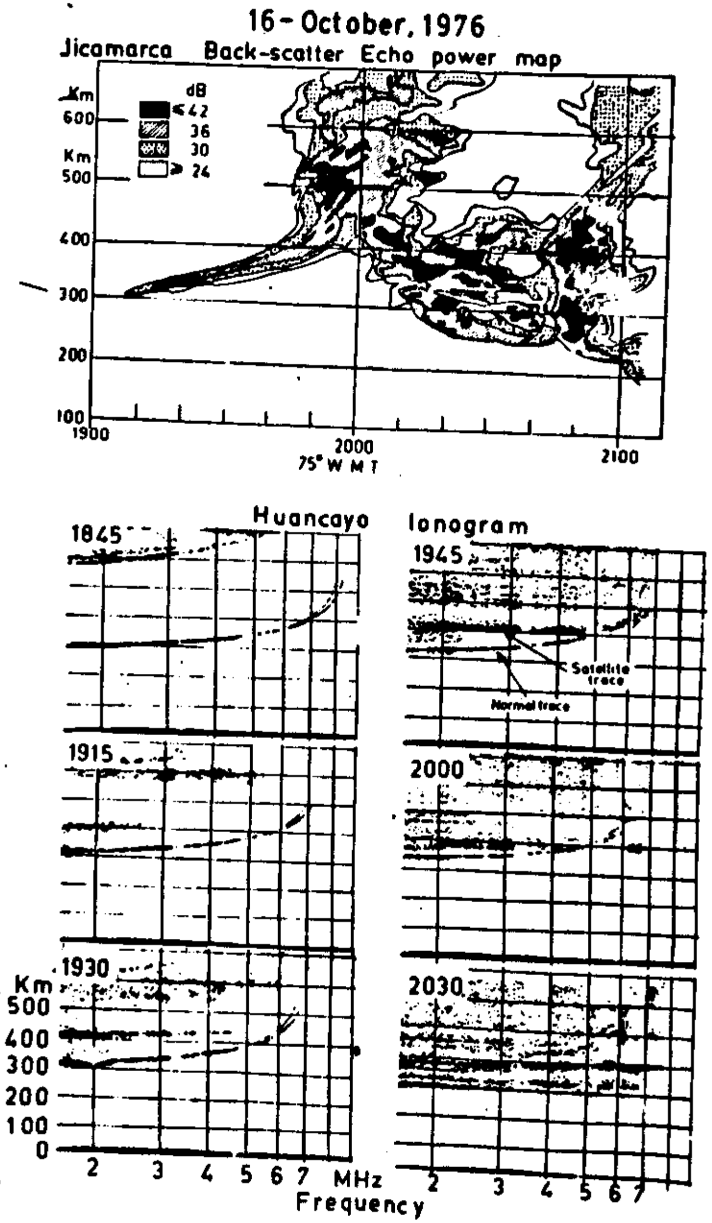

16-October, 1976
Jicamarca Back-scatter Echo power map
dB
Km
600
500
400
300
200
100
1900
2000
75° W M T
2100
Huancayo Ionogram
1845
1915
1930
1945
2000
2030
Satellite trace
Normal trace
Km
2 3 4 5 6 7 MHz
Frequency

Fig 36

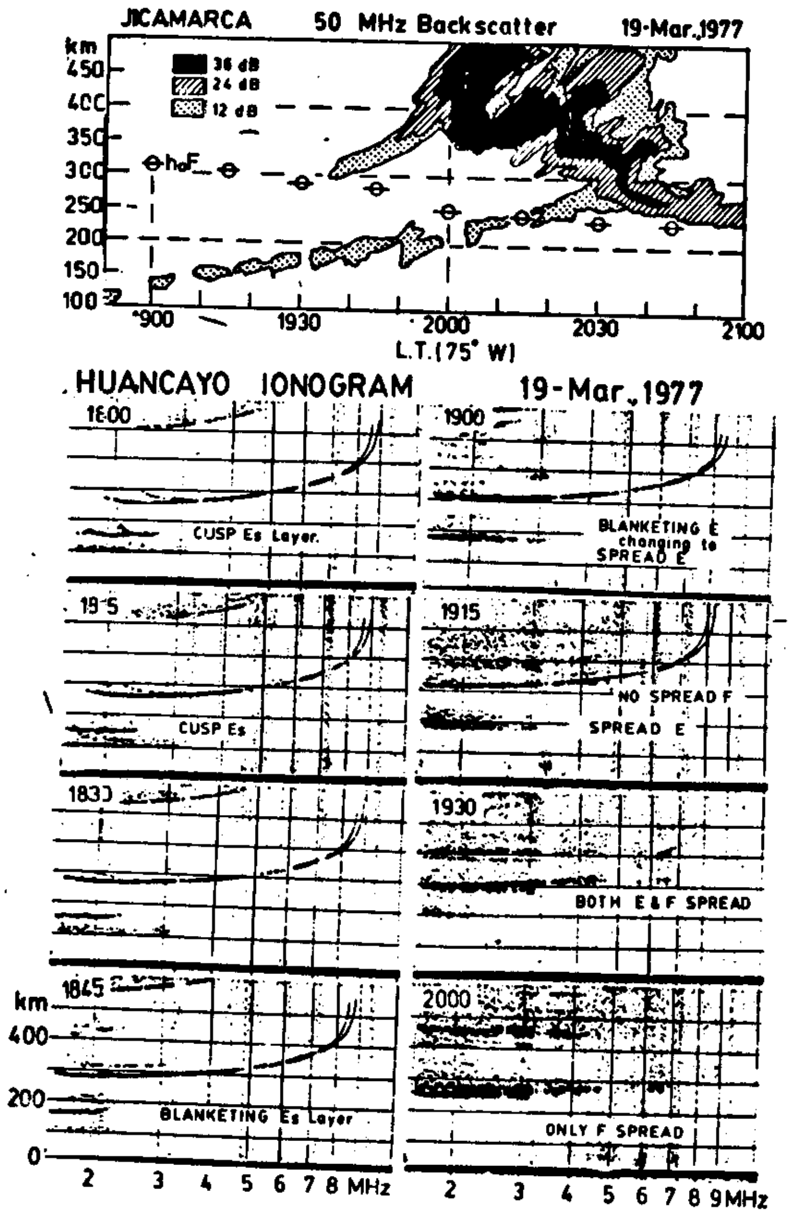

JICAMARCA 50 MHz Backscatter 19-Mar.,1977
km
36 dB
24 dB
12 dB
hoF
L.T.(75° W)
HUANCAYO IONOGRAM 19-Mar.,1977
CUSP Es Layer.
BLANKETING E changing to SPREAD E
CUSP Es
NO SPREAD F
SPREAD E
BOTH E & F SPREAD
BLANKETING Es Layer
ONLY F SPREAD
2 3 4 5 6 7 8 MHz
2 3 4 5 6 7 8 9MHz

Fig 37

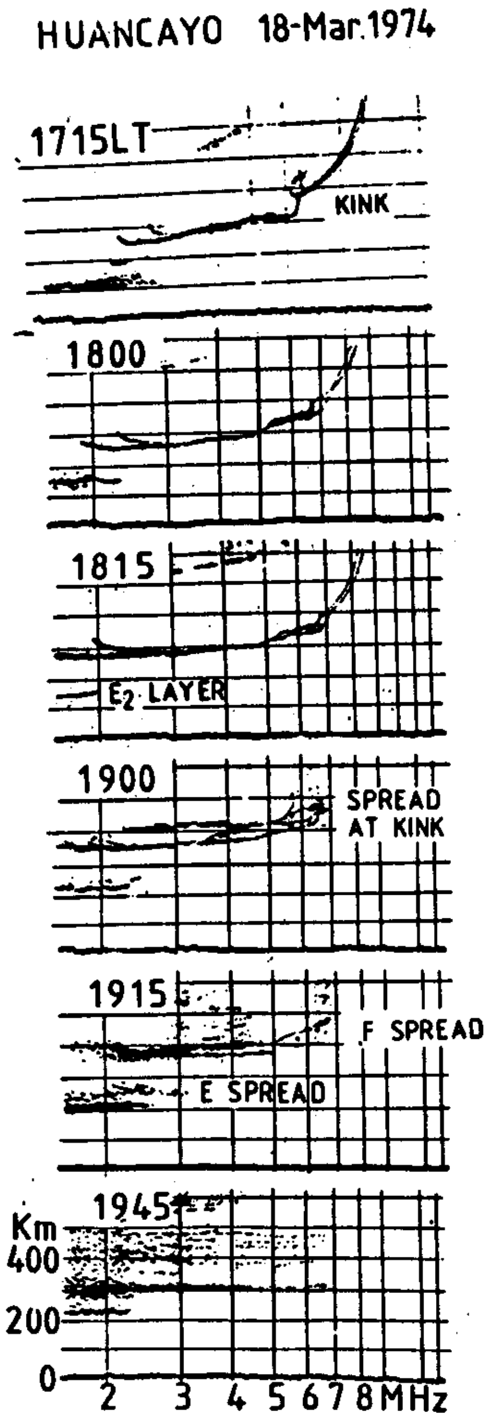

HUANCAYO 18-Mar.1974
1715LT
KINK
1800
1815
E2 LAYER
1900
SPREAD AT KINK
1915
F SPREAD
E SPREAD
1945
Km
400
200
0
2
3
4
5
6
7
8
MHz

Fig 38

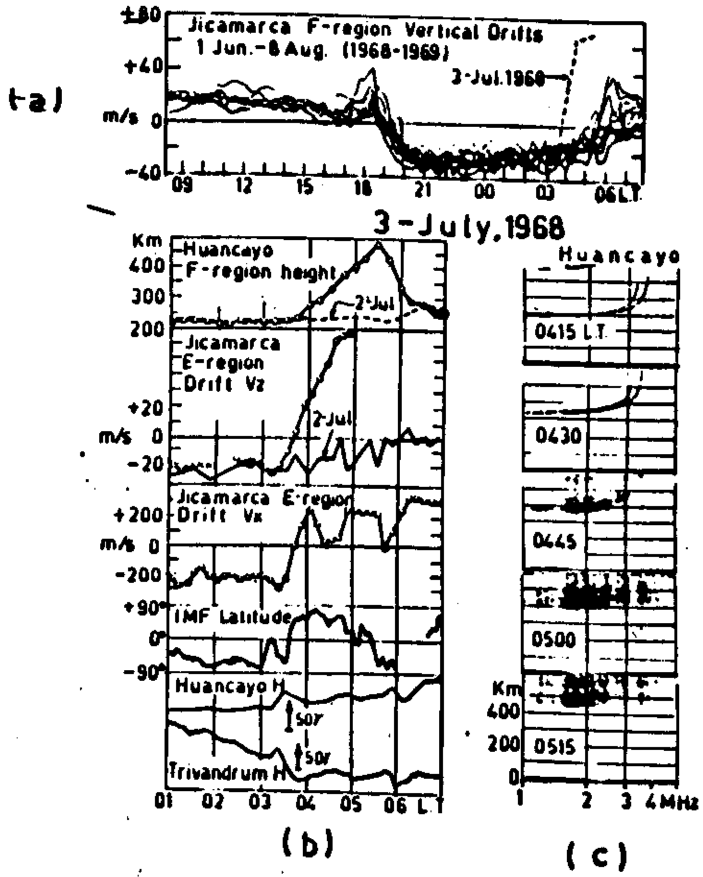
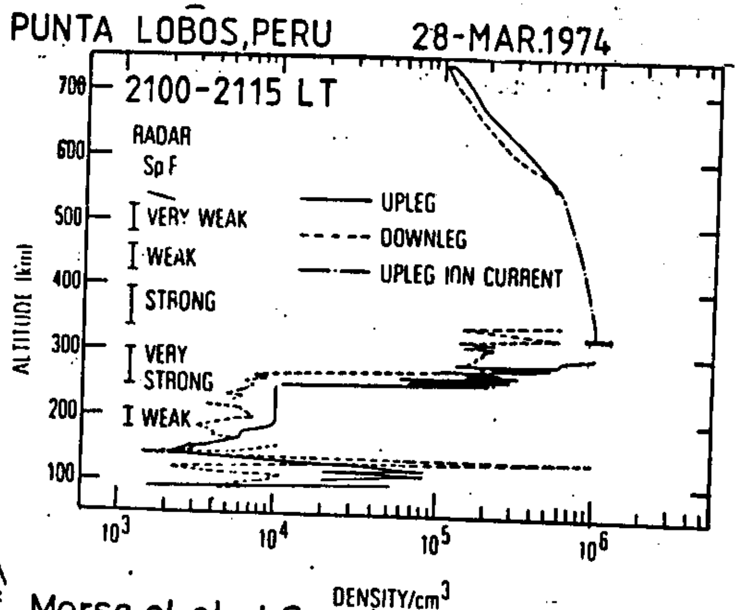
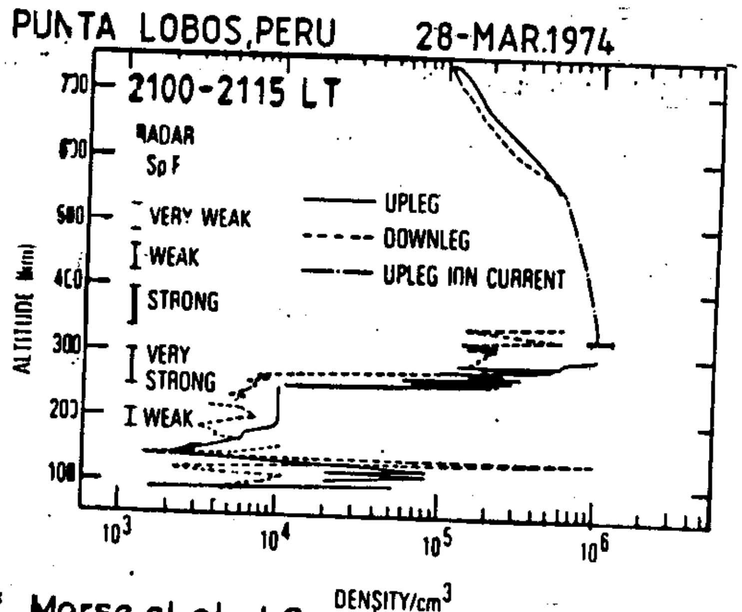

(a)
Jicamarca F-region Vertical Drifts
1 Jun.-8 Aug. (1968-1969)
3-Jul.1968
+80
+40
m/s 0
-40
09
12
15
18
21
00
03
06 L.T.
3-July,1968
Km
Huancayo F-region height
2 Jul
400
300
200
Jicamarca E-region Drift Vz
+20
m/s 0
-20
Jicamarca E-region Drift Vx
+200
m/s 0
-200
+90°
IMF Latitude
0°
-90°
Huancayo H
50γ
Trivandrum H
01
02
03
04
05
06 L.T.
(b)
Huancayo
0415 L.T.
0430
0445
0500
0515
Km
400
200
0
1
2
3
4 MHz
(c)

Fig. 39



Ref. Morse el.el. J.Geophys.Res. 82,578,1977



Ref. Morse el.el. J.Geophys.Res. 82,578,1977

Fig. 40

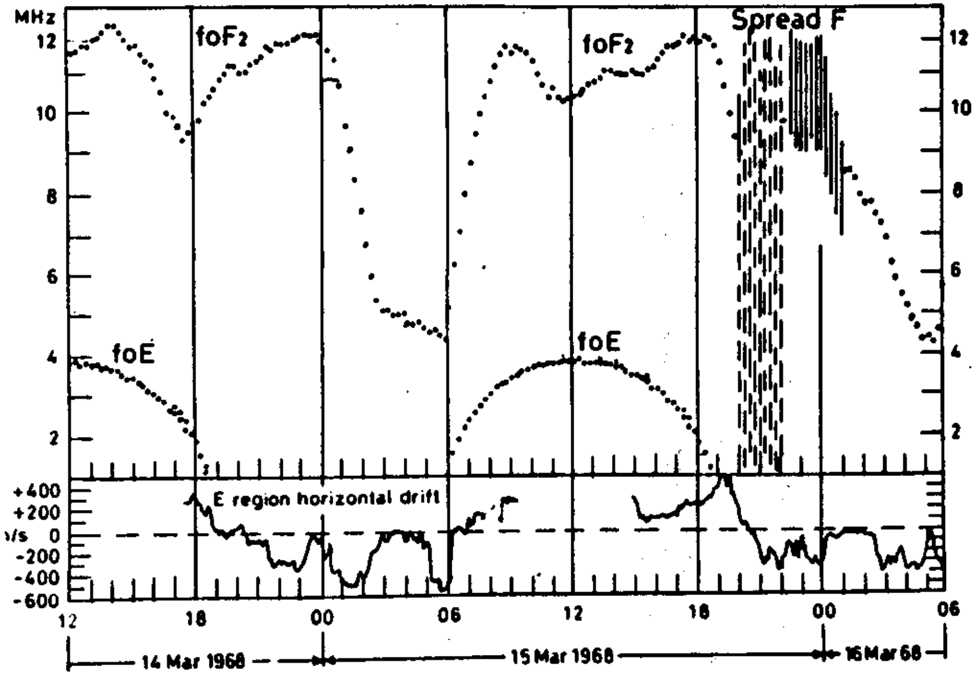

MHz
foF2
Spread F
foE
E region horizontal drift
m/s
14 Mar 1968
15 Mar 1968
16 Mar 68

Fig 41

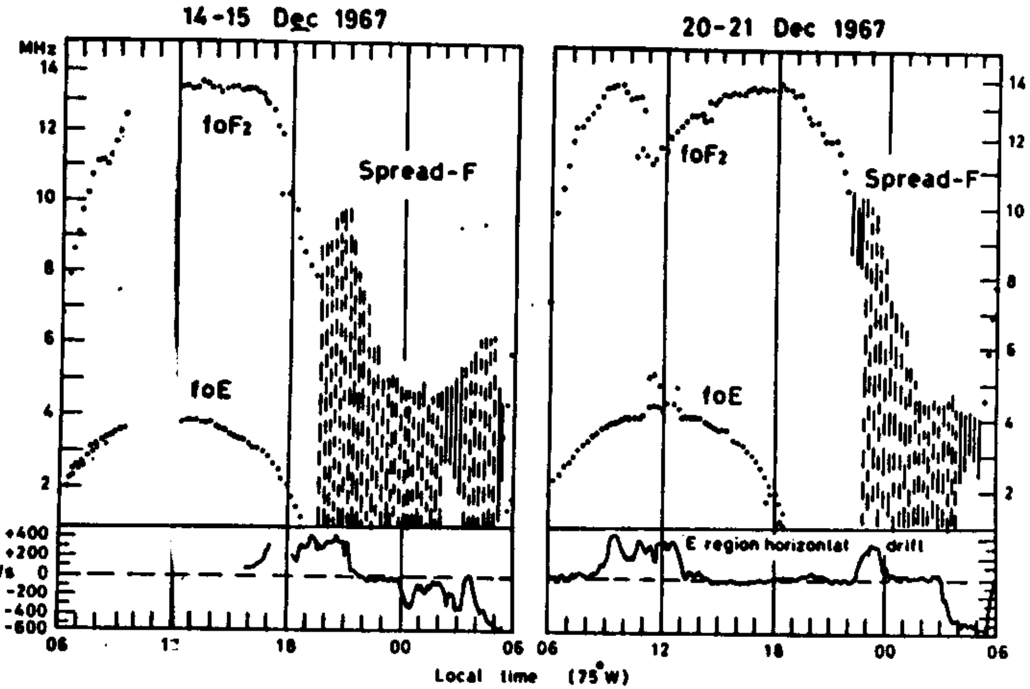

14-15 Dec 1967
20-21 Dec 1967
MHz
foF2
Spread-F
foE
E region horizontal drift
m/s
Local time (75°W)

Fig. 42

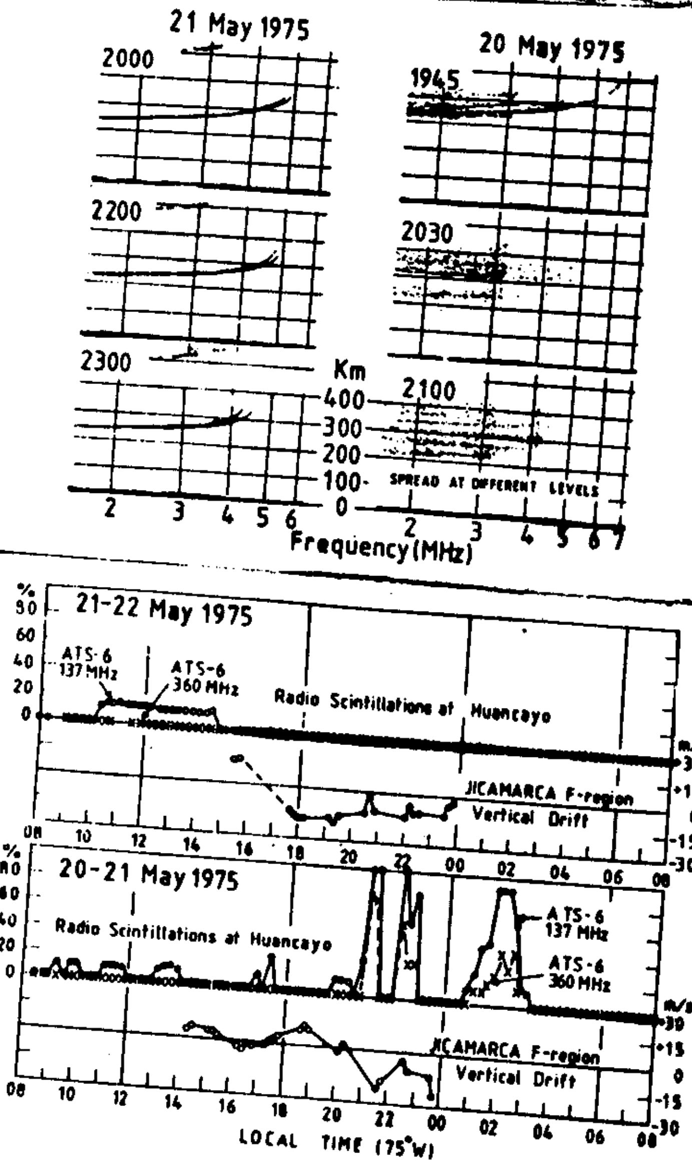

21 May 1975
20 May 1975
2000
1945
2200
2030
2300
2100
Km
400
300
200
100
0
SPREAD AT DIFFERENT LEVELS
Frequency (MHz)
21-22 May 1975
ATS-6 137 MHz
ATS-6 360 MHz
Radio Scintillations at Huancayo
JICAMARCA F-region Vertical Drift
20-21 May 1975
Radio Scintillations at Huancayo
ATS-6 137 MHz
ATS-6 360 MHz
JICAMARCA F-region Vertical Drift
LOCAL TIME (75°W)

Fig. 43

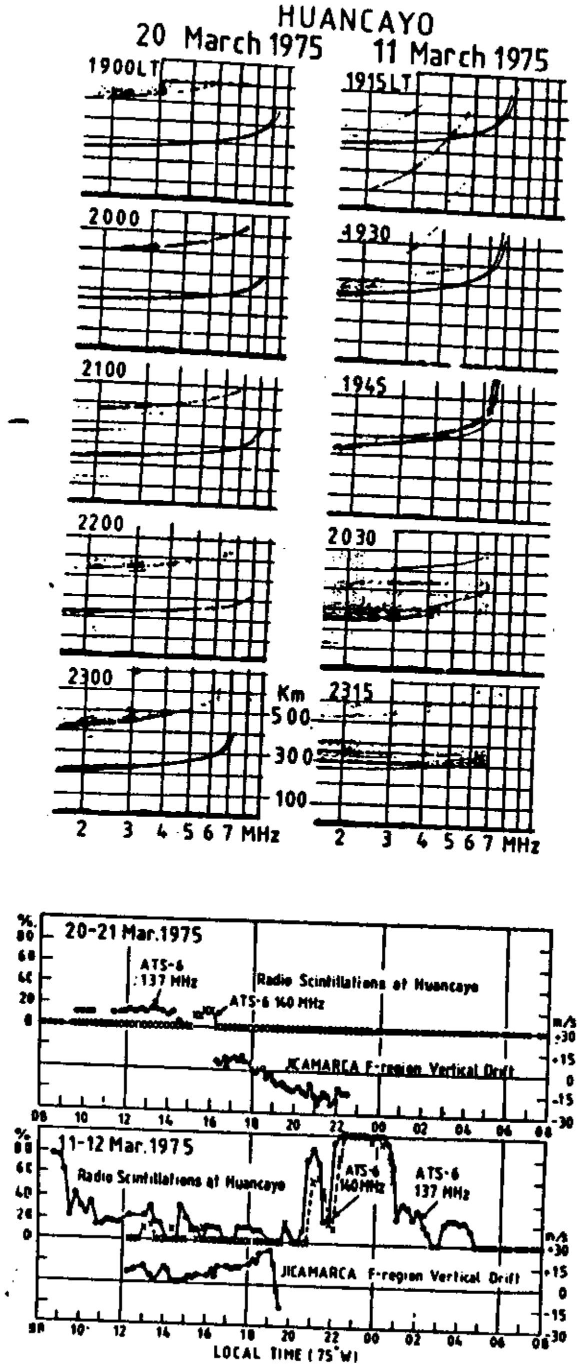

HUANCAYO
20 March 1975
11 March 1975
1900LT
1915LT
2000
1930
2100
1945
2200
2030
2300
2315
Km
500
300
100
MHz
20-21 Mar. 1975
ATS-6 137 MHz
Radio Scintillations at Huancayo
ATS-6 140 MHz
JICAMARCA F-region Vertical Drift
11-12 Mar. 1975
Radio Scintillations at Huancayo
ATS-6 140 MHz
ATS-6 137 MHz
JICAMARCA F-region Vertical Drift
LOCAL TIME (75°W)

Fig. 44

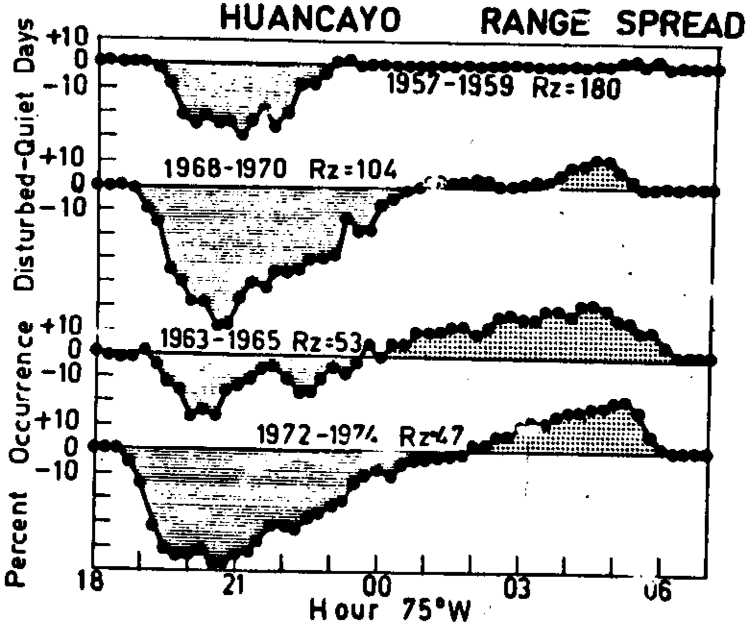

HUANCAYO RANGE SPREAD
1957-1959 Rz=180
1968-1970 Rz=104
1963-1965 Rz=53
1972-1974 Rz=47
Percent Occurrence Disturbed-Quiet Days
Hour 75°W

Fig 45

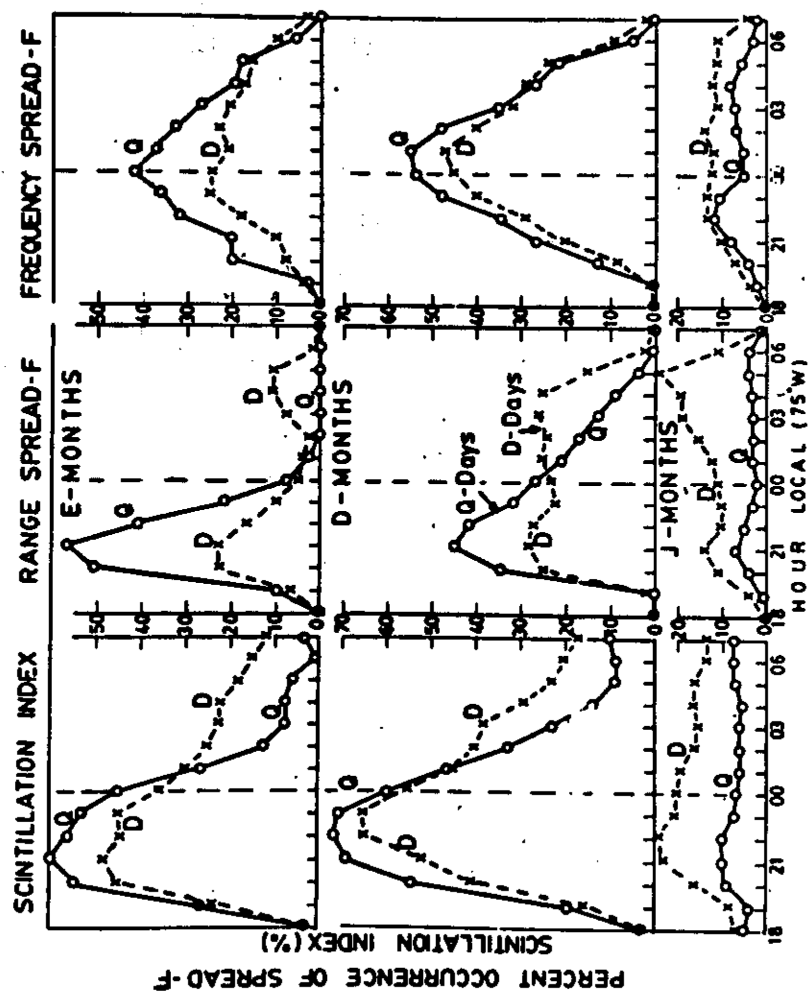
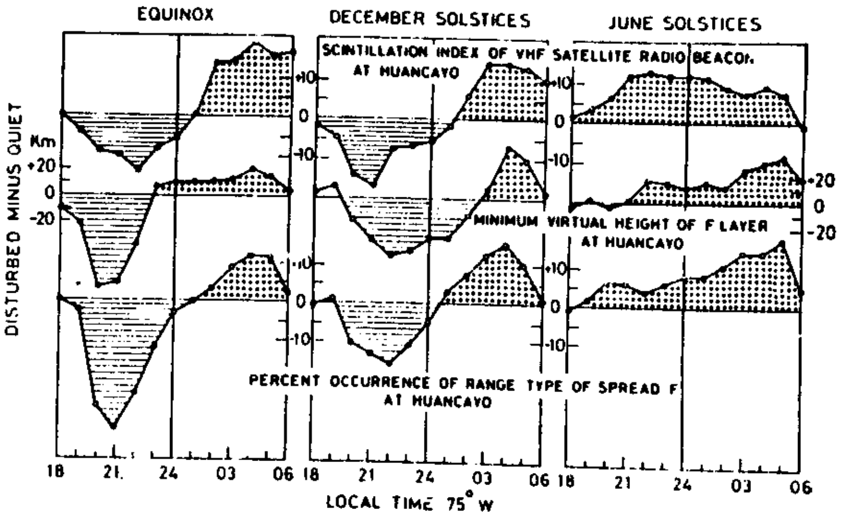
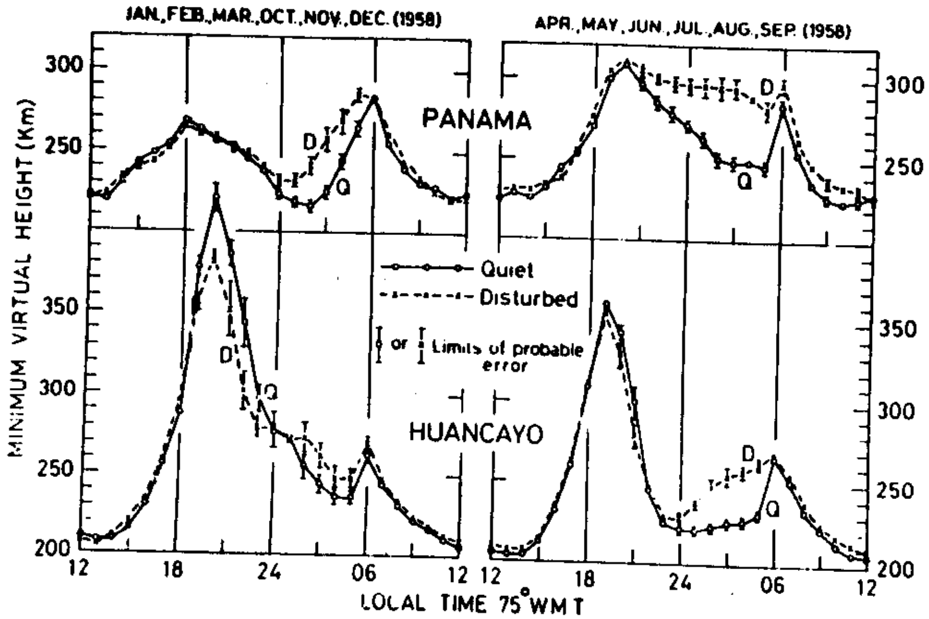

SCINTILLATION INDEX
RANGE SPREAD-F
FREQUENCY SPREAD-F
E-MONTHS
D-MONTHS
J-MONTHS
Q-Days
D-Days
HOUR LOCAL (75°W)
PERCENT OCCURRENCE OF SPREAD-F
SCINTILLATION INDEX (%)

Fig 46



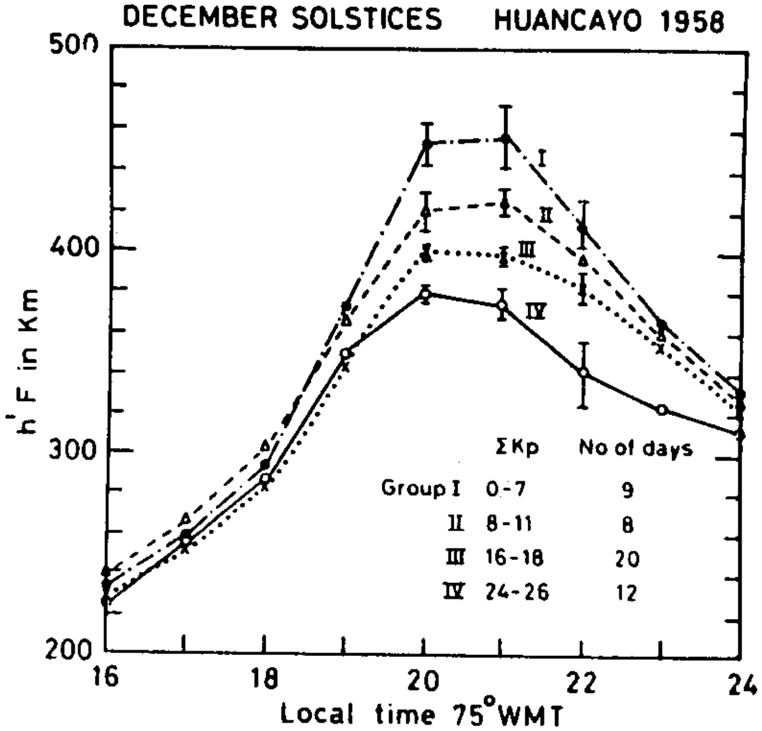
EQUINOX
DECEMBER SOLSTICES
JUNE SOLSTICES
SCINTILLATION INDEX OF VHF SATELLITE RADIO BEACON AT HUANCAYO
MINIMUM VIRTUAL HEIGHT OF F LAYER AT HUANCAYO
PERCENT OCCURRENCE OF RANGE TYPE OF SPREAD F AT HUANCAYO
DISTURBED MINUS QUIET
Km
LOCAL TIME 75° W

Fig 47



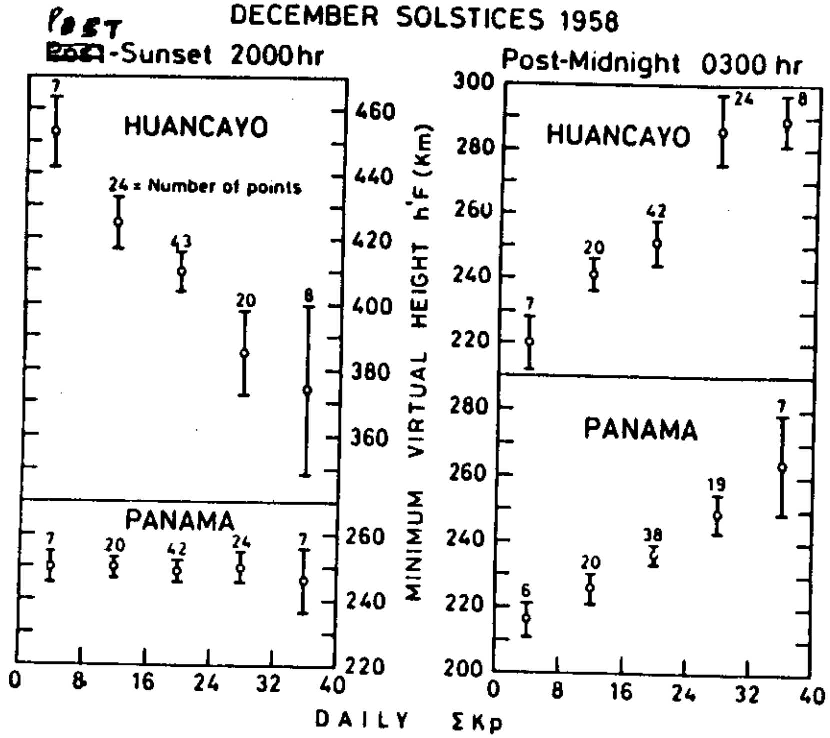
JAN., FEB., MAR., OCT., NOV., DEC. (1958)
APR., MAY, JUN., JUL., AUG., SEP. (1958)
PANAMA
HUANCAYO
MINIMUM VIRTUAL HEIGHT (Km)
Quiet
Disturbed
or Limits of probable error
LOCAL TIME 75° WMT

Fig 48



DECEMBER SOLSTICES HUANCAYO 1958
h'F in Km
Local time 75°WMT
ΣKp No of days
Group I 0-7 9
II 8-11 8
III 16-18 20
IV 24-26 12

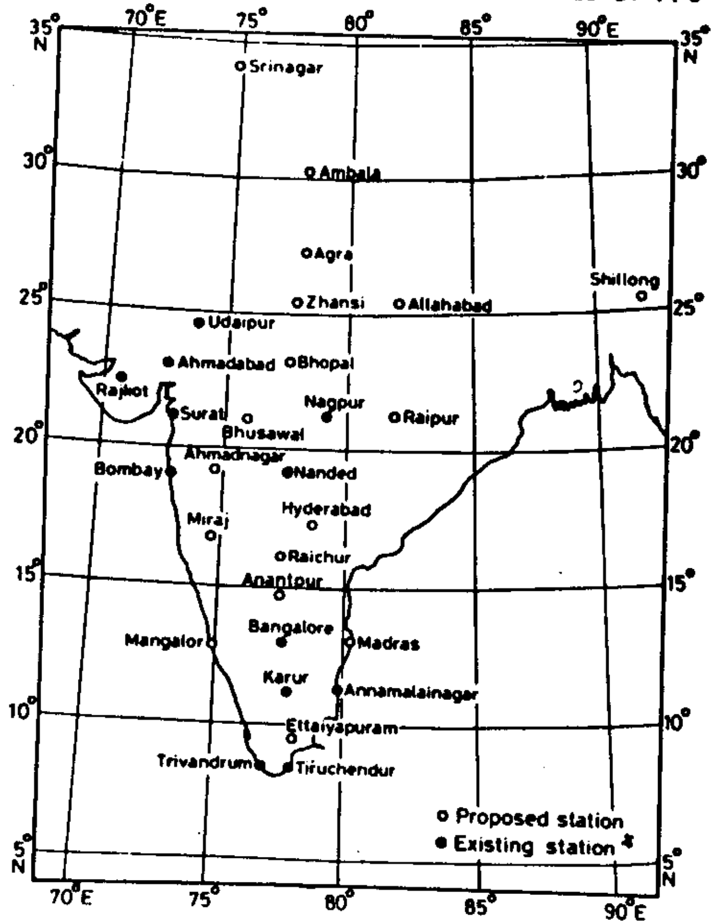
Fig. 49



DECEMBER SOLSTICES 1958
Post-Sunset 2000hr
Post-Midnight 0300 hr
HUANCAYO
24 = Number of points
PANAMA
MINIMUM VIRTUAL HEIGHT h'F (Km)
DAILY ΣKp

Fig. 50

CHAIN OF STATIONS RECORDING VHF IONOSPHERIC SCINTILLTIONS ON 244 MHz FROM FLEETSAT (73°E) AS ORGANISED BY IIG



* As on 15th JAN 1987.

Fig 57

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Tropical Spread-F

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Received 13 *May* 1983

It is shown that the equatorial range spread-F is due to scattering of radio waves from a series of levels of large plasma density gradients, and that the equatorial frequency spread is the decay process of the range spread following the lifting of the irregularities to higher heights. The spread-F at tropical latitudes is due to the superimposition of additional off-vertical *h'-f* traces from the patches of irregularities drifting from the equatorial region along the geomagnetic field lines. The range and frequency spread at tropical latitudes are just different manifestations of additional ionogram traces over the normal one. The occurrences of equatorial and low latitude spread are interconnected through a fountain of plasma irregularities similar to the daytime fountain of the plasma causing tropical maxima of F2 critical frequencies.

1 Introduction

Scattering of the radio waves from the-region of the ionosphere was detected during the very early stages of ionospheric research[1,2]. The scattering of radio waves from the F-region of the ionosphere, at low latitudes, was first detected by Booker and Wells[3]. They described ionograms at Huancayo showing diffuse echoes from the F-region received continuously at night over a wide range of frequency and virtual height. The phenomenon was seen between 1900 and 2000 hrs LT and was preceded by a marked rise of 100 km or more in the height of the F-region. Meek[4] was the first to use the term 'spread' echoes to describe diffuse ionograms at high latitudes. He found that during these events a main part of the echo was reasonably steady and the spread part was very variable and suggested the spread echoes to be due to reflections from non-zenith directions. Osborne[5] described the phenomenon of spread-F echoes at the equatorial station, Singapore, to be similar in nature to that at Huancayo. He noted that on several occasions echoes from several distinct layer heights were simultaneously obtained at low frequencies although a clean single reflection was present at higher frequencies.

The characteristics of equatorial spread-F have been described by a series of papers on spread-F at Ibadan (dip 6°N). The spread-F occurrence was maximum around midnight with an indication of pre-sunrise secondary maximum[6]. The development of spread-F at Ibadan could be categorized into two classes, viz. (i) ionograms with no signs of group retardation at all, with a number of stratifications widespread in both height and frequency, usually occurring between 1900 and 2200 hrs and (ii) ionograms with group retardation visible, but widespread particularly at higher frequencies with no stratifications, usually occurring from 2300 hrs LT onward. The layer trace was seen to double before the development of spread echoes suggesting the occurrence of reflectors from a layer tilt which developed just before the occurrence of spread-F[7].

2 Data

Chandra and Rastogi[8] described the characteristics of spread-F echoes at Thumba (magnetic dip 0.6°S). They clearly defined the equatorial spreading as falling into two categories, viz. (i) range spreading when the diffuseness is principally along the horizontal part of the *h'-f* trace giving rise to the ambiguity in *h'-f* but the critical frequencies are clearly identified, and (ii) frequency spreading when the spreading is maximum at frequencies close to the penetration frequencies causing ambiguities in the identification of f_oF2 while the trace is clear and sharp at lower frequencies. The two kinds of equatorial spread-F were shown to have different temporal variations and geomagnetic storm effects. Effective studies of range and frequency types of spread-F at Huancayo have been published by Rastogi and Vyas[9,10], Rastogi[11-13], Rastogi *et al.*[14] and Chandra *et al.*[15]

Comparing the vertical incidence ionograms at Huancayo and the vertical drifts at Jicamarca, Rastogi[13] showed that a strong peak in the eastward electric field to the eastward direction during any time of the night is followed by the generation of range type of spread-F configurations in the ionograms. Rastogi[12] showed that the conditions for the start of equatorial spread-F are (i) the existence of strong plasma density gradients, (ii) the existence of eastward electric field and (iii) the continuation of the above two conditions for about an hour or so. Rastogi[16] suggested that the first seeding of the spread irregularities at the equatorial ionosphere in the evening hours occurs due to a gradient drift instability at any height between the E and F layers wherever a large plasma density gradient exists. Later, the irregularities extend upwards throughout the F-region due to the buoyancy effects through Rayleigh-Taylor instability mechanism.

In Fig. 1 are shown some typical ionograms of equatorial spread-F to clearly define the differences in the characteristics of spread-F at an equatorial and at non-equatorial (tropical) station. Fig. 1(a) shows the ionogram at the initial stage of the range spread-F. Note that the normal *h'-f* traces are clearly distinguishable within the diffused echoes and the critical frequencies are clearly defined. The scatter echoes are at a virtual height lower than the minimum virtual height of the normal *h'-f* trace and the scatter trace does not show any group retardation effects, i.e. the increase of virtual height with increasing frequency of the exploring radio wave. The spread echoes, instead of being uniformly scattered on the ionogram

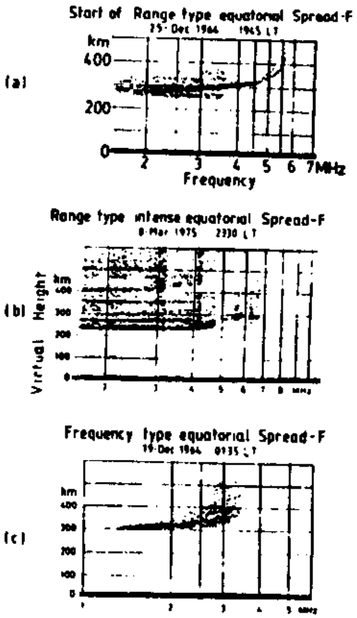

Fig. 1 Typical ionograms at the equatorial station Huancayo showing (a) initial stage of range type of equatorial spread-F, (b) fully developed stage of range type of equatorial spread-F and (c) frequency type of equatorial spread-F

are concentrated at a number of layers. The ionogram in Fig. 1(b) is an example of intense, fully developed stage of range equatorial spread when scatter is extended over a large amount of frequency and height scale. Still, within this area a number of traces are distinctly distinguishable, each of which shows complete absence of group retardation suggesting multiple levels of scattering either at the base or within the F-layer. Fig. 1(c) shows a case of equatorial frequency spread-F. Here the height range of scattering increases uniformly with the frequency of the radio wave. At lower frequencies the scattering is too small and the minimum vertical heights are clearly seen at all frequencies. It is to be noted that the individual echoes are randomly distributed on the ionogram and do not show a tendency to fall on any definite *h'-f* trace suggesting that these echoes are due to weak scatter by irregularities within the F-layer, simply adding echoes with range higher than the minimum virtual height for any particular frequency. It will be shown later that even though the terms range and frequency spread, are used for tropical spread-F the characteristics of the spread from these two regions are different.

Probably the most extensive study of the non-equatorial spread-F has been done by the Australian scientists, especially at Brisbane. Gipps *et al.*[17] have found that the diffuseness on the ionograms first appears in the form of clouds corresponding to frequencies above the critical frequencies and as the irregular clouds of ions gradually descend they produce scattering from lower heights and frequencies. The second type of spread shows apparent reflecting regions at slightly different heights and with different critical frequencies. The classifications of 'range spreading' and 'frequency spreading' were first used in a series of papers describing the spread-F at Brisbane[18,19]. Range spread manifests itself as a multiplicity of discrete F-region traces, all of closely similar range frequency characteristics. In the case of frequency spread, the widening of *h'-f* traces near the critical frequency is sometimes resolved into a number of fairly distinct upward sweeping traces.

Bowman[20] has categorized the characteristics of tropical spread-F (at Brisbane) into four broad types which are redrawn in Fig. 2. The spread-F at Brisbane makes itself manifest on ionosonde records by additional traces which are generally similar to the main *h'-f* trace but with critical frequencies which may be greater than or lesser than that of the main trace. Observation of these satellite traces at the lower frequency end of the ionograms where retardation can be neglected indicate, at certain times, ranges more than 10 km greater than the true range of the main echo. This type is classified as range spreading. At

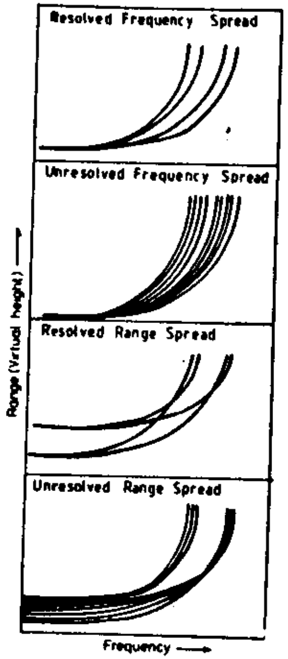

Fig. 2—Typical types of spread-F at non-equatorial (tropical) latitude station, Brisbane[20]

other periods, the true range of the satellite echo is little greater than the main trace but the critical frequencies are different: this configuration is classified as frequency spread. Other ionograms exhibit diffuse traces which on critical examination suggest that these configurations are the result from satellite traces so close in true range or critical frequency that the resolution of the equipment is insufficient to separate them. It is convenient to classify spreading into further two groups 'resolved' and 'unresolved'.

3 Analysis

Now we shall interpret some of actual ionograms recorded at different tropical latitude stations. In Fig. 3 are reproduced ionograms at a tropical latitude station, Grand Bahama, showing the broad characteristics of the spread-F. The ionogram in Fig. 3(a) shows *h'-f* traces with broadening only for frequencies close to f_oF2 and f_xF2 and with both *o* and *x* traces are well resolved; this would be classified as weak frequency spread. Fig. 3(b) shows an ionogram with no spreading at lower frequencies (less than 2

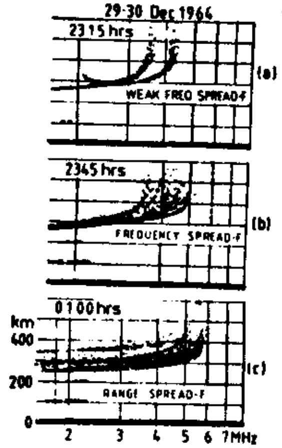

Fig. 3—Typical ionograms at tropical latitude station, Grand Bahama showing different types of spread-F

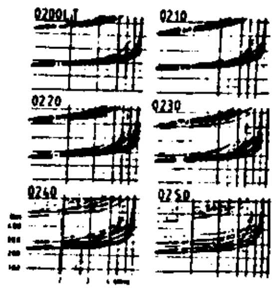

Fig. 4—Ionograms at Brisbane on 31 May 1948 showing the characteristics of tropical spread-F

MHz) whereas there is complete spreading for frequencies in the range 3.5 to 5.3 MHz. Even within the diffused echoes it is easy to trace out some of the individual *h'-f* traces. This would be classified as 'tropical frequency spread' and is different from the characteristics of equatorial frequency spread where the echoes are completely randomly distributed. Fig. 3(c) shows the ionogram which distinctly is a composite of a number of individual *h'-f* traces with different minimum virtual heights and penetration frequencies. This ionogram, classified as tropical range spread, again differs from the equatorial range spread in that individual traces within the spread area do show the effects of group retardation.

Now we examine the characteristics and the development of the spread-F at a few tropical stations. To begin with in Fig. 4 are shown the ionograms at Brisbane after Fig. 4 of a paper by Bowman[21]. The ionograms for 0200 and 0210 hrs LT show some spreading close to critical frequencies. The ionograms for 0220 and 0230 hrs LT indicate further a satellite trace to the main trace and thus spreading has extended to a lower frequency. The ionograms at 0240 and 0250 hrs LT show a number of h'-f traces almost parallel to each other and each of them shows group retardation effects. This type of range spread is distinctly different from the equatorial range spread shown in Fig. 1(b).

In Fig. 5 are shown two spread-F ionograms at another tropical latitude station, viz. Bogota. Fig. 5(a) represents the frequency type of spread-F. There is very little spreading below 2 MHz and there is extreme spreading between 2 and 4 MHz. It is interesting to note that, even within the spread-F, individual h'-f traces can be easily identified. Fig. 5(b) representing 'range spread-F' is again a mosaic of a number of individual h'-f traces such that both the penetration frequency as well as minimum virtual heights are not the same.

In Fig. 6 are shown the ionograms at Bogota for the period 1800 to 2130 hrs LT on 7 Dec. 1954. The ionogram for 1800 hrs LT shows clear h'-f trace with very distinct critical frequencies of o and x components. In the ionogram for 1830 hrs LT one can see some additional traces on frequencies close to the critical frequencies. At 1915 hrs LT two parallel h'-f traces are seen with different h'F and f_oF2. At 1945 and 2000 hrs LT, strong range spread can be seen with a number of individual h'-f traces embedded within the spread.

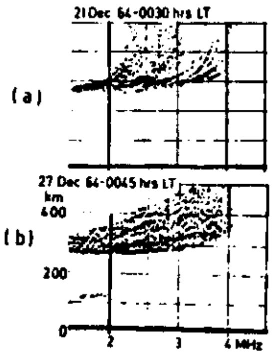

Fig. 5—Frequency and range type of spread-F at Bogota showing overlapping h'-f traces

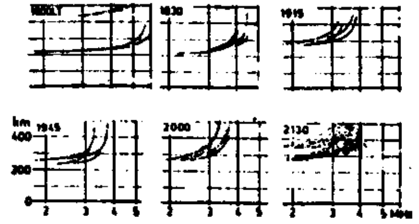

Fig. 6—Ionograms at Bogota on 7 Dec. 1954 showing the development of range spread at tropical latitudes

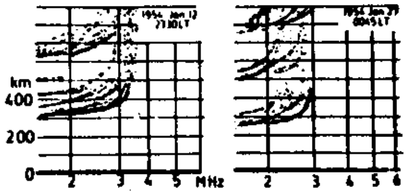

Fig. 7—Ionograms at Panama showing the tropical range type spread-F

In Fig. 7 are shown two spread-F ionograms at another tropical latitude station, Panama. It can be seen that the spread-F at the western zone station, Panama, is also the result of number of h'-f traces with different $h'F$ and critical frequencies, each trace showing group retardation similar to that in the first order F-layer trace.

In Fig. 8 are shown the development of tropical spread-F at Grand Bahama on 28-29 Dec. 1964. At 2300 hrs LT there are no signs of spreading on the 1 × F or 2 × F traces. At 2315 hrs LT extra traces are seen on 1 × F trace specially near the critical frequencies while 2 × F trace is still clear. At 2330 hrs LT strong range splittings with a number of multiple traces are seen on 1 × F trace while the 2 × F trace is still clear with critical frequencies clearly defined. At 2345 hrs LT spread traces are seen on 2 × F trace too and at 0000 hrs LT, range splittings are seen on both the first as well as second order traces. It is to be noted that there is no Es trace visible and so these multiple traces cannot be interpreted in terms of M or N echoes due to reflections between Es and F layers.

During 1962, extensive ionospheric instrumentation was established in the central Pacific area. A total of twelve vertical incidence ionosondes and seventeen oblique incidence ionosondes were operated in an area of 2800 km in radius centering on the magnetic equator at 173° W longitude. Lomax[22] has described the occurrence of spread-F at these stations on 27 Oct. 1962. Here we describe the characteristics of spread-F

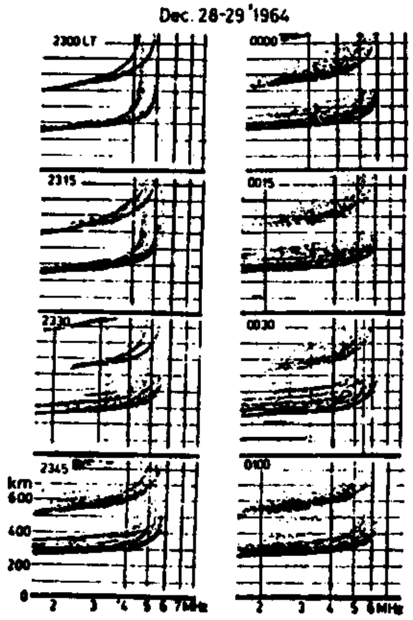

Fig. 8—Ionograms at Grand Bahama showing the development of tropical spread-F

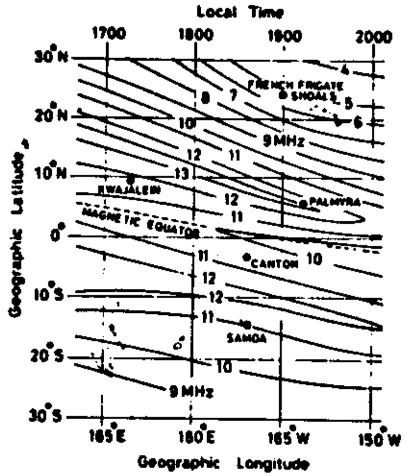

Fig. 9—Contours of F2-region critical frequency, f_oF2 at 0600 hrs UT on 27 Oct. 1972 in the Pacific Ocean region

at some typical stations on one particular day. First in Fig. 9 are shown the contours of F2-region critical frequency, f_oF2, at 0600 hrs UT using the data from all the stations operating in the region. In Fig. 9 one can see the maximum of f_oF2 both in the northern and southern regions with low values of f_oF2 along the magnetic equator. From the contours shown one can identify that Canton (lat. 5°S) and Kwajalein (lat. 5°N) are equatorial stations, Palmyra (dip. lat. 7°N) occupies the region of maximum f_oF2, Samoa (dip. lat. 14°S) is just outside the F2 anomaly crest and French Frigate Shoals (dip. 24°N) is well outside the F2-region anomaly. The distribution of these stations covered time zones of an interval of 2 hr. Some selected spread-F records at these stations are reproduced in Fig. 10. The spread-F at Kwajalein was typical of equatorial range type, the diffuseness being primary at low frequency end of the ionogram. At Canton, the first sign of spread was indicated by a strong oblique echo at virtual range of 400 km at 1832 hrs LT. Fifteen minutes later, strong spreading was evident on both the main as well as on the oblique traces. This process continued to develop with time. At Palmyra, where the value of f_oF2 was large (about 13 MHz), the spread-F started with a scattered type on the oblique echo. It is to be noted that there are no Es reflections and the satellite F-trace cannot be interpreted as M or N type of echoes between F and Es layers. Later development of spread-F at Palmyra consisted of a series of parallel h'-f traces typical of non-equatorial range spread discussed earlier in this paper. At Samoa too, the oblique returns were obtained as virtual ranges of 380 to 400 km; later multiple ranges of scattered echoes with minimum range decreasing with time was noticed. At French Frigate Shoals, the main 1 × F and 2 × F traces were always clear but strong scattered traces were observed in between. Further as seen in the ionogram for 1921 hrs LT, the scattered trace had much higher critical frequencies than that of the main trace indicating that the scattering (spread-F) was due entirely to off-vertical returns, and irregularities were not present vertically above the station. No spread was recorded at the stations Mauii, Rarotonga or Tongatapu which were well outside the F2-anomaly crests.

As the stations were spread over about 45° longitude equivalent to the 3-hr time difference, the analyses of the stations had to be simplified by interchanging the time and longitude and the problem reduced to two dimensions, viz. the local time and the distance of the station from the magnetic equator. With this assumption the onset times of spread-F at all the stations were noted and indicated in Fig. 1.2.17 of the paper by Lomax[22]. He had also drawn a diagram [Fig. 1.2.18] giving the percentage occurrence of

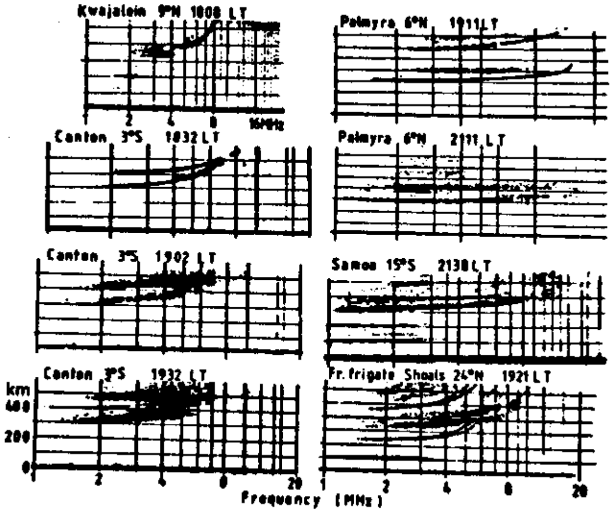

Fig. 10—Typical spread-F ionograms at the vertical incidence ionosonde stations in the Pacific Zone on 27 Oct. 1962 (after Lomax[22])

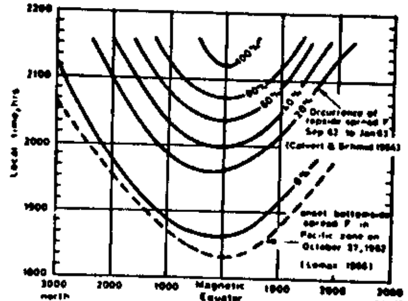

Fig 11—Local time dependence of the onset of bottomside spread-F and the percentage occurrence of the topside spread-F with the distance of the station from the magnetic equator

topside spread-F based on the study by Calvert and Schmid[23]. Both these diagrams are combined in Fig. 11. The zero per cent curve for topside spread-F may be interpreted as representing the onset time of the earliest occurring case of spread-F, during the period covered in the data. Higher percentage curves are believed to describe onset time versus latitude of subsequently occurring cases. As the spread-F once initiated may continue for several hours, in the time interval between the 20% and 40% contours, it is unlikely that any of those spread-F represented on 20% occurrence figure will change. The same day, therefore, is represented in the 40% curves, and the 20% difference represents the onset of spread-F on an additional 20% of the days. Thus the family of occurrence curves is representative of a family of onset curves. Then it is clear from Fig. 11 that the initial onset spread-F is a strong function of the distance from the equator. The bottomside spread-F starts at the magnetic equator around 1820 hrs LT and is delayed by about 20 min at a distance of 1000 km from the equator; at a distance of 2000 km, the spread-F occurs at 1930 hrs LT, about 1 hr after its onset at the equator, and the onset is further delayed by 1 hr at a distance of 3000 km from the equator. Chandra and Rastogi[24] have shown that the equatorial spread-F at the stations Huancayo, Ibadan, Djibouti or Kodaikanal occurs most frequently before midnight during maximum sunspot years and around midnight during minimum sunspot years. At a tropical latitude station, Ahmedabad, the spread-F is most frequent after midnight during low sunspot years[25]. Similar results were found at Nairobi[26]. At a low latitude station, Baguio, the peak occurrence of spread-F was around 2100 hrs LT during 1956-58 (high sunspot) and around 0100 hrs LT during the low sunspot periods 1953-55[27]. These results based on statistical analyses of long period data indicate that spread-F is most frequent at a later hour of the night as its distance from the equator is increased.

There has been a good network of ionospheric stations in India from the magnetic equator to a latitude well beyond the peak of equatorial F2-region anomaly. During 1965 four automatic ionosondes were operating in India at Kodaikanal (equatorial station), Hyderabad (within F2-anomaly region), Ahmedabad (at the anomaly peak latitude) and at Delhi (well-outside the anomaly region). The occurrence of the spread-F were noted at these stations and in Fig. 12 the percentage occurrence of the spread echoes versus time has been shown for these stations. The peak of spread-F occurrence at Kodaikanal (geogr. lat. 10°N) during 1965 was around 0000 hrs LT while at the low latitude station Hyderabad (lat. 17°N) the peak occurrence was around 0200 hrs LT and the peak value was slightly decreased. The peak occurrence at Ahmedabad (lat. 23°N) was around 0230 hrs LT and at Delhi (lat. 28°N) it was around 0330 hrs LT. It is also to be noted that the frequency of occurrence of the spread-F decreases slightly with increasing distance from the magnetic equator besides the systematic shift of the time of occurrence.

McNicol and Bowman[28] examined the ionograms at stations between the magnetic equator and the latitude 50° for the month of January 1956 for the occurrence of nighttime spread-F satellites, recorded as discrete extra traces of range greater than the main F-region echo on ionograms. These characteristics represent what is now designated as range type of non-equatorial spread-F. They found that the occurrence of range spread showed as a very irregular function of geographic latitude. However, in terms of geomagnetic latitudes the data were quite regularly distributed and the phenomenon was found to be most common between the latitudes of 20° and 45°. The irregularities data are replotted in Fig. 13 against the magnetic dip angle of the station. The latitudinal variations of noontime f_oF2 during the periods 1953-54 and 1957-58 (after Rastogi[29]) are also included in Fig. 13 to show the F-region anomaly. It is very clear that the multiple h'-f traces type of spread-F is not seen at the region close to the equator and is most common around the region of F2-anomaly crest which experiences the largest share of the plasma diffusion from the equator along the lines of force. It is to be noted that the F2-anomaly is a daytime phenomenon and spread-F is a nighttime phenomenon. The comparison is not made to show the association between the two. However, a similarity between the latitudinal variations of the two phenomena indicates some similar mechanism for both, which will be explained later. The statistical studies of the spread-F data obtained from IGY stations had shown the existence of a belt of enhanced occurrence frequency around the magnetic equator[30-32]. In Fig. 14 are plotted some of the phenomena which are associated with the magnetic equator, viz., the equatorial electrojet depicted by the daily range of geomagnetic H field (after Onwumechili[33]), the F2 equatorial anomaly depicted by the f_oF2 (after Rastogi[34]), the bottomside spread after Shimazaki[30] and the topside spread-F occurrence after Calvert and Schmid[23]. The

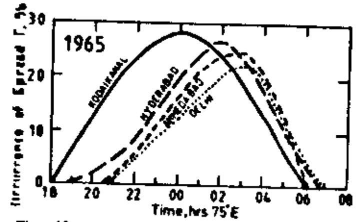

Fig. 12—Nocturnal variation of the present occurrence of spread-F echoes at Indian stations averaged for the year 1965

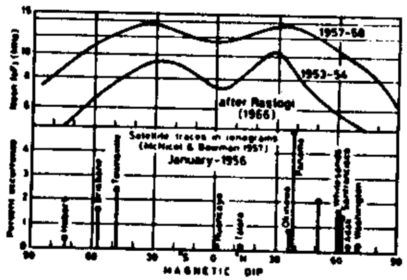

Fig. 13—Latitudinal variation of the occurrence of range type of non-equatorial spread-F (after McNicol and Bowman[28]) compared with latitudinal variation of midday critical frequency of the F2-layer (after Rastogi[29])

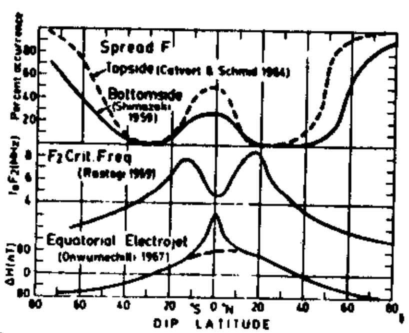

Fig. 14—Latitudinal comparisons of equatorial electrojet (after Onwumechili[33]), critical frequency of the F2-layer of the ionosphere (after Rastogi[34]), occurrence of bottomside spread-F (after Shimazaki[30]) and of topside spread-F (after Calvert and Schmid[23])

equatorial electrojet is confined to ±5° dip and is a daytime phenomenon. Another ionospheric phenomenon very similar in latitudinal variation is the occurrence of *q* type of equatorial sporadic-E layer during the daytime. The F2-anomaly shows itself by the depression of F2-layer critical frequency over the magnetic equator and two maxima at regions around 15°N and 15°S dip latitudes. The width of the F2-anomaly is much larger than that of the equatorial electrojet. Its explanation is given in terms of equatorial plasma fountain in which the plasma in the F-region over the magnetic equator is lifted upwards due to the eastward electric field and on reaching higher regions, the plasma diffuses along the lines of force giving rise to a concentration of plasma around 15° dip latitudes. It is interesting to note that the width of the spread-F belt corresponds to that of F2-region anomaly and not to the width of the electrojet. This suggests that the low latitude spread-F has in it some dynamic features similar to those of daytime equatorial plasma fountain.

Rastogi[11] has stressed that the primary parameter for the post-sunset generation of spread-F in the equatorial regions is the horizontal electric field in the F-region which has to be eastward to produce the spread-F irregularities. Rastogi[12] further suggested that the initial seeding of the irregularities in the equatorial ionosphere during the nighttime hours is due to the gradient drift instability mechanism. In the presence of favourable conditions these irregularities develop throughout the F-layer by Rayleigh-Taylor instability mechanism.

It is suggested here that these irregularities, when raised high up in the equatorial latitudes, diffuse northward and southward along the lines of force in a fashion similar to the diffusion of equatorial plasma along the lines of force during the daytime. Approaching a tropical latitude station, these irregularities are seen as a ripple or a wave on a regular plasma distribution and are detected as satellite traces over the normal h'-f ionogram traces. This idea explains the fact that at middle latitude the spread-F is just seen at the higher frequency end and later it extends to lower frequencies. The occurrence of spread-F being delayed at increasing distance from the equator is again analogous to the occurrence of the forenoon peak of f_0F2 at a later time at a station away from the equator[35].

4 Discussion

King[36] has suggested that spread-F echoes are not due to partial reflection from small irregularities but are rather due to total reflection from a large titled surface of ionization. He also considered range spreading to be due to steps or ridges in the iso-ionic surface and the frequency spreading as the decay product of the range spreading.

Bowman[37] has concluded that satellite traces are an integral part of the spread-F phenomenon. He has also shown that directions of arrival for diffuse echoes and the westward movement of the spread-F are virtually the same as has been found for nighttime TIDs[38]. He suggested that the diffuse nature of some of the specular reflections may be due to scattering by small scale structures which are also present.

Bowman and Dunne[38] studied the zenith and azimuth angles of the spread-F echoes using directional ionosonde at Brisbane. They detected that spread-F occurrence on some occasions was associated with tongues of ionization which extended some tens of kilometres below the normal level of the F2-layer. Departures from spatially uniform airglow emissions have been detected at low latitudes. Inter-tropical arcs of enhanced 6300 Å OI are maximum in the regions roughly coinciding with the tropical peaks of Appleton anomaly in F2-layer critical frequencies[39]. Smaller scale airglow structures of 6300 Å intensity having a dimension of about 500 km have also been detected[40]. Less frequently, highly structured north-south aligned ridges on fingers of enhanced 6300 Å emission have been observed.

Weber *et al.*[41], have shown the existence of north-south aligned depletions in regions of decreased intensity in the 6300 Å OI airglow using an all sky imaging photometer installed in the Airborne Ionospheric Observatory at the AFGL. These depletions have east-west dimensions from 50 to 200 km with fine structures as small as 2.5 km and often larger than 1200 km north-south. Simultaneous ionosonde measurements showed that the depletions were accompanied by strong spread-F[42].

Sobral *et al.*[43] studying simultaneous observations of the 6300 Å OI emission intensity and the ionosonde records at low latitudes, detected wavelike structures propagating poleward at an average speed of 240±70 m/sec. These disturbances had wavelengths of a few hundred kilometres and were associated with spread-F in the ionograms. They suggested that the poleward propagating airglow disturbances observed over Cachocira Paulista could be the manifestation of vertical propagation of plasma bubbles over the magnetic equator. In a later publication, Sobral *et al.*[44] showed that the airglow disturbances had north-to-south and west-to-east velocity components during the pre-midnight period and almost all these disturbances were accompanied by strong range type spread-F in the ionograms. The most important result of their study was that an often observed feature of the meridional profile of the airglow intensity was the propagating disturbances superimposed on otherwise

rather slowly varying spatial gradients, and that these disturbances were caused by corresponding disturbances in the electron density rather than by the height changes in the F-region.

Thus there are ample evidences that at tropical latitudes one gets disturbances in the electron density over the smoothly varying latitudinal component, and that these move away from the equator.

One of the other manifestations of the spread-F irregularities is the scintillation of radio waves from a satellite received on the ground. Rastogi[45] has shown that it is the range type of spread-F with multiple layers of scattering in the F-region which produces equatorial radio wave scintillation. Scintillations at tropical latitudes are also associated with range type of spread[46].

Using a large array of receivers, McDougall[47] has studied the distribution of nighttime irregularities which produce scintillations at midlatitudes. The irregularities were found to occur preferentially near the F-region ionization peak, are aligned along the earth's magnetic field and appear to extend from top to bottom of the F-region.

5 Conclusion

The spread-F irregularities are first generated at the base of the F-region over the magnetic equator as a cross-field instability due to the action of an eastward electric field on a large plasma gradient at the base of nighttime F-region. These irregularities are later lifted upward over the equatorial regions by the buoyancy effects associated with Rayleigh-Taylor instability mechanism. This gives rise to the following sequence of traces on an equatorial ionogram, viz. first, range spread at lower frequencies and heights close to h'_{min} F; second, filling up of a large height range and also frequency extent with spread echoes; later a transformation of range spread to frequency type of spread, and finally, the decay of spreading at equatorial regions. This process, though at its maximum over the magnetic equator, may exist to a lesser degree over a reasonably wide belt of say ±10° of the equator. Having lifted up, the patches of irregularities drift north and south along the lines of earth's magnetic field in a process similar to the daytime fountain of equatorial F-layer plasma and produce extra traces in the ionograms at tropical latitudes. With the progress of time, the region of F-region irregularities widens in its latitudinal extent and at a particular tropical latitude, extends from the F2-layer peak to lower heights changing the character of tropical spread from frequency type to range type spread. Thus the spread-F phenomenon over the whole width of ±20° from the magnetic equator is a single complex series of events starting at the base of F-layer at the equator due to the eastward electric field, generally after sunset period, or during certain disturbed periods of the night when normal westward electric field is reversed eastward.

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On the equatorial spread F

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Abstract. The post-sunset maximum in virtual height of the F region near the magnetic equator is associated with the general rise of the whole F region from the base to the height of peak ionisation with little change in the semi-thickness of the layer. This rise of F region is accentuated on days with large evening peak in the vertical drift velocity or the horizontal electric field in the F region. The range type of equatorial spread F first occurs only if the F region drift velocity remains significantly upwards after sunset but the maximum intensity of spread F occurs when the drift velocities are low or even downwards. The range spread first appears at or below the base of the F layer and later spreads into the F layer due to downward movement of the layer and/or upward movement of the irregularity. Spread F seen on VHF backscatter records corresponds to the range type of spread F seen on normal ionograms. The frequency type of spread F does not produce VHF echoes. A strong peak in the electric field seems to be a necessary condition for the generation of equatorial spread F.

Keywords. Spread-F; equatorial F-region; F-region irregularities.

1. Introduction

The early observations of spread F at equatorial stations—Huancayo by Booker and Wells (1938) and Singapore by Osborne (1952) had suggested that the phenomenon is correlated with the marked rise in the height of the F region between 1800 and 2000 LT. Similar correlations were later found between the temporal variation of the virtual height of the F layer and the occurrence of spread F at the other equatorial stations Kodaikanal (Bhargava 1958), Ibadan (Lyon *et al* 1971) and Thumba (Chandra and Rastogi 1972).

The data from large number of stations operating during IGY had revealed a very high probability of occurrence of spread F at equatorial latitudes (Shimazaki 1959; Wright 1959; Singleton 1960). It was also noted that the latitudinal plots of the percentage occurrence of spread F showed significantly less scatter against dip latitude than against geomagnetic dipole or geographic latitude. The equatorial belt of spread F was shown to be associated with similar belt of high value of virtual height of the F layer (Lyon *et al* 1960; Rao 1966). Thus it was clear that equatorial spread F is closely associated with the magnetic dip equator even though there is no concentration of equatorial electrojet during the night time.

With the use of powerful VHF radar at Jicamarca, the profiles of electron density with height have been computed in the ionosphere even for regions above the peak ionisation level of the F region (h_mF_2). Number of contour diagrams of electron density on the grid of actual height versus local time have been published by Farley (1966) and by McClure *et al* (1970). The vertical drift velocities in the F region,

$V_z(F)$, have also been measured through the Doppler shift of the backscattered echoes. Woodman (1970) has described the result of these measurements over the period 1968–70. On certain days both the electron density contour and the vertical drift velocity are available (Woodman and La Hoz 1976).

The present paper compares the occurrence of spread F as seen on the VHF backscatter records at Jicamarca with the spread F configuration on the ionograms at Huancayo. Some of the data used in the present analysis have been kindly provided to the author by Dr R F Woodman. It is to be noted that the two sets of data are not from identically the same location and hence no comparison of short period variations is attempted here.

2. Variations of the F region parameters over the magnetic equator in the evening hours

The post-sunset rise of the F region has been generally inferred from the increase of the minimum virtual height of the F layer, $h'F$, because this parameter is easily available for most of the ionospheric stations in their data bulletins. Lyon *et al* (1961) compared the variations of $h'F$ and h_mF (true height of maximum electron density as determined by Kelso method) at Ibadan and found that the variations of $h'F$ are very similar to that of h_mF during the period 1700–2000 LT. As there are large longitudinal differences in the characteristics of equatorial spread F, it was considered necessary to study the variation of F layer parameters in the American zone for comparison with the Jicamarca data. In figure 1 are shown the daily variations of $h'F$ at Huancayo as taken from routine tabulations as well as of h_mF and y_mF

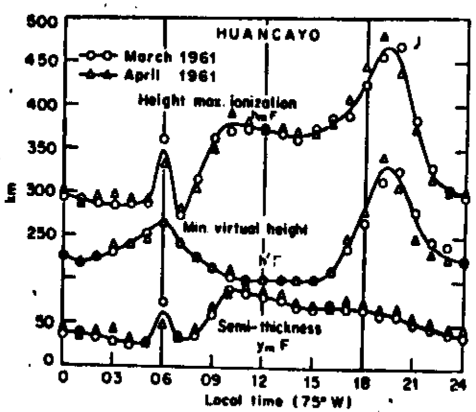

Figure 1. Daily variations of minimum virtual height of F region ($h'F$), height of maximum ionization density in the F region ($h_m F$) and the semithickness of the F region ($y_m F$) at Huancayo during the months of March and April 1961. Note the simultaneous increase of $h'F$ and h_mF during the post-sunset period without any large change in y_mF at the same time.

(semi-thickness of the layer) as derived from full *N–h* computations by Budden's matrix method for two months March and April 1961.

The minimum virtual height, *h′F*, shows a very flat minimum around midday hours and a flat peak around sunrise and a prominent peak after sunset. The *h′F* starts increasing even after 1500 LT, reaches a maximum value at 1900–2000 LT and slowly decreases till about midnight, the total increase of *h′F* being more than 100 km. The h_mF shows a very sharp peak around sunrise which is due to the generation of fresh ionisation at higher heights, it again starts increasing after 1400 LT and reaches a peak between 1900 and 2000 LT. The variations of *h′F* and h_mF are very similar during the afternoon and evening hours. The semi-thickness y_mF is maximum at 1000 LT and slowly decreases from 1000 LT till the next sunrise. Thus it is to be concluded that there is a genuine uplifting of the *F* region over the magnetic equator as a whole during the sunset period without any large change in the thickness of the layer. Rishbeth (1971) has suggested that this rise in the height of the *F* region in the evening hours is primarily caused by an eastward electric field. Schieldge *et al* (1973) have suggested this occasional increase of the electric field as due to the polarization charges which tend to build up in regions where the conductivity has a strong horizontal gradient.

3. Frequency and range types of spread *F*

We next compare in figure 2 the daily variations of the occurrence of range and frequency types of spread *F* and that of *h′F* at Huancayo for different seasons of the

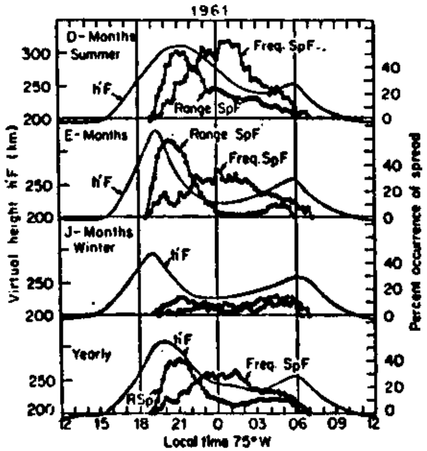

Figure 2. Daily variations of the occurrence of 'range' and 'frequency' types of spread *F* compared with the daily variations of *h′F* at Huancayo for different seasons of the year. Note that the post-sunset spread *F* associated with the large rise of *h′F* is the range type and not the frequency type.

year. The year 1961 was chosen for these comparisons because the regular tabulations of *h′F* were discontinued for later years. It is clearly seen that the evening increase of *h′F* is present at Huancayo during any of the seasons.

The occurrence probability of either types of spread *F*, frequency of range type, is remarkably low during *J*-months (winter) even though the evening rise of *h′F* is not much different during this season as compared with other seasons. Thus the seasonal variation of either types of equatorial spread *F* is similar with a peak around December and a minimum around July. Nocturnally the frequency type of spread *F* occurs most commonly around midnight hours. The probability of the occurrence of range type of spread *F* increases rapidly shortly after sunset and reaches a peak around 2000 LT. From these features, it can be concluded that it is the range type and not the frequency type of spread *F* which is directly associated with the evening rise of the *F* region. The routine monthly ionospheric data bulletins denote the occurrence of spread *F* based on the criterion as to what extent the spreadness makes the scaling of f_oF_2 uncertain. The results based on the study of spread *F* occurrences from the routine monthly ionospheric bulletins would be highly biased in favour of frequency type of spread *F*.

In figure 3 we compare the occurrence of range spread at Huancayo with the *F* region vertical drift velocity at Jicamarca during summer months of 1968–69. It may be mentioned that in the *F* region the vertical drift velocity is directly related to east-west electric field, a velocity of 40 m/s upwards corresponds to an eastward electric field of about 1 mV/m. The vertical drift, $V_z(F)$, decreased steadily with time in the afternoon hours followed by a relatively sharp peak at about 1830 LT and reversed its direction downward at about 1930 LT; it remained downward throughout the night and reversed to upward direction around sunrise. The onset of range type of spread *F* occurs when the *F* region drifts are upward, i.e. when the electric fields are eastward but the peak occurrence frequency of the spread *F* occurs about an hour later and by that time the *F* region drifts get reversed downward.

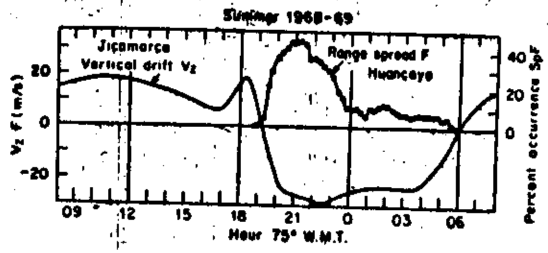

Figure 3. Comparison of the temporal variation of the occurrence of range spread *F* at Huancayo with the daily variation of vertical *F* region velocity at Jicamarca. Note that the phenomenon of spread *F* occurs for the most part when the *F* region drifts are downwards (negative).

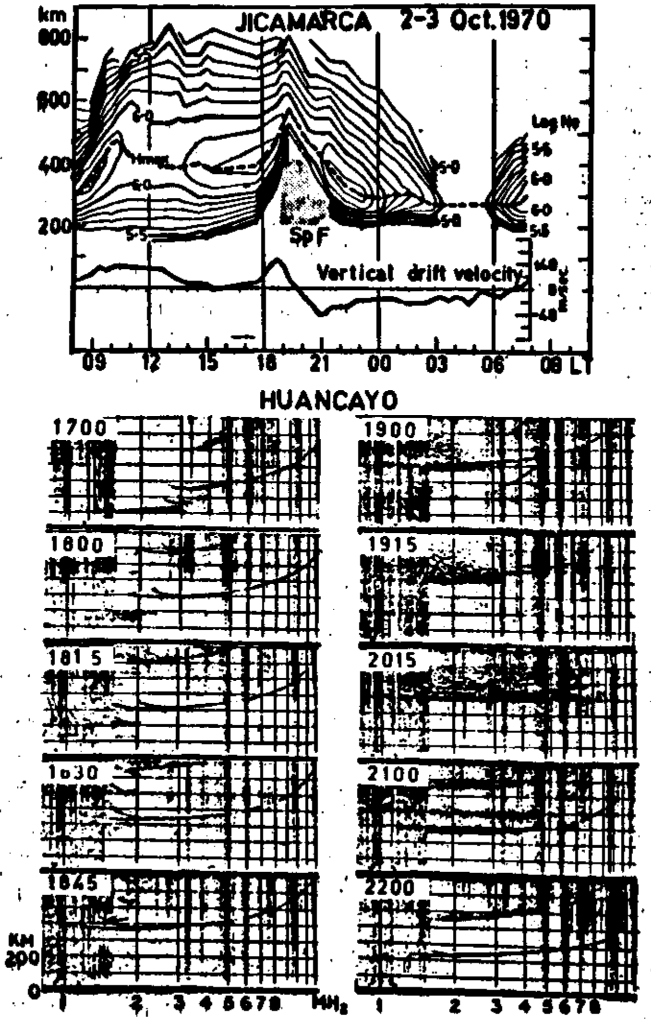

Figure 4. Iso-electron density contours and *F* region vertical drift velocity at Jicamarca compared with the ionograms at Huancayo on 2-3 October 1970. Note spread *F* started when *F* region drift velocity was downward. VHF spread *F* occurred in the lower half of the *F* region and was associated with the 'range' type of spread *F* on the ionograms.

4. Spread *F*, vertical *F* region drifts and iso-electron density contours

We now compare the characteristics of the spread *F* at Huancayo ionograms in relation to the electron density contours and the vertical *F* region drifts at Jicamarca. In figure 4 are shown the iso-electron density contours and vertical *F* region drift velocity at Jicamarca on 2–3 October 1970 compared with the ionograms at Huancayo. The iso-electron density contour at the base of the *F* region is seen to increase even during the afternoon hours but the overall increase of the height of contours up to the height h_{max} started at about 1730 LT and the peak height was reached at 1930 LT. The *F* region drift had a flat peak around midday, decreased to almost zero value around 1530 LT, and again increased to form a sharp peak at 1845 LT, reversed its direction at 1930 LT and remained negative (downward) during the whole night. The spread *F* was seen by the VHF radar between 1900 and 2115 LT only in the lower portions of the *F* region. The isoionic contours were clear below h_{max} indicating that the *F* region near the height of peak electron density did not have the irregularities responsible for VHF back-scattering. The ionogram at 1700 LT showed the *Es-q*, *Es-c* and the normal *F* region traces. At 1800 LT the *Es-q* had disappeared, *Es-c* had risen to 175 km, and the *F* region had also gone up in height. At 1815 LT the cusp type *Es* was clearly present at 200 km indicating the presence of large *N–h* gradient at 200 km. At 1830 LT the f_{min} *F* had greatly reduced but the presence of low level ionisation was indicated by the group retardation in *F* layer traces. At 1845 and 1900 LT high multiple echoes were recorded due to the existence of large horizontal gradients in the isoionic surfaces in the *F* region (Rastogi 1955). The first indication of spread *F* was seen in the lower frequency portion of the *F* region trace at 1900 LT. At 1915 LT and 2015 LT the spread *F* had increased in intensity. It is interesting to note that the *F* region critical frequencies were clearly seen even in the presence of intense range spread at 2015 LT. At 2100 LT the intensity of spread *F* had diminished and it disappeared by 2200 LT. This example shows that range spread *F* can coexist with very clear critical frequencies. Further, the occurrence of range spread on the ionogram is closely linked with the spread echoes seen in the VHF radar.

We now compare in figure 5 the ionograms and the iso-electron density contours during the occurrence of a very strong spread F on 22–23 September 1971. It is seen that *h'F* started increasing even before the increase of the evening peak in *F* region vertical drifts. The *F* region continued to increase as long as the *F* region drift was upward and the peak value of *h'F* occurred almost at the time of the reversal of V_z. Examining the ionograms, one finds high multiple echoes at 1900 LT indicating large gradient in the isoionic surface which is confirmed from the contours of the electron density (*Ne*) derived from VHF data. At 1915 LT both frequency and range spread are seen on the ionograms and some portion of *h'F* trace is also discernible indicating normal electron density variation with height. At 2000 LT the ionogram shows complete spread with no group retardation in the traces; there are a number of horizontal traces at slightly different heights. These conditions continued up to 2200 LT after which the spread *F* gradually decreased in intensity. The VHF radar echoes indicated spread *F* throughout the entire height of the *F* region from 1930 to 2200 LT. It is to be noted that the onset of spread *F* was when the V_z was upwards although it continued even later when the V_z had reversed downwards. Thus it is again seen

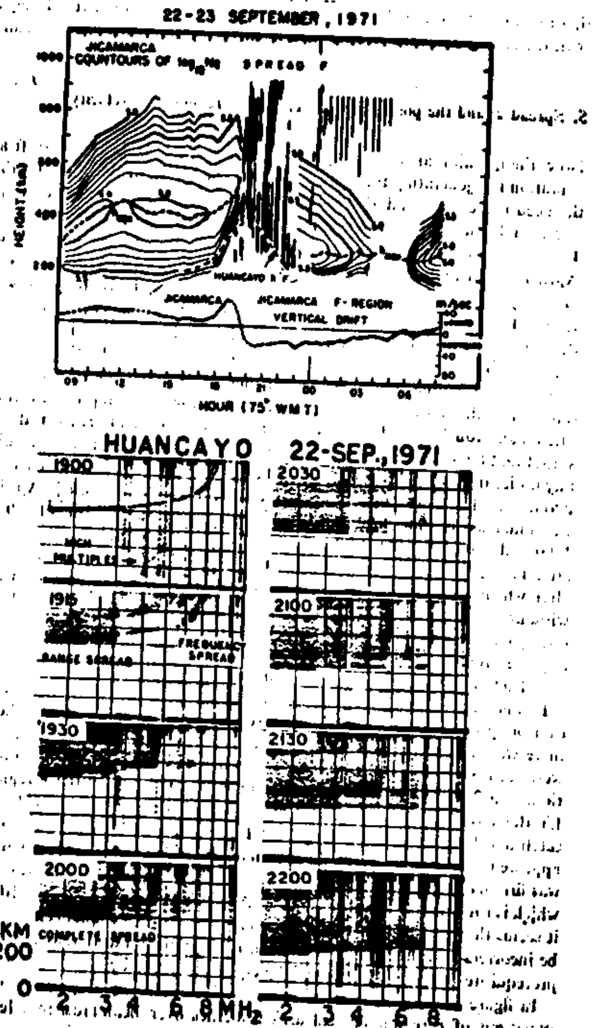

Figure 5. Iso-electron density contours in the F region over Jicamarca, the vertical F region drift at Jicamarca, minimum virtual height of the F region at Huancayo compared with the ionograms at Huancayo on 22 September 1971. Note the complete spread in the ionograms, with no group retardation in $h'F$ seen; no indication of critical frequencies can be seen and the VHF radar indicated spread over the entire F region at the same time.

that the uplifting of the F region and the onset of range spread are closely associated with the strong eastward electric field in the F region during the post-sunset period.

5. Spread F and the post-sunset increase of F region drift velocity

Now, the question arises is the post-sunset increase of the F region drift an essential condition for generating the spread F or is it the height of the F region that controls the occurrence of spread F? It was sought to find out two close-by days with distinctly different variations of $V_z(F)$ during the evening period and to examine the Huancayo ionograms on these two days. It was possible to find two such days in April 1971. In figure 6 are shown the variations of $V_z(F)$ at Jicamarca with $h'F$ at Huancayo together with some of the ionograms at Huancayo on 26 and 28 April 1971. The variations of the geomagnetic H field at Huancayo are also shown for these days to check if the changes are associated with any geomagnetic disturbances. The most interesting feature noticed in the diagram is that $V_z(F)$ at Jicamarca on 28 April 1971 was almost zero in the evening hours and later reversed to downward direction without showing any positive peak before changing its direction. On the other hand, on 26 April 1971, $V_z(F)$ showed a prominent sharp peak shortly after sunset and later the direction was reversed. The magnetogram traces did not show any noticeable differences which could be attributed as due to differences in $V_z(F)$ on two days. The minimum virtual height of the F region ($h'F$) on 28 April 1971 showed an increase beginning 1500 LT from 200 km to the peak value of 280 km between 1800 and 2100 LT. On 26 April 1971 $h'F$ did start increasing since 1500 LT but after 1700 LT the rise was very rapid, the peak value of $h'F$ was 380 km at 1915 LT after which $h'F$ decreased slowly. Thus it is concluded that even on normal days without any large value of V_z near sunset hours, the virtual height of the F region does go up since the afternoon hours till a few hours after sunset. On the days with large pre-reversal peak in V_z, an additional upward lifting occurs when the $h'F$ is raised by more than 100 km within an hour or so.

Examining the ionograms one notices that on 28 April 1971 there was no indication of spread F echoes on the first order F region reflections. On 26 April 1971, there were no scatter echoes till 2045 LT. At 2115 LT no overhead scatter echoes were seen on $1 \times F$ trace but a satellite scatter trace was seen due to oblique reflection. At 2145 LT spread F echoes were seen at the base of the F region. By 2200 LT the spread F region had decreased to the height lower than $h'F$. At 2215 LT satellite echoes were seen and by 2245 LT the spread F echoes had more or less disappeared. It is to be noted that around 2100 LT on 26 April 1971 when spread F was first seen on the ionogram the minimum height of the F layer was about 270 km which is roughly the value of $h'F$ on 28 April 1971 between 1800 and 2100 LT. Thus it seems that a threshold value of $h'F$ only above which spread echoes can be seen to be incorrect and the post-reversal peak in the F region drift velocity is an important prerequisite for the generation of the equatorial spread F.

In figure 7 is reproduced the figure 2 of Woodman (1970) showing the temporal variations of F region vertical drift velocities over Jicamarca on a few days in the months of May and June. The shaded bands in the diagram indicate the times when spread F was seen by the VHF radar. It is seen that spread F was seen during the

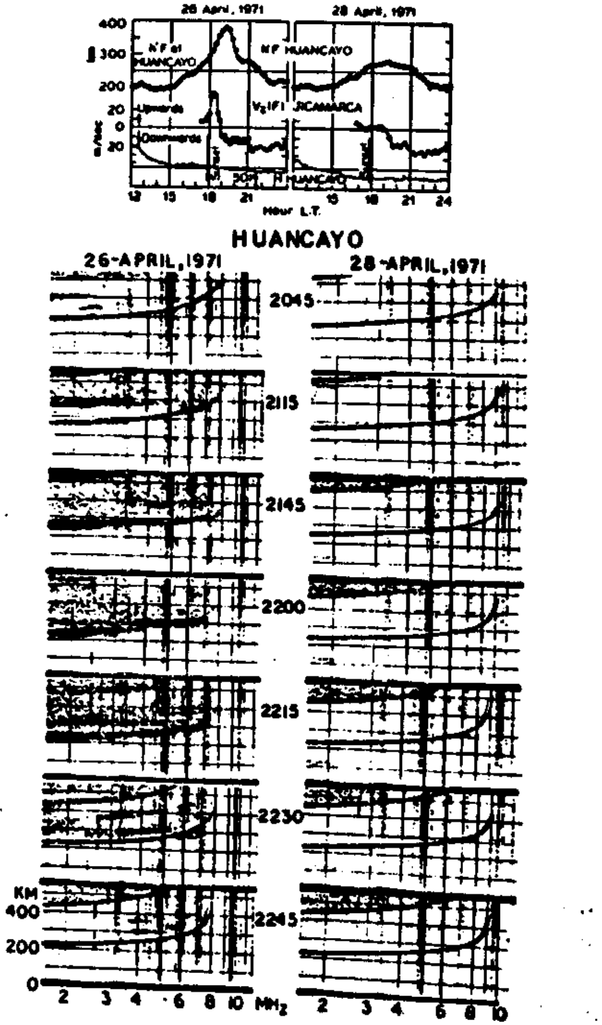

Figure 6. Variations of $h'F$ at Huancayo, geomagnetic field (H) at Huancayo and F region vertical drift velocity at Jicamarca $V_z(F)$ compared with some of the ionograms at Huancayo on 26 and 28 April 1971. Note strong spread on 26 April 1971 when the post-sunset peak of $V_z(F)$ was present and absence of spread F on 28 April 1971 when no increase of $V_z(F)$ occurred during the sunset period.

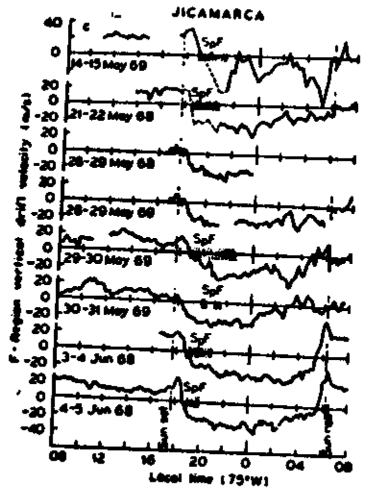

Figure 7. Temporal variations of the vertical F region drift velocities over Jicamarca on a number of days in northern solsticial months. Shaded bands are times during which spread F was present. Note absence of strong evening peak of V_z at nights with no spread F.

post-sunset periods on 14–15 May 1969, and on 21–22 May 1968 and on both these days $V_z(F)$ was sufficiently high around sunset periods. On 28–29 May 1968 and 28–29 May 1969, the $V_z(F)$ was very low at sunset and no spread F was indicated. On 29–30 May 1969, strong $V_z(F)$ was present at sunset and spread F echoes were seen after 1900 LT. On 30–31 May 1969, no evening peak of $V_z(F)$ was evident and no post-sunset spread F was present. On 3–4 June 1968 and 4–5 June 1968 strong peaks in $V_z(F)$ shortly after sunset were followed by the occurrence of spread F.

It is thus concluded that the existence of a strong upward drift or a strong eastward electric field in the F region is a necessary condition to exist for some time after sunset to initiate equatorial spread F.

4. Spread F seen through HF ionosonde and VHF radar

We now compare the characteristics of spread F on Huancayo ionograms and on VHF radar at Jicamarca. One such example for 15–16 October 1964 is reproduced in figure 8 (after McClure *et al* 1970). The isoelectron density contours showed increasing height after about 1700 LT with the peak around 2000–2100 LT. The VHF radar indicated spread echoes from 1945 to 2300 LT. It is interesting to note that these irregularities were seen by VHF radar only in the lower half of the F region.

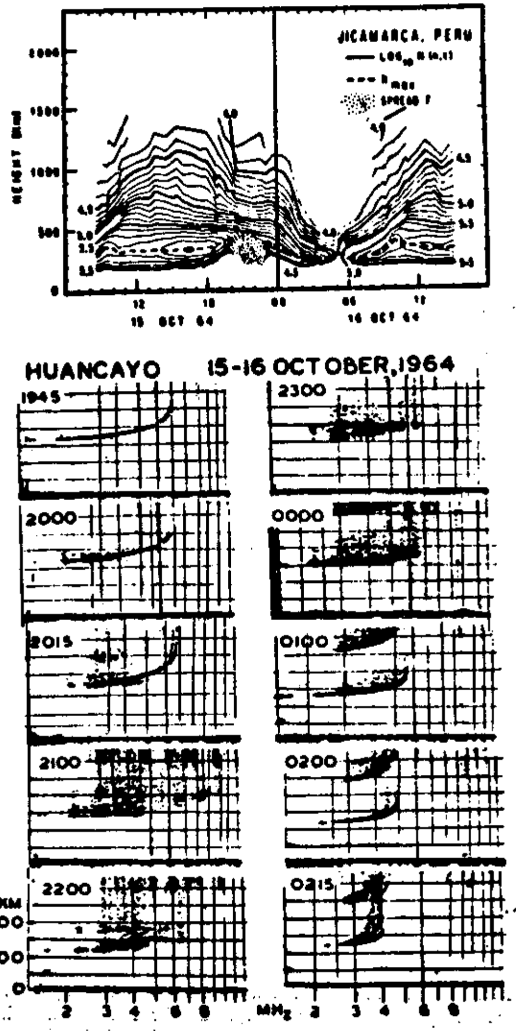

Figure 8. Iso-electron density contours obtained by VHF radar at Jicamarca compared with the ionograms at Huancayo on 15-16 October 1964. Note that the VHF spread *F* echoes occurred in the lower half of the *F* region and were associated with range type of spread *F*. No spread *F* was seen in VHF when the ionogram showed strong frequency type of spread *F*.

The ionograms first indicated some scatter echoes at 2000 LT on lower frequencies. At 2015 LT range type spread *F* was quite clear and the critical frequencies were distinctly distinguishable. At 2100 LT the spread had reached to the critical frequencies and some layered structures were evident within the spread *F*. After 0000 LT the spread *F* started to transform into frequency type i.e., the spread was absent at the lowest frequency end of the trace and increased towards the critical frequency region. At 0200 LT and 0215 LT strong frequency spread *F* was present. The VHF radar did not show spread *F* after midnight when the characteristics of the spread *F* were of frequency type.

In figure 9 are shown another comparison of VHF scatter data and ionograms on 10–11 December 1964. The contours of N_e show a rapid rise of $h_m F$ after about 1800 LT with the occurrence of spread *F* after 1930 LT and ending at 2200 LT; but the spread *F* was seen only in the lower half of the *F* region. The ionograms did not show any spread *F* at 1845 LT while at 1915 LT a few scatter echoes were seen at lower frequencies and the critical frequencies were quite clear. At 1930 LT spread *F* had extended up to the critical frequencies and discrete layers of irregularity were evident. After 2200 LT the character of spread had changed into frequency type. Strong frequency spread can be seen on the ionogram at 2315 LT. The spread *F* condition extended up to about 0230 LT. It is to be noted that the VHF radar did not indicate spread *F* during these periods of strong frequency spread.

We show in figure 10 an example of VHF spread when the *hf* ionosonde did not show any spread at all. The isoionic contours over Jicamarca for 25 June 1969 indicated significant rising of the $h_{max}F$ in the post-sunset period. Spread *F* was also seen in the VHF radar between 1900 and 2200 LT. Examining the ionograms, one can see high multiple echoes from 1815 to 1900 LT indicating large gradients in the isoionic surfaces but no indication of spread *F* can be seen on any of the ionograms at Huancayo that evening. It thus seems that even on occasions when the conventional *hf* ionosonde does not receive any spread *F* echoes, the VHF radar can detect scattered signals which may be identified as caused by spread *F*.

7. Discussion

The occurrence of equatorial spread *F* during the evening hours when the *F* region is rising rapidly had prompted many workers to associate the spread *F* with the movement or with the height of the layer.

Osborne (1952) suggested that $h'F$ reached the maximum value at the time of sunset at the ionospheric heights when the layer disintegrates into scattered clouds. Clemesha and Wright (1966) reported that the onset of spread *F* at Ibadan occurs at the time of peak $h'F$ and is preceded by the satellite traces. The model suggested by them assumes the presence of irregularities above a certain height in the *F* region and the spread *F* is seen when the *F* layer rises above this threshold height. Rao (1966) had shown that $h'F$ at Huancayo has to cross a threshold value of about 400 km for the production of spread *F*. He used the published monthly f_oF_2 data bulletins and as such was unable to identify the range spread which does not affect the identification of the critical frequencies. If it is assumed that irregularities in the *F* region are already there and the spread *F* is seen on the ionograms only after the *F* layer has

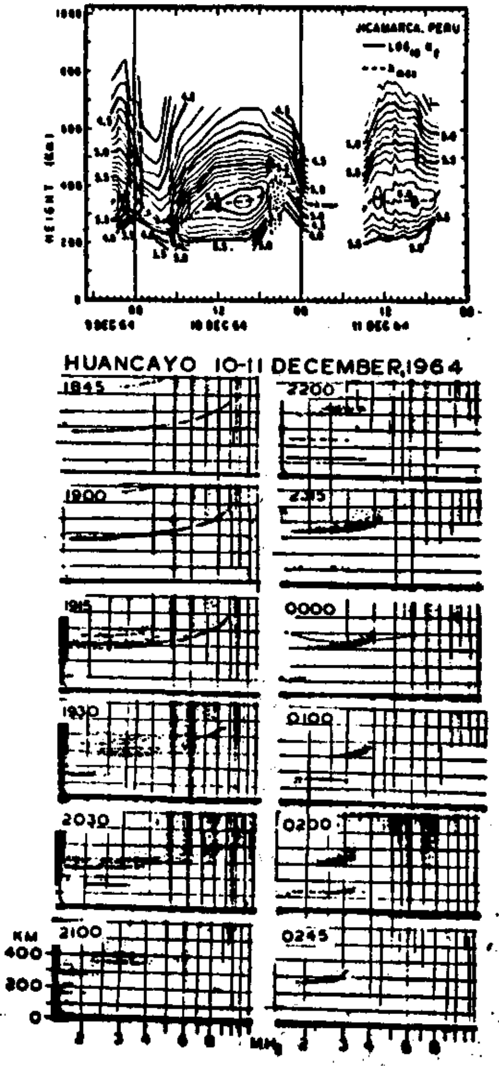

Figure 9. Iso-electron density contours obtained by VHF radar at Jicamarca compared with the ionograms at Huancayo on 10-11 December 1964. Note that the VHF spread *F* occurred in the lower half of the *F* region and were associated with range type of spread *F*. No spread *F* was seen in VHF when the ionograms showed strong frequency type of spread *F*.

risen above this threshold height, then the onset of spread *F* should start first on higher frequencies and then gradually to lower frequencies, but the case is just opposite to this. Farely *et al* (1970) also suggested that there is a threshold altitude above which the bottom of the *F* layer has to rise before the irregularities are generated. Rastogi (1977) has shown that range spread as seen on the ionograms appears at heights significantly lower than the base of the *F* region and only afterwards mixes up with the main *F* region due to downward movements of the layer or possibly upward movement of the irregularity itself.

Booker (1956) was the first to suggest that the irregularities responsible for spread *F* was below the base of *F* layer. He suggested that the spread *F* on the ionograms is due to the forward scattering of *HF* radio waves by a scattering screen between the *F* region and the ground probably at the height of 180 km and such that the screen is not directly detectable with the conventional ionosondes. Cohen and Bowles (1961) studying the transequatorial forward scattering of 50 MHz signal in Peru during IGY concluded that the range spread designated by them as the equatorial spread *F* results from scattering by thin sheets of irregularities situated at about the bottom of the *F* layer or as much as 100 km below it although at times the scattering layer can occur up to heights of 450 km or more.

McNicol *et al* (1956) combined the vertical ionograms at Brisbane with range-time recordings of spaced (95 km apart) transmitters, phase-path recordings and the direction of arrival of the echoes and concluded that the range type of spread *F* is due to the number of individual traces which are not resolved.

Bowman (1960 a, b) combining the oblique sounding link and spaced loop direction finding with the vertical ionospheric soundings of Brisbane concluded that the irregularities responsible for the spread *F* at Brisbane are ripples of considerable extent with wavelength varying from 20 to over 100 km. King (1970) has suggested that range spread is caused by total reflection of radio waves due to the passage of a step or ridge in the isoionic surface in the *F* region. Calvert and Cohen (1961) have explained the variety of equatorial spread *F* configurations on the basis of partial reflection from a single irregularity moving horizontally at different heights with respect to the *F* region. Their model attributes most of the features of the spread *F* configuration to refraction and retardation imposed on the radio waves by the ionosphere as they travel to and fro from the position of scattering.

Booker (1961) has suggested the existing of holes in the ionosphere to explain the bottomside spread *F*. Inside each hole the electron density is lower than that of the ambient ionosphere. When these holes are overhead the station, the number of penetration frequencies would be observed giving rise to number of cusps on the ionogram at the same virtual height giving rise to the frequency spread configuration on the ionograms. Holes at a distance from the station would show up at greater virtual heights and would be generally at a lower critical frequency than the ambient, giving rise to range spreading configuration on the ionograms.

Rastogi and Woodman (1977a) by comparing the ionograms at Huancayo with corresponding MRTI records of VHF radar at Jicamarca have shown that the range type of spread *F* is very efficient for back-scattering of the VHF radio waves. On the other hand, the frequency type of spread *F* does not produce strong echoes. Later Rastogi and Woodman (1977b) by comparing the vertical *F* region drifts measured by the VHF back-scatter radar at Jicamarca and the vertical incidence ionograms at Huancayo, have shown that a reversal of the *F* region vertical drifts to positive

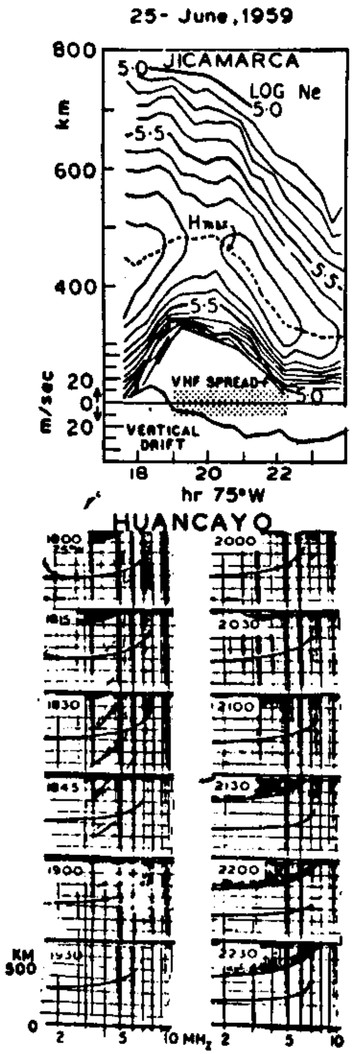

Figure 10. Temporal variations of the isoionic density contours and vertical drifts in the *F* region over Jicamarca after Farley *et al* (1970) and some of the ionograms at Huancayo on 25 June 1969. Note complete absence of the spread *F* on the ionograms for the period when VHF radar indicated spread *F*.

(upward) value during any time of the night is followed by the generation of range type of spread *F* configuration on the ionograms with a delay of half to one hour.

Thus it is seen that the essential condition for the generation of range spread at the equatorial latitudes is firstly that the nighttime condition is not necessary but only the post-sunset period is necessary and secondly the existence of eastward electric field.

The rocket flights during the nighttime hours at equatorial latitudes have shown very large positive as well as negative electron density gradients at heights below the *F* region (Aikin and Blumle 1968; Prakash *et al* 1970; Kelley *et al* 1976; Morse *et al* 1977).

It is suggested that the range type of spread *F* first occurs at the base of *F* region during any part of the night when there exists a steep electron density gradient and provided that the horizontal electric field is eastward. The frequency spread is the later development of the range spread.

Thus it is seen that besides finding out a suitable theory for the generation of spread *F* irregularities, interpretation of spread *F* ionograms is not unique and needs detailed study using simultaneously different techniques. The recent launching of EQUION rocket from Peru is a welcome effort in this direction (Morse *et al* 1977).

8. Conclusions

(1) The spread *F* associated with the post-sunset uplifting of the *F* region is the 'range' type showing spread at lower frequency regions of the ionograms with clear critical frequencies. (2) The vertical drift velocity in the *F* region over the equator has an evening peak around 1800 LT. The onset of the 'range' spread *F* occurs around the period of peak upward velocity and most of the development of spread *F* occurs later when the *F* region drifts are decreasing or even downwards. (3) Spread echoes in VHF back-scatter records are seen during the period of occurrence of 'range' spread *F* on the ionograms. (4) The presence of frequency type of spread *F* on the ionograms does not cause spread in VHF echoes. (5) Range spread is absent on days with no evening peak of *F* region drift velocity and is present in the evenings with large peak of drift velocity. (6) The range spread occurs only at regions below or at the base of the *F* region and extends to within the *F* region gradually with time. (7) The threshold of the *F* region height above which only the spread *F* occurs seems to be untenable. The more necessary condition for the generation of range spread is the large vertical drift velocity in the evening hours.

Acknowledgements

Grateful thanks are due to Drs R F Woodman, M K V Bappu, Alan H Shapley and other colleagues for providing their data which has enabled this study. Thanks are also due to the US Academy of Sciences for the Arthur L Day Grant No. 30 for the consolidated study of the equatorial ionosphere as investigated by different experimentations. Thanks are also due to Senora Esther Carazao for hospitality offered to the author during his stay in Lima, Peru where these studies were initiated. The research at the Physical Research Laboratory is financed by the Department of Space, Government of India.

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Spread F in equatorial ionograms associated with reversal of horizontal F region electric field

by

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ABSTRACT. – *Comparing the vertical F region drifts measured by the VHF back scatter radar at Jicamarca and the vertical incidence ionograms at Huancayo, it has been found that a reversal of the F region vertical drift to positive (upward) value during any time of the night is followed by the generation of Range type spread F configurations in the ionograms, with a delay of half to one hour. It is suggested that the reversal to a strong eastward electric field is an essential condition for producing Range type of equatorial spread F at late times of the night when no spread F has occurred early.*

RÉSUMÉ. – *La comparaison des dérivés de la région F verticale mesurées par le radar à rétrodiffusion VHF à Jicamarca et d'ionogrammes d'incidence verticale à Huancayo, a montré qu'une inversion de la dérive verticale de la région F à une valeur positive (vers le haut) à tout moment pendant la nuit est suivi par la génération de configurations du type Range du spread F dans les ionogrammes, avec un retard d'une demi-heure à une heure. On suggère que ce renversement d'un champ électrique fort vers l'est est une condition essentielle pour la production du Spread F equatorial du type Range à la fin de la nuit lorsqu'aucun spread F ne s'est produit plus tôt.*

Introduction

Even the earliest observations of equatorial spread F by Booker and Wells (1938) at Huancayo and by Osborne (1952) at Singapore had shown that the minimum virtual height of the F region ($h'F$) increased rapidly after sunset reaching a maximum between 1900 and £ 2000 T; after reaching its maximum height, diffused echo pattern was seen over a wide range of height and frequency. Later, the occurrence of spread F at other equatorial stations Ibadan, Kodaikanal and Thumba was shown to be closely associated with the post-sunset rise of the minimum virtual height of the F region, $h'F$ (Bhargava, 1958; Lyon et al., 1961; Chandra and Rastogi, 1972a).

Recently Rastogi (1977) has studied the occurrence of spread F at Huancayo in relation to the vertical F region drift velocity as computed from the doppler shift of VHF back scatter echoes at Jicamarca. Firstly it was shown that the Range spread occurs following the general upward rising of the whole of the F region as evidenced by the increase of the height of the F_2 peak as well as the base. It was also shown that on days when the vertical drift V_z shows a large increase before the reversal of its direction in the evening, the rise of the F region is very prominent and strong spread F is observed in the ionograms. Thus, the post-sunset occurrence of spread F is shown to be closely associated with the large peak of V_z and large height rise of the F region.

Examining critically the ionograms at the equatorial station Thumba, Chandra and Rastogi (1972a) had shown that the equatorial spread F is of two distinctly different types : (i) Range spread F which occurs mainly in the pre-midnight period and is well correlated with the post-sunset increase of $h'F$ and (ii) Frequency spread F which usually occurs in the post-midnight period and which has no dependence on $h'F$ variation. Sastri and Murthy (1975) too showed that the spread F at Kodaikanal is of Range type during the pre-midnight period and of Frequency type during the post-midnight period.

In this paper, we discuss a rather little described phenomenon, i.e. the sudden onset of Range type of equatorial spread F at night time period other than that associated with post sunset changes in the F region based on the Huancayo ionograms. To assess the possible changes in the electric field in the F region during such events, the measurements of the vertical drifts in the F region, $V_z(F)$, at Jicamarca are also studied during these events. Fejer et al. (1976) have suggested a close connection between a reversed electric field during the night and the onset of spread F in VHF back-scatter records.

(*) On leave of absence from Jicamarca Radio Observatory, Instituto Geofísico del Peru, Lima, Peru.

Results

In Figure 1 are shown the whole year average nocturnal variation of Range and Frequency spread F at Huancayo during the moderately solar activity period 1972. It is seen that the onset of Range spread occurs at 1845 LT and the frequency of occurrence of Range spread increases very rapidly to a value of more than 50 % of time at 2000 LT. After about 2030 LT, the occurrence of Range spread continues to decrease with time till the sunrise. The Frequency type of spread has a very broad peak occurrence of about 30 % of time around midnight hours.

In Figure 2 are shown the variations of vertical F region drift at Jicamarca (V_z) compared with the geomagnetic H field at Huancayo and Trivandrum and the $D_{st}(H)$ values on 9-10 August 1972. SR and SS indicate the times of local sunrise and sunset respectively. Some ionograms at Huancayo on 9-10 August 1972 are reproduced in Figure 3. There had occurred a SC type of geomagnetic storm on 8 August 1972 at 1854 LT and at 1937 LT and thus the period under study was a storm recovery period and is evidenced by comparatively high $D_{st}(H)$ values being higher than $-50\ \gamma$. The $V_z(F)$ had reversed from upward to downward as usual at about

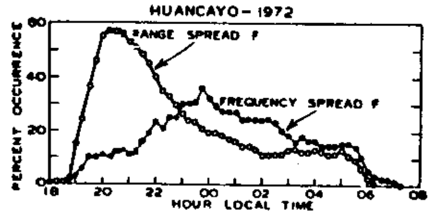
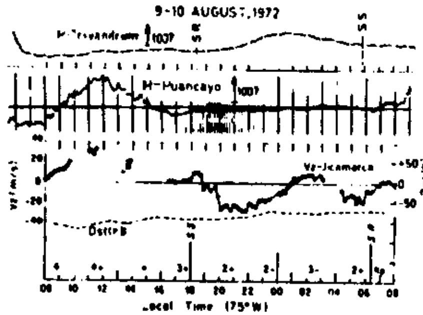


Fig. 1

Yearly average nocturnal variations of the Range and Frequency types of spread F at the magnetic equatorial station Huancayo.



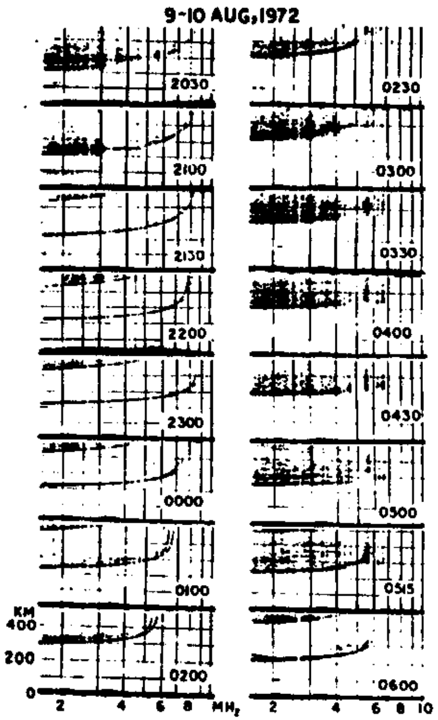


Fig. 3

A few ionograms at Huancayo on the night of 9-10 August 1972. Note the normal occurrence of Range type of spread F at 2030 LT and its decay by 2130 LT. The sudden onset of spread F at 0200 LT is associated with the reversal of V_z at 0100 LT.

Fig. 2

The variations of vertical F region drift (V_z) at Jicamarca and the geomagnetic horizontal field (H) at Huancayo and Trivandrum on 9-10 August 1972. Note the reversal of V_z at 0100 LT.

1845 LT and had a small positive peak immediately after sunset. $V_z(F)$ remained negative (downward) till about midnight but had turned again positive at 0100 LT and remained so for a couple of hours. There were no significant disturbances in the H field at Huancayo or at Trivandrum during this period ; the three hourly K_p value was around 3 between 0000 and 0400 LT. Examining the ionograms in Figure 3 one finds normal Range spread F at 2030 LT and 2100 LT which vanished in subsequent records. Perfectly clear $h'F$ traces were recorded at 2130 LT till 0000 LT. At 0100 LT some satellite echoes are seen over the first order $h'F$ trace and at 0200 LT strong scatter echoes are seen along with the $h'F$ trace. At 0230 LT these diffuse echoes had clearly developed into Range type spread F. It is also to be noted that $h'F$ had continuously increased from about 210 km at 0000 LT to 300 km at 0230 LT. By 0330 LT the spread F had extended upto the maximum frequency range. At 0500 LT multiple spread F layers are evidenced. The spread F disappeared by 0600 LT. It is clear that the onset of Range spread F at 0200 LT and upto 0515 LT was associated with the abnormal reversal of the $V_z(F)$ between 0100 and 0400 LT.

We now present another case where $V_z(F)$ had been negative in the afternoon hours due to the counter equatorial electrojet and this condition continued for a few hours after sunset. In Figure 4 are reproduced $V_z(F)$ at Jicamarca, H field at Huancayo and Trivandrum and $D_{st}(H)$ values on 13-14 May 1975, while some of the ionograms for the same day at Huancayo are reproduced in Figure 5. A SC type of geomagnetic storm was evident in Trivandrum magnetogram at 1900 UT (1400 75° WMT) but no evidence of the same could be seen in Huancayo magnetogram. However, this was immediately followed by the occurrence of a counter equatorial elec-

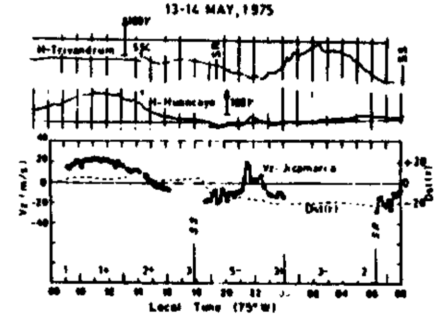


Fig. 4

The variations of vertical F region drift (V_z) at Jicamarca and the geomagnetic H field (H) at Huancayo and Trivandrum on 13-14 May 1975. Note the upward $V_z(F)$ between 2100 and 2300 LT.

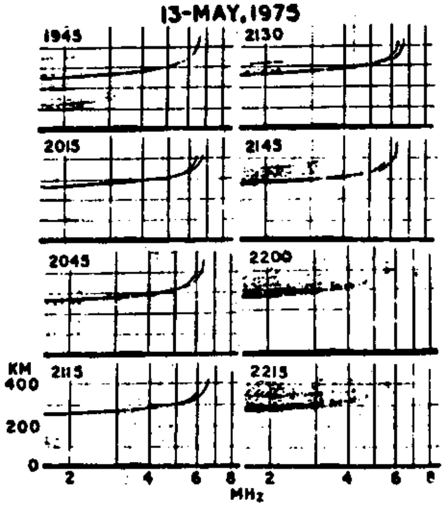


Fig. 5

A few ionograms at Huancayo on 13 May 1975 showing sudden onset of the Range type of spread F at 2130 LT associated with the reversal of V_z at 2130 LT.

trojet starting at 1500 LT. The drift remained negative till 2100 LT. But just after 2100 LT $V_z(F)$ became positive and remained so upto 2230 LT. The $D_{st}(H)$ values were slightly positive till 1900 LT after which it became negative but still weak being about − 20 γ. Thus the period of abnormal reversal of $V_z(F)$ at night was during the main phase of a mild storm. Examining the ionograms in Figure 5 one sees a complete absence of spread F condition which is usually seen after sunset period. Only at about 2130 LT a satellite echo was seen and Range spread F appeared at 2145 LT. By 2200 LT the spread F condition was extended upto the whole range to frequencies reflected from the F region. It is to be noted that the height of the F region did not show any significant rise during this period. Thus the absence of evening peak of V_z had inhibited the occurrence of spread F and the late onset of spread F was associated with the reversal of V_z at 2100 LT.

We next present a case when a sudden onset of Range spread occurred in the post midnight hours. In Figure 6 are presented the variations on 30-31 August 1960 of $V_z(F)$ at Jicamarca compared with corresponding variations of H at Huancayo and at Trivandrum and of $D_{st}(H)$ values, while a few ionograms are reproduced in Figure 7. This was a fairly quiet day with very low $D_{st}(H)$ values although a weak SC in H was evident in both the Trivandrum and Huancayo ionograms. The

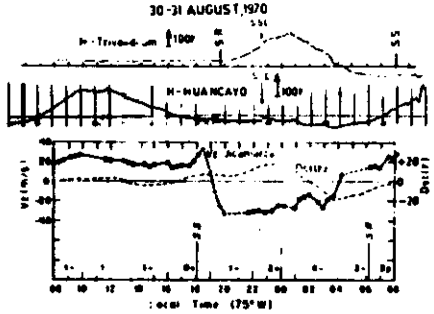


Fig. 6

The variations of vertical F region drift (V_z) at Jicamarca and the geomagnetic h field at Huancayo and Trivandrum on 30-31 August 1970. Note the reversal of $V_z(F)$ at 0400 LT about two hours before sunrise.

$V_z(F)$ had shown nice peak at about 1830 LT which was followed by a strong spread F condition which had vanished by 2100 LT. Around 0400 LT V_z had suddenly became positive and remained so even upto 0800 LT. This sudden reversal of V_z seems to have caused intense spread F condition at 0515 LT which continued even after layer sunrise at 0545 LT.

We now present a case of sudden onset of spread F at Huancayo during a rather geomagentically disturbed night following a GC type of storm. In Figure 8 are shown the variations of the following parameters on 15-16 May 197… : (i) $V_z(F)$, (ii) H field at Huancayo, (iii) H field at Trivandrum and (iv) $D_{st}(H)$ values, while some ionograms at Huancayo are reproduced in Figure 9. The V_z had reversed its direction at sunset and remained negative till 2200 LT. For less than an hour between 2200 LT and 2245 LT, V_z was positive but very small of the order of 5 m/s. At about 0330 LT the V_z had become significantly positive and it remained positive even upto sunrise and later on. The ionograms did not show any spread echoes upto 0430 LT and strong Range spread F started at 0445 LT and continued to be present even after the sun had regenrated the new F layer ionization after sunrise.

Finally we present the case of Range spread at a night with highly geomagnetic disturbed condition. The variations of parameters V_z at Jicamarca, H at Huancayo and at Trivandrum and $D_{st}(H)$ values on 13-14 September 197… are shown in Figure 10, while some of the ionograms at Huancayo are reproduced in Figure 11. A SC type of geomagnetic storm had starded on 13 September at 1240 UT (or 0740 LT). The K_p values were exceptionally high on this day, the highest value of 8 being recorded between 2200 LT and 0100 LT. The $D_{st}(H)$ values were more than − 100 γ during the pe-

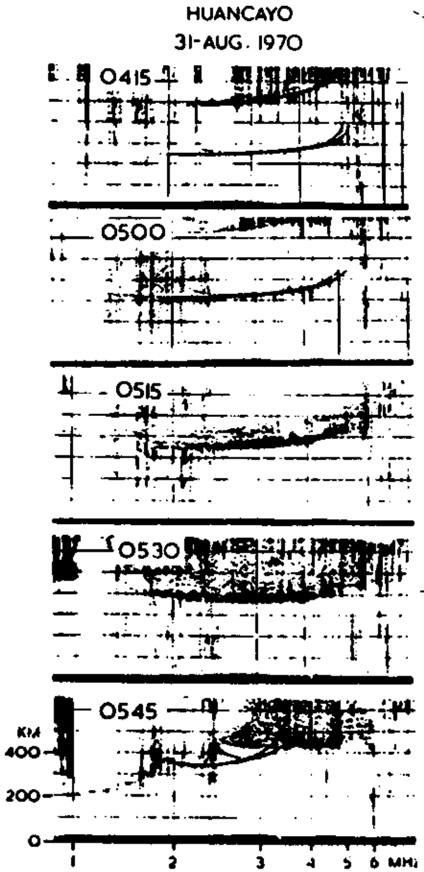


Fig. 7

A few ionograms at Huancayo on 31 August 1970 showing sudden onset of the Range type of spread F at 0515 LT associated with the reversal of V_z at 0400 LT.

riod. Large fluctuations in $V_z(F)$ were noted both during the daytime as well as during the nighttime. The $V_z(F)$ was negative during the evening hours but became significantly positive at 2315 LT with the peak value of + 30 m/s. The ionograms at Huancayo indicated some satellite traces at 000 LT followed by a strong Range spread at 0015 LT and on subsequent records.

The equatorial spread F is supposed to be a post sunset phenomenon associated with the rapid rise the F region. Due to this basic fact many theories hav…

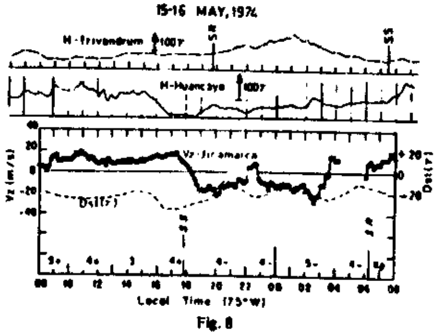


Fig. 8

The variations of V_z at Jicamarca and the H field at Huancayo and Trivandrum together with $D_{st}(H)$ values on 15-16 May 1974.

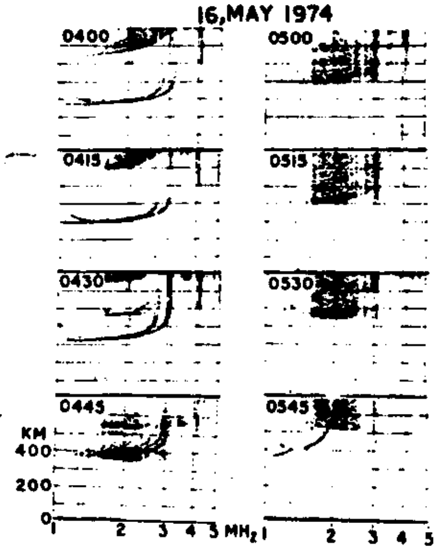


Fig. 9

A few ionograms at Huancayo on 16 May 1974 associated with the reversal of $V_z(F)$ at about 0300 LT.

been suggested on the basis of changes that occur during sunset periods.

Martyn (1959) suggested the amplification of weak irregularities in the F region due to its movement ...ward against the ambient ionization. The driving me...nism to move the irregularities relative to the ambient ionization is proposed to be vertical drift driven

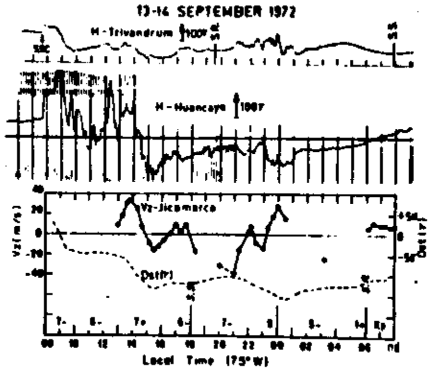


Fig. 10

Variations of the $V_z(F)$ at Jicamarca, H field at Huancayo and Trivandrum as well as $D_{st}(H)$ values on 13-14 September 1972. Note highly disturbed conditions with very high K_p values.

by east-west electrostatic field. Calvert (1963) suggested the contraction of the neutral atmosphere due to its cooling by downward thermal conduction after sunset as the source of setting up instability in the ionosphere similar to that caused by the electrostatic field. This theory cannot account for the onset of the irregularities late in the night when the temperature distribution has been stabilized. The theory most suitable for the generation of spread F should take into account the necessity of having strong eastward electric field in the F region heights.

Woodman and La Hoz (1976) have classified the spread F observed by the Jicamarca radar on the basis of their spectrum and dynamics of the backscatter echoes. They have also suggested different mechanisms for these different types of spread F irregularities. Morse et al. (1977) have suggested a gradient drift instability as responsible for the late and sudden appearance of strong echoes in the Jicamarca radar after a reversal in the electric field. The evidence presented here supports the idea that a gradient drift instability is responsible for the late onset of the spread F. The gradient being positive in the lower side of the F region, the eastward electric field (denoted by the upward velocity measured by the radar) causes the generation of irregularities through the gradient drift instability mechanism.

Contrary to the existing understanding that the geomagnetic storms inhibit the Range spread F (Lyon et al., 1958, 1961 ; Rangaswami and Kapasi, 1963 ; Chandra and Rastogi, 1972a, b) is has been shown that even strong geomagnetic storms can generate Range spread F. Future statistics should differentiate the correlation between the early (19-20h) and late Range spread F and magnetic storms.

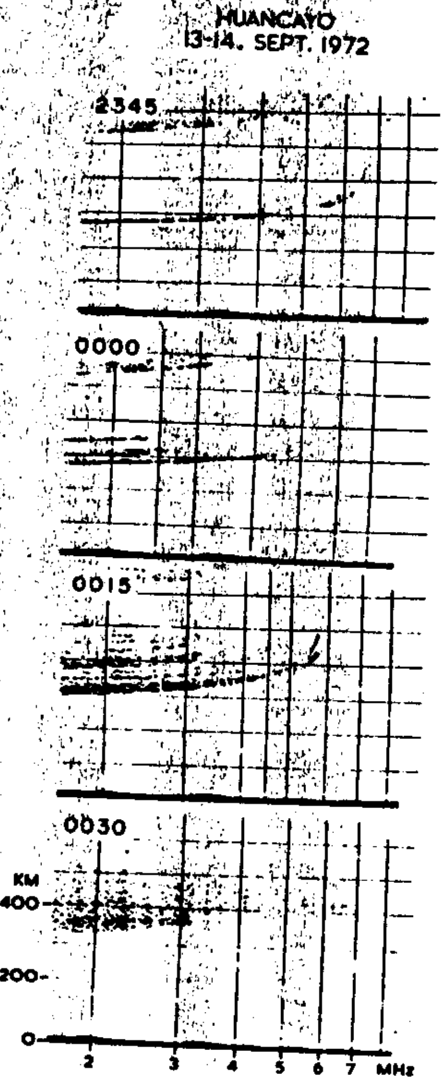


Fig. 11

Some ionograms at Huancayo on 13-14 September 1972 showing Range type of spread F.

Acknowledgements

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On the occurrence of equatorial spread-F in the evening hours

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Abstract— By comparing electron drift velocities at Jicamarca with corresponding ionograms and VHF radio scintillation records at Huancayo it has been shown that the day-to-day variability in the occurrence of equatorial spread-F irregularities in the post-sunset period depends critically on the time of reversal of the Sq electric field. The field reversal before sunset does not produce any spread-F in the evening hours, while the continuation of the day-time electric field for a couple of hours after sunset at normal strength is a favourable condition for generating spread-F.

1. INTRODUCTION

Interest in studies of equatorial spread-F has increased almost explosively in recent years with the availability of VHF backscatter echo power maps from Jicamarca, with the development of theoretical simulation of the irregularities and with the rapid growth of satellite communications. Thus spread-F, first identified on the routine vertical incidence ionograms of Huancayo, is now studied by VHF backscatter echoes, satellite radiowave scintillations, airglow depletion cells, *in situ* satellite measurements, etc. Rastogi (1980) has shown that the occurrence of post-sunset, range-type spread-F at Huancayo shows a very consistent and strong seasonal variation, with maximum around the December solstice and minimum around the June solstice during any of the years of the solar cycle. It was shown that reversal of the electric field during the June solstice occurs in general at about the same time as sunset at F-region heights (1915 LT) and that spread-F irregularities do not get sufficient time to develop. During the December solstice the electric field reverses at about 2115 LT, while F-region sunset occurs at about 2000 LT and thus enough time is provided for the irregularities to develop and produce spread-F echoes on the ionograms. Nevertheless the question is asked why on some evenings the spread-F occurs very strongly and on others it does not? The present paper is an attempt to understand this problem and provide some definite suggestions.

The data utilised are horizontal drift velocities from the Jicamarca VHF backscatter radar, vertical incidence ionograms at Huancayo and VHF radio wave amplitude scintillations at Huancayo. Balsley (1969) showed that the electron drift velocity (V_e, m s^{-1}) measured by the Jicamarca VHF backscatter radar may be used to estimate a value for the horizontal electric field responsible for the drift, using the expression

$$E_y = -0.88 + 10^{-6} V_e \, (\mathrm{V\,m^{-1}}).$$

Woodman (1970) presented a large amount of data on vertical drift velocities in the F-region over Jicamarca and suggested that vertical drifts can be taken as a measure of the horizontal electric field (1 mv m^{-1} corresponds to approximately 40 m s^{-1}). Balsley and Woodman (1969) had earlier shown that there was a good correlation between horizontal drift velocities in the E-region and vertical F-region velocities at Jicamarca. Thus a vertical upward or horizontal westward velocity corresponds to an eastward electric field characteristic of day-time conditions, while a vertical downward or horizontal eastward velocity corresponds to a westward electric field characteristic of night-time conditions. These facts are the basis of the discussion in the present paper.

2. SOME CASE STUDIES

Figure 1(a) shows comparisons between horizontal E-region drifts at Jicamarca and f-plots at Huancayo for the period 1200 LT on 14 March to 0600 LT on 16 March 1968. It will be seen in Fig. 1(a) that on the evening of 14 March the day-time positive drifts had decreased to zero before 1900 LT, approximately at the time when the E-region critical frequency decreased below 1 MHz. Thus the E-region had already reversed to the night-time condition even around the sunset period. No spread-F was observed on the ionogram on the night of 14–15 March and

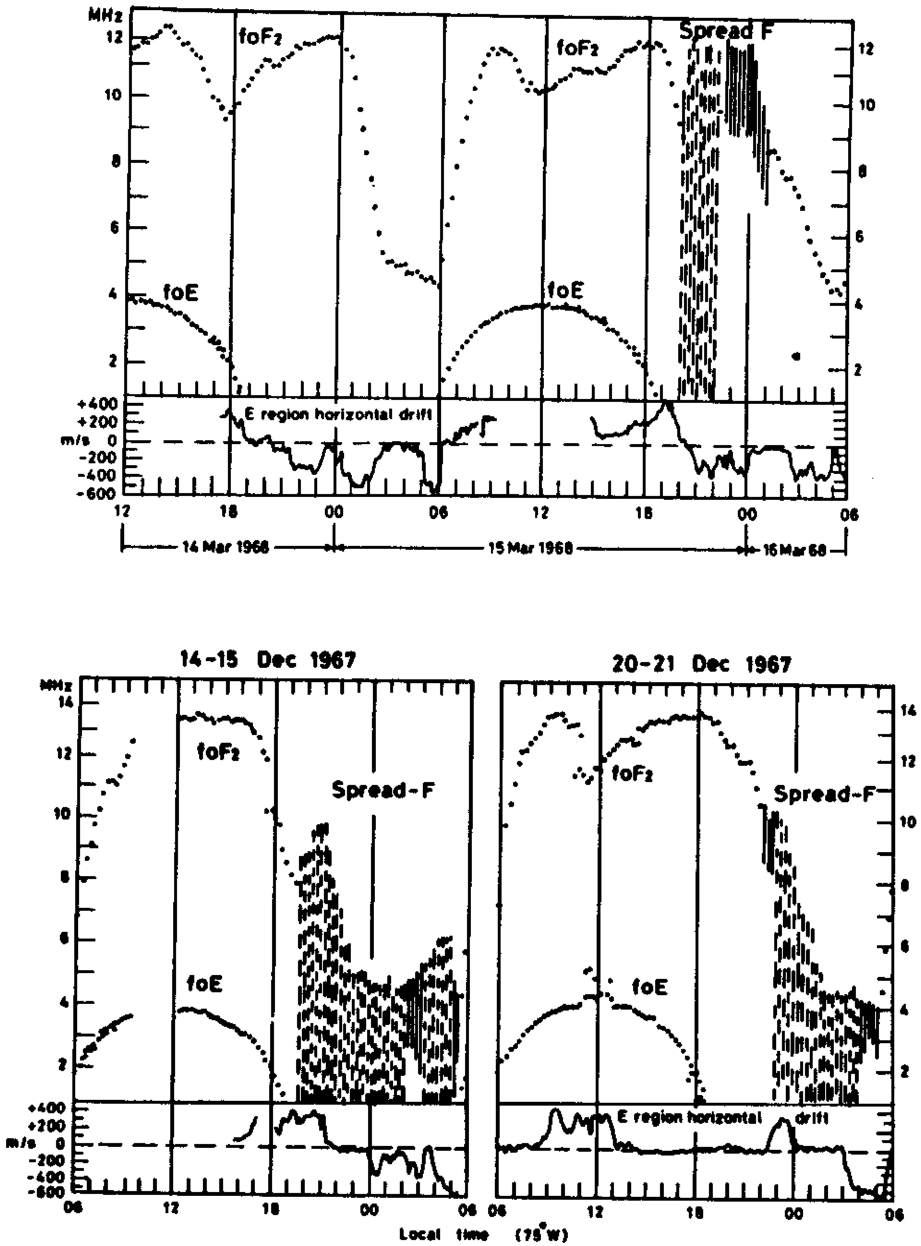

Fig. 1. Variation of *E*-region horizontal electron drifts at Jicamarca and *f*-plots of ionograms at Huancayo for two sets of days: (a) 14–15 and 15–16 March 1968; (b) 14–15 and 20–21 December 1967.

each 15 min value of foF_2 was clearly identifiable. On the evening of 15 March *foE* had decreased below 1 MHz at 1845 LT, but the *E*-region drifts were around 400–500 m s^{-1} even up to 1930 LT and only reversed to the night-time condition after 2000 LT. The ionosphere was thus subjected to an eastward electric field for at least 1 h after sunset. Strong range spread did occur on the evening of 15 March.

Referring to Fig. 1(b) it is seen that on the evening of 14 December 1967 the *E*-layer had disappeared by 1900 LT, but strong positive drifts continued even up to 2100 LT. Strong range spread-*F* started at 1930 LT and continued the whole night. On 20 December the *E*-region drifts had decreased to zero, even in the afternoon at 1300 LT, and remained so until about 2200 LT, and it is to be noted that no spread-*F* was observed in the evening hours. Thus during the evening hours no eastward electric fields were present in the ionosphere and no spread-*F* was generated. It will be noted that between 2230 and 2330 LT the drifts had become strongly positive and were associated with strong spread-*F* during the night starting at 2200 LT. Events of this kind have been reported by RASTOGI and WOODMAN (1978).

In Fig. 2 we compare vertical drifts at Jicamarca with VHF scintillation records and ionograms on two sets of days, 11–12 and 20–21 March 1975. It is seen that on 20–21 March the vertical drifts had reversed at about 1800 LT. No sign of spread-*F* was observed on the ionogram (reproduced here) and no scintillations were observed on signals from the ATS-6 beacon satellite on 140 or 137 MHz received at Huancayo. Thus an early reversal of vertical drift was associated with a complete absence of *F*-region irregularities in the evening hours. On 11 March 1975 the vertical drifts were strongly positive in the evening hours up to 1900 LT and reversed to night-time conditions only at about 1930 LT. The ionograms indicate satellite traces at 1945 LT and strong range spread-*F* at later times. The radio beacon signals on 137 and 140 MHz from ATS-6 to Huancayo had almost saturated scintillations on the evening of 11–12 March. Thus a strong and late reversal of *F*-region vertical drift appears to be very conducive to the generation of spread-*F* irregularities.

Figure 3 compares variations of vertical drifts at Jicamarca with the ionograms and VHF scintillations recorded at Huancayo on 20–21 and 21–22 May 1975. It is seen that on 21–22 May the drifts had reversed from positive values during day-time to night-time values even before 1800 LT and remained so during the rest of the night. No scintillations on 137 or 360 MHz beacons from ATS-6 to Huancayo were observed on the night of 21–22 May and no spread-*F* was observed on ionograms recorded at 2000, 2200 and 2300 LT at Huancayo. On 20 May the values of vertical drifts were slightly negative during 1600–1700 LT, but had become positive before sunset and

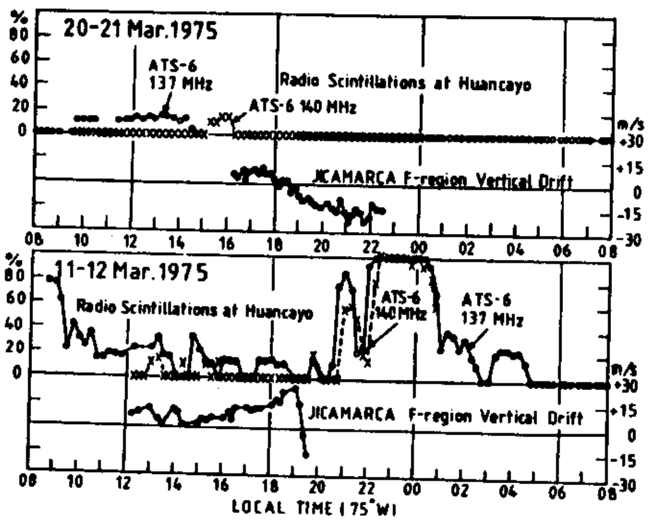

Fig. 2. (a) Comparison of vertical *F*-region electron drifts at Jicamarca with the amplitude scintillations of ATS-6 signals at Huancayo on 11–12 and 20–21 March 1975.

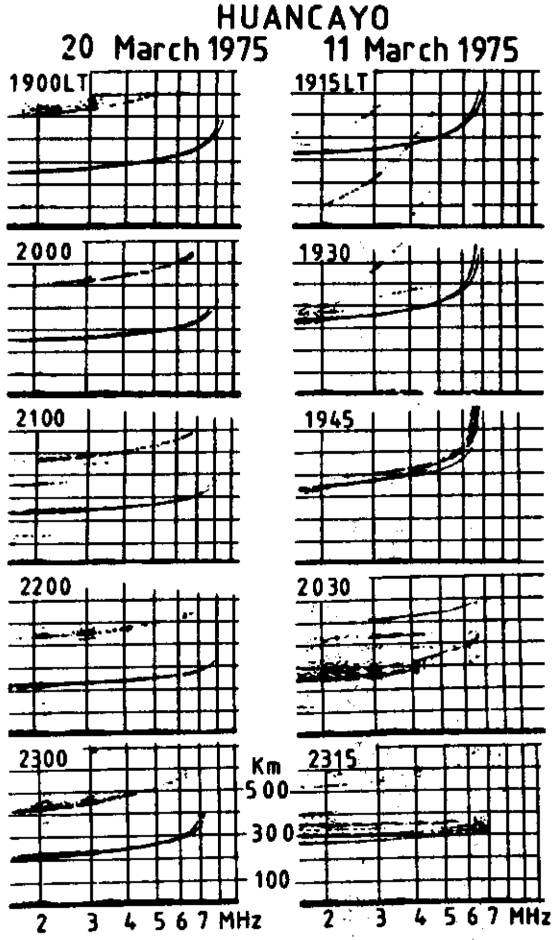

Fig. 2. (b) Some of the ionograms at Huancayo on 11 and 20 March 1975.

reversed to night-time conditions only after about 2000 LT. Strong scintillations were seen on the 137 and 360 MHz signals from ATS-6 to Huancayo during that night and strong spread-*F* was also observed on the ionograms at Huancayo. The ionograms reproduced here also show that the spread-*F* was of the range type, with scattering layers at a number of altitudes occurring simultaneously. This case also confirms that an eastward electric field in the post-sunset hours is a necessary condition for the generation of spread-*F* in the equatorial ionosphere.

During the vertical electron drift velocity mode of operation of the Jicamarca radar, the quality of the echo has also been monitored by the operators and any *F*-region irregularities which they observed have been recorded as spread-*F*. Using these drift and spread-*F* data, both made by the Jicamarca radar, FARLEY *et al.* (1970) have made an extensive study of equatorial spread-*F* and found that these irregularities can be generated anywhere in the *F*-region, no matter with what velocity the region is moving. Quite a large set of vertical drift plots are available in the paper by FARLEY *et al.* (1970) and by WOODMAN (1970) and the ionograms for the days for which this drift data is given

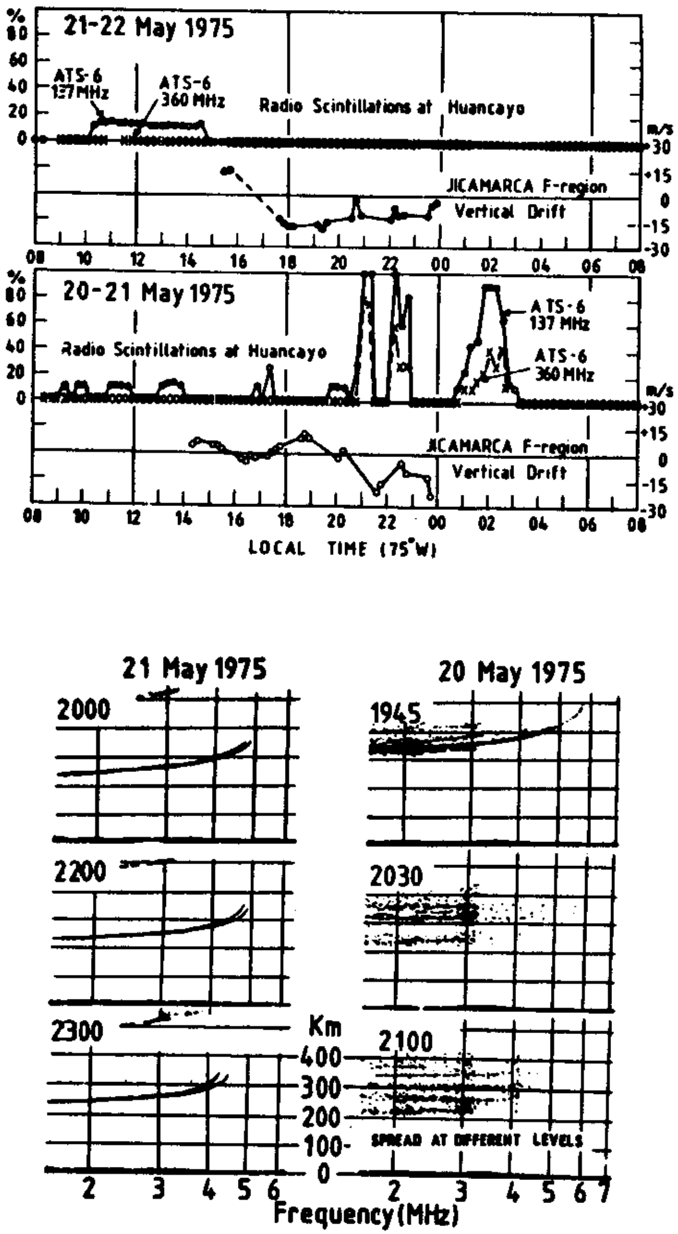

Fig. 3. (a) Comparison of vertical *F*-region electron drifts at Jicamarca with the amplitude scintillation of ATS-6 signals at Huancayo on 20–21 and 21–22 May 1975. (b) Some of the ionograms at Huancayo on 20 and 21 May 1975.

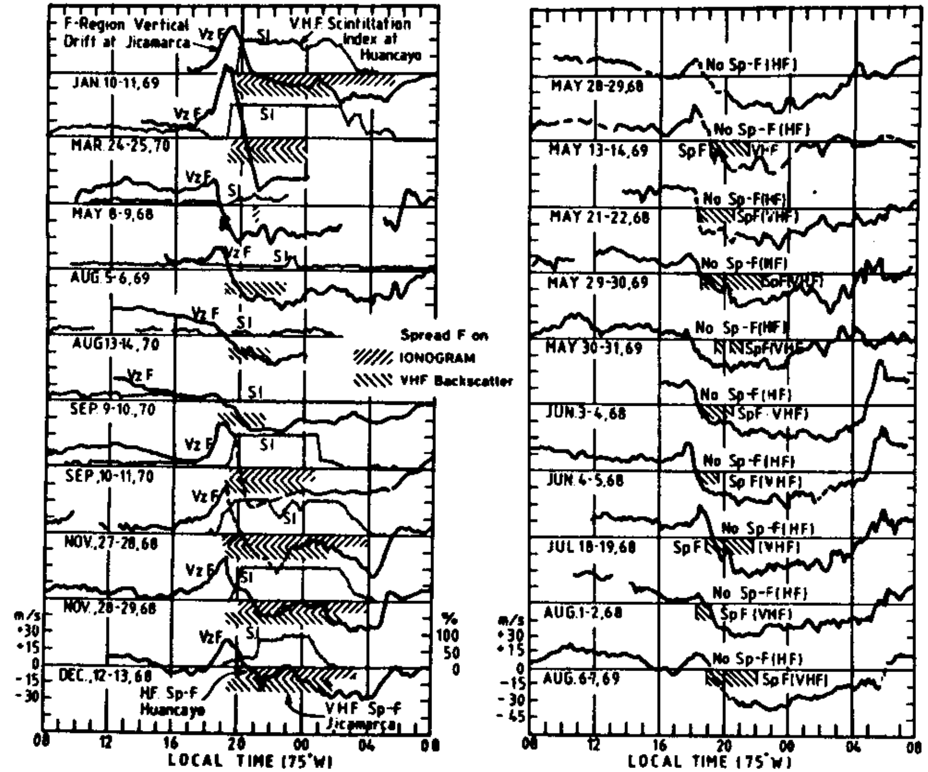

Fig. 4. Temporal variations of (a) vertical F-region electron drifts (V_zF) at Jicamarca, (b) the VHF scintillation index (*SI*) at Huancayo, (c) the occurrence of spread-*F* on the backscatter radar at Jicamarca (VHF S_pF shaded \\\\\ and (d) on the normal incidence ionosonde at Huancayo (HF S_pF) shaded /////.

for Huancayo have been examined for the occurrence of spread-*F*. In Fig. 4 are reproduced some of the drift plots, together with the temporal occurrence of HF spread (as observed on the Huancayo ionosonde), VHF spread (as observed with the Jicamarca radar) and VHF scintillations (observed on satellite signals received at Huancayo). Examining these plots individually, one finds that on 10–11 January and on 24–25 March 1969 there was a strong peak of vertical drift between 1900 and 2000 LT, which reversed to night-time conditions only around 2030 LT, well after the layer sunset. On both evenings HF as well as VHF spread was observed beginning at 1930 LT. The amplitude scintillations were almost saturated up to about 0200 LT. Thus there were excellent correlations between the Jicamarca vertical drift data, the Huancayo ionosonde data and the Huancayo amplitude scintillations data. On 8–9 May 1968 and 5–6 August 1969 the vertical drifts were strong in the afternoon hours, but reversed to night-time conditions earlier than 1900 LT. Sunset in the *F*-region during these months being around 1915–1930 LT, there was insufficient time for irregularities to develop. Little or no HF spread or VHF radio scintillations were observed on 8–9 May, but some VHF spread was observed on 5–6 August. On 13–14 August and 9–10 September 1970 the drifts were again weak and reversed very early in the evening hours. No spread-*F* was observed on the ionograms, but some scintillations on VHF radio waves were observed. The next four cases, for 10–11 September 1970 and 27–28 November, 28–29 November and 12–13 December 1968, are examples in which a large peak in the drift was observed before its reversal around 2000–2100

LT, and in all four cases strong spread-*F* and scintillations were observed.

The second set of data illustrated in Fig. 4 are examples in which the drift had reversed to the night-time condition comparatively early and in no case was spread-*F* observed on the ionograms at Huancayo. However, VHF radar recorded spread-*F* on these nights. RASTOGI (1978) has shown an example of complete absence of spread-*F* on the ionograms when VHF spread-*F* was noted on vertical drift records. These VHF spread could be the weak irregularities well below the normal ionosphere reported by FARLEY *et al.* (1970).

Thus it would appear that the day-to-day variability in the occurrence of spread-*F* is dependent on the time of reversal of the *Sq* electric field with respect to the time of sunset at ionospheric levels. If the reversal precedes sunset then there is no chance of spread-*F* generation on that night. If, however, the electric field remains eastward (as in the day-time) for even an hour or so after sunset, then there is a very good chance of spread-*F* generation. It may be mentioned that due to the slow growth rate of irregularities in the *F*-region the electric field may have reversed slightly before the irregularities have fully developed, so as to produce their effects on the reflection, scatter or in transmission of radio waves. Thus, just at the time of occurrence of spread-*F* the electric field may be positive or negative. What is important is that the electric field should remain eastward for about an hour after sunset, when ionisation in the lower part of the region will have disappeared leaving an *F*-layer with a sharp plasma gradient at its base.

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Study of Equatorial Ionospheric F-region Irregularities by Reflection, Backscatter & Transmission of Radio Waves

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The modified range time intensity (MRTI) records of 50 MHz backscatter radar at Jicamarca are compared with simultaneous vertical incidence ionograms at Huancayo and the amplitude scintillations of VHF radio waves from geostationary satellite ATS-3 received at Huancayo. The altitudes of range spread echoes in the ionogram, distinguished from the virtual height of normally reflected echoes, correspond very well with the altitudes of the maxima in the intensity of scatter echoes in VHF backscatter MRTI records. This suggests that the range type of equatorial spread F echoes on the HF ionogram as well as the backscatter echoes of frequencies greater than the plasma frequencies involve thesame process which is the scattering by layers of sharp plasma density gradient. The generation of post-sunset evening spread-F is inhibited during events of the early reversal of the electric field. The irregularities are generated when the F-region drifts are upward, i.e. the horizontal electric field is eastward, but may continue to grow even after the drift is very low or even reversed. The vertical movement of the scattering layers may be independent of the general movements of the main F-layer.

1 Introduction

The first routine observation of the equatorial ionosphere was started in 1933 by the establishment of an automatic vertical incidence ionospheric sounder at Huancayo[1]. Due to the unique configuration of orthogonality between the northward magnetic field, vertical plasma density gradient and the east-west electric field over the magnetic equator, the equatorial ionosphere has been found to be a region of host of plasma irregularities and discontinuities and these were detected to be present during both daytime[2] and nighttime hours[3]. In the presence of these irregularities, the HF ionosonde records show large amount of scatter echoes. During the daytime hours *h*'-*f* trace from the E-layer is generally obliterated due to scatter from the *q* type of sporadic layer and during the nighttime the F-region trace can be indistinguishable among the scatter echoes from the spread-F.

The radio waves from artificial satellites traversing the equatorial ionosphere undergo changes of phase as well as amplitude if these irregularities are present on the intervening path. During the daytime hours, the normal *q* type of Es produce the fluctuations of the radio beacons on VHF range up to about 1-2 dB in the American sector and about 5-6 dB in the Indian sector[4]. However, in the presence of blanketing type of Es the scintillations may exceed even 10-20 dB (Ref. 5). During nighttime, strong scintillations are observed around 2200 hrs LT with the peak-to-peak fluctuations exceeding 20 dB. The nighttime equatorial scintillations were shown to be associated with range-type spread-F showing multiple layers of scattering with no group retardation effects[6]. It has been found that intense nighttime scintillation (exceeding 20 dB) of VHF radio waves was observed when the ionograms showed blanketing Es simultaneously at different heights[7].

Farley *et al.*[8] showed that the field-aligned irregularities associated with equatorial spread-F can backscatter 50 MHz radio waves such that the echoes may attain a strength of perhaps 10^7-10^8 times the background thermal level. Fejer *et al.*[9] described the modified range time intensity (MRTI) technique to study the height variation of the backscatter power. The incoming signal is attenuated by an amount that is increased linearly from 0 to 70 dB in 30 sec and thus the region corresponding to the strongest echoes persists the longest in the film strip recording the echoes. The technique has been further developed producing digital power map showing the echo power variation with altitude as a function of time[10]. It has been shown by Rastogi and Woodman[11] that the range-type spread-F is very efficient for the backscatter of VHF radio waves while the frequency spread does not seem to produce strong VHF echoes. Air Force Geophysics Laboratory, Bedford, Massachusetts, USA, in collaboration with the Instituto Geophysico del Peru, has been recording amplitude scintillations of VHF radio beacons from geostationary satellites at Huancayo. An index of scintillation has been derived from the records of amplitude according to the method described by Whitney *et al.*[12]

In this paper the VHF backscatter records at Jicamarca are compared with the simultaneous HF ionosonde records at Huancayo and with, the VHF radio scintillation observations at Huanayo.

2 Observation

In Fig. 1 are shown an excellent example of MRTI record of VHF backscatter echoes at Jicamarca at 2107 hrs LT and the ionogram at Huancayo at 2100 hrs LT on 16 Apr. 1974. The variation of the scintillation index of 137 MHz radio beacon from ATS-3 received at Huancayo is also shown in Fig. 1. The MRTI record showed strong echo at 100 km and at a number of altitudes between 200 and 400 km. The ionogram did not show the normal p'-f trace and a fully developed range-type spread F was present, with strong echoes returned from a number of altitudes. It is remarkable to note that the altitudes of spread F layers seen on the ionogram and the altitudes of the strong echoes seen on the MRTI records had excellent correspondence. The VHF scintillations at those periods were saturated with the index of 100%. This shows that during a fully developed stage of range spread, there are a number of levels in the F region which strongly scatter radio waves from 2 to 50 MHz and these layers of irregularities are very effective for producing scintillations of the radio waves traversing through the ionosphere.

In Fig. 2 are shown the MRTI records and the corresponding ionograms on 25 June 1974. At 2030 hrs LT and 2100 hrs LT strong range type of spread-F as well as strong VHF backscatter echoes were present at 300-400 km altitudes. At 2130 hrs LT the structure of spread-F on the ionogram had transformed into the

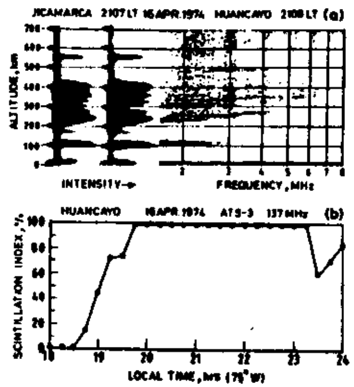

Fig. 1—(a) MRTI record of 50 MHz backscatter radio waves at Jicamarca and the corresponding vertical incidence ionogram at Huancayo on 16 Apr. 1974; and (b) variation of the scintillation index of ATS-3 (137 MHz) beacon at Huancayo on the night of 16 Apr. 1974

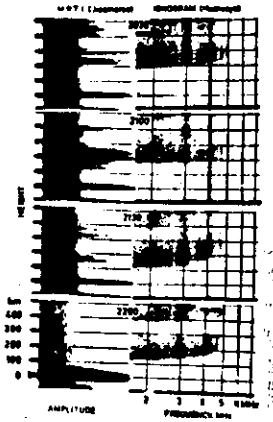

Fig. 2—Comparison of the MRTI records of 50 MHz backscatter echoes at Jicamarca with the vertical incidence records at Huancayo on 25 June 1974

frequency type showing broad range of diffuse scatter and scattering from a definite altitude was not seen. The corresponding VHF echoes on MRTI records were weak. At 2200 hrs LT, (i) the spread-F was clear of frequency type, (ii) the record clearly showed group retardation effects, (iii) no multiple scattering layers were seen on the ionograms and (iv) the corresponding MRTI records did not show any VHF echoes. It is thus seen that only those types of spread-F echoes which do not show group retardation are effective in producing VHF backscatter echoes.

In Fig. 3 are shown the ionograms, MRTI records and the scintillation index on 19 Nov. 1970. At 1900 hrs LT the ionogram trace was clear without any scatter echoes and high multiple echoes were seen suggesting an increase in the height of the F-region around that period, and satellite traces were recorded due to off-vertical echoes. The MRTI records did not show any scatter echo and the scintillations were very low in magnitude. At 1930 hrs LT a scattering layer had developed definitely below the F-layer which itself was quite clear. The MRTI record showed echoes and the scintillation index of 137 MHz radio beacon had increased to 60%. At 1945 hrs LT and subsequent periods the spread-F layer at the base of the F-layer (as seen in the ionogram) grew stronger, VHF backscatter echo on the MRTI record also grew stronger and the scintillations grew almost to saturation level. The ionogram at 2200 hrs LT showed multiple layers with no group retardations; MRTI record indicated multiple altitudes of strong echoes and the scintillation index was 100%.

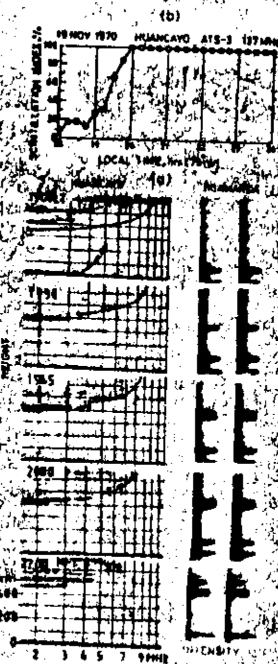

Fig. 3—(a) Comparison of ionograms at Huancayo with the MRTI records of 50 MHz backscatter echoes at Jicamarca on 19 Oc .1970; and (b) variation of the scintillation index of ATS-3 (137 MHz) beacon at Huancayo on 19 Nov.1970

In Fig. 4 are compared the development of the spread-F and the VHF scintillations on 22 Mar. 1974. The ionogram at 1745 hrs LT showed a strong layer of ionization at 150 km intermediate between E- and F-regions. At 1800 hrs LT the critical frequency of the normal E-layer had decreased to less than 2 MHz, but ionization density of the intermediate layer remained the same although the height had increased to 170 km. At 1830 hrs LT the height of the intermediate layer increased to 200 km and strong spread type echoes had developed between 200 and 300 km, while the F-layer trace was clear with minimum virtual height portion of the trace extending to almost the lowest frequency end of the ionogram indicating the absence of irregularities in the main F-layer. At 1845 hrs LT very conspicuous spread echoes at a number of altitudes well below the F-region had developed. It is interesting to note that the scintillation index of the VHF radio beacon at 1845 hrs LT was more than 60% even when no spread echoes

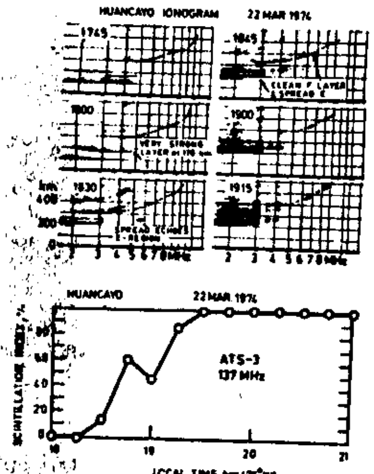

Fig. 4—Comparison of the ionograms at Huancayo and the scintillation index of 137 MHz ATS-3 radio beacon at Huancayo on 22 Mar. 1974

in the F-region were evident. These scintillations were due to irregularities situated at different levels in between the E- and F-layers.

In Fig. 5 are shown the ionograms and the corresponding MRTI records on 22 Mar. 1974. The records at 1915 hrs LT clearly show VHF scatter at 230 and 300 km corresponding to the spread-F echoes below the F-region. At 1945 hrs LT the irregularities had gone up and joined the F-region and the MRTI record showed echoes up to 350 km. The record of 2145 hrs LT showed excellent correspondence in altitude of VHF backscatter echoes at 300, 375 and 400 km and the corresponding altitudes of the spread-F echoes.

In Figs 6 and 7 we compare the ionograms at Huancayo, MRTI records at Jicamarca and the VHF scintillations at Huancayo on 24 Mar. 1974. The ionogram at 2000 hrs LT showed clearly the first and second order reflection trace. Except for some random signals around the trace, no spread-F irregularities seemed to be associated with the base of the F-layer. There were some echoes in between the first and second order traces due to off-vertical irregularities. The MRTI record showed some extremely thin layer at 220 km at 2000 hrs LT and the scintillation index of VHF beacon was zero. It may be mentioned that MRTI records showed echoes at 100 km even when the ionograms did not record the Es reflections from the same height. At 2015 hrs LT spread-F irregularities had developed at the base of the F-layer as well as at higher altitudes; MRTI record did not show any strong echo region and scintillations were too weak (less than 10% or 1 dB). The ionogram at 2045 hrs LT showed strong spread-F irregularities at the base (250 km) of the F-layer. At 2100 hrs LT, the MRTI record showed definite layers of backscattering of VHF radiowave from different altitudes between 300 and 450 km and the VHF radio scintillations had recorded to almost saturation level. At 2130 hrs LT the MRTI record showed another region of scatter at altitudes of more than 600 km.

In Fig. 8 are shown the comparison of MRTI records and the ionograms on 15 and 16 Oct. 1970. In Fig. 9(a) are reproduced the temporal variation of F-region vertical drift at Jicamarca on 16-17 Oct. 1970 and in Fig. 9(b) are shown the temporal variations of the scintillation index of 137 MHz radio beacon from ATS-3 to Huancayo on certain days of October 1970. On 15 Oct. 1970, strong spread-F were recorded at Huancayo in the evening hours up to 2215 hrs LT. The Jicamarca MRTI records also showed strong echoes from the F-layer during the corresponding period. On

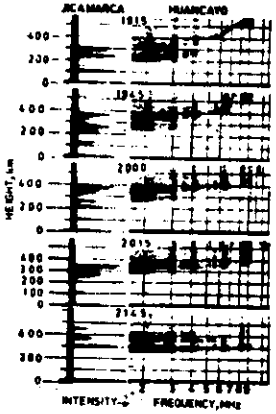

Fig. 5—Comparison of the MRTI records of 50 MHz backscatter echoes at Jicamarca with the vertical incidence ionogram at Huancayo on 22 Mar.1974

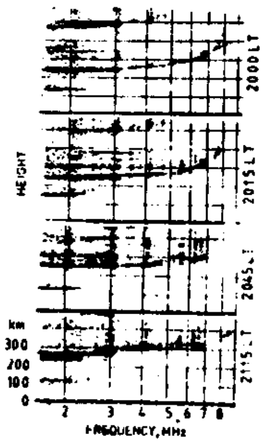

Fig. 6 Set of ionograms at Huancayo on 24 Mar.1974

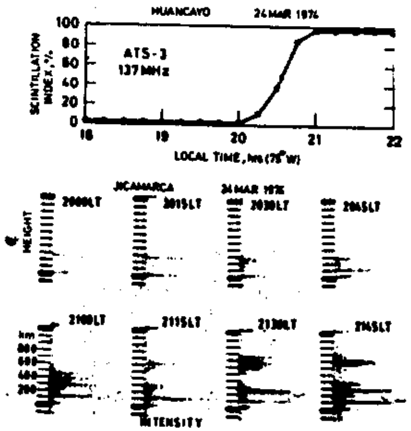

Fig. 7—Comparison of MRTI records of 50 MHz backscatter echoes at Jicamarca and the scintillation index of 137 MHz ATS-3 radio beacon at Huancayo on 24 Mar.1974

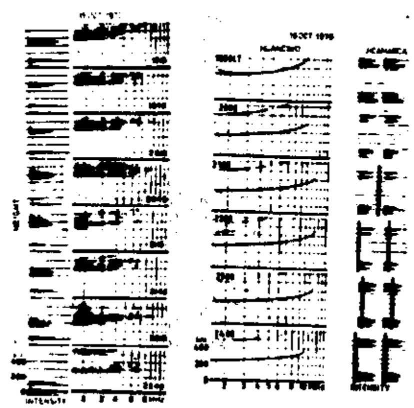

Fig. 8—Comparison of MRTI records of 50 MHz backscatter echoes at Jicamarca and vertical incidence ionograms at Huancayo on 15 and 16 Oct.1970

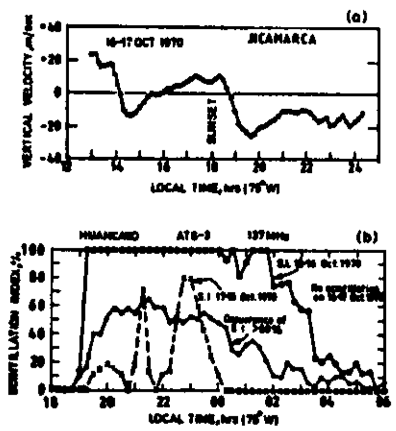

Fig. 9—(a) Variation of the vertical drifts at Jicamarca on 16 Oct.1970; and (b) variation of scintillation index of 137 MHz (ATS-3) radio beacon at Huancayo during Oct.1970

16 Oct. 1970 no F-region echoes were observed on the MRTI records; correspondingly the ionograms at Huancayo on 16 Oct. 1970 were exceptionally clear devoid of any spread-F. The F-region drift indicated a counter electrojet event (downward drift during the daytime) in the afternoon hours followed by weak drift corresponding to weak horizontal electric field in the ionosphere and later early reversal of the drift at sunset to the nighttime downward direction. Rastogi[13] has shown that the scintillations of VHF radio waves at Huancayo have a positive correlation with solar activity and seasonally October - February are the months of strong VHF scintillations at Huancayo. Thus the month of October 1970 (mean Zurich sunspot number = 87) would be expected to be a period of intense scintillations. Referring to Fig. 9(b) the percent of time the scintillation index of VHF radio waves at Huancayo exceeded the level of 80% was more than 50% between 2000 and 0000 hrs LT. The scintillation index on 15 October was 100% from 1915 hrs LT to midnight. Absolutely no scintillations were observed at Huancayo on the night of 16-17 Oct. 1970. On the next night of 17-18 Oct. 1970 the scintillations were moderate for some brief periods during the first part of the night. These observations correspond very well with the absence of irregularities on HF ionosonde and on VHF backscatter radar on 16-17 Oct. 1970. This absence of irregularities was due to weak electric field in the afternoon and an early reversal of the electric field in the evening as shown by Jicamarca VHF F-region drift observations. A sudden commencement type of storm had occurred on 16th October at 0917 hrs UT (0417 hrs LT for Huancayo), and continued for the next two to three days. The day 15 Oct. 1970 was one of the ten quiet days of the month and 16, 17 and 18 Oct. 1970 were included in the five disturbed days of the month. The A_p index on 15 and 16 Oct. 1970 were, respectively, 4 and 37. Thus, these observed features of the F-region electric field were the result of the worldwide geomagnetic disturbance starting in the early morning of the 16 Oct. 1970.

The absence of sufficient positive drifts or an eastward electric field near the sunset period leading to the absence of F-region irregularities is well displayed in Fig. 10 which shows the F-region vertical drifts and the VHF scintillation index on 2-3 and 3-4 Jan. 1975. It is seen that although both on 2 and 3 January counter-electrojet occurred in the afternoon hours, yet on 2 January there was a strong upward drift at sunset while on 3 January the drift velocity remained downward during the sunset period. The scintillations of VHF signals were saturated during the post-evening hours of 2 January and were practically absent in the night of 3-4 Jan. 1975. This confirms that a strong eastward electric field (vertical F-region drift) is a necessary condition to produce irregularities causing the VHF scintillations in equatorial regions.

3 Comparison of Height Profile of Drift & Echo Power with Ionogram

Woodman[14] has discussed the technique of measuring vertical drifts in the F-region by measuring the Doppler shift of the incoherently backscattered echoes. The velocities are upward during day and downward during night with the magnitude of about 20 m/sec. The reversal times are usually 1-2 hr after sunset. McClure and Woodman[15] have described the scattering cross-section and vertical drift velocities of the spread-F irregularities as a function of altitude and time.

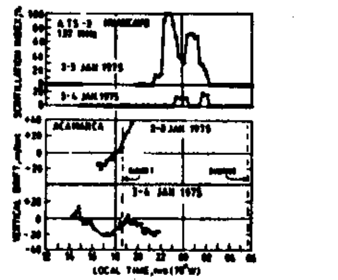

Fig. 10—Variation of the vertical F-region drift at Jicamarca and the scintillation index of 137 MHz (ATS-3) radio beacon at Huancayo on 2-3 and 3-4 Jan.1975

extending throughout the whole F-region at later stages. In certain cases the movement of the irregularities and the general F-layer may be both upwards and apparently the spread-F would remain only at the lower side of the F-layer leaving the critical frequency identifiable throughout the period of spread-F activity.

In Fig. 12 are shown the development of spread-F activity at Huancayo on 4 May 1975. The ionogram at 1815 hrs LT is a typical record around sunset. Between 1815 and 1930 hrs LT the gradual uplifting of the F-layer was very clear and minimum virtual height increased from 290 km at 1815 hrs LT to 420 km at 1930 hrs LT. Decreasing slightly to 300 km by 2015 hrs LT it rose up again to about 300 km by 2115 hrs LT. The development of spread-F overhead was preceded by the occurrence of satellite trace at 1830 and 1845 hrs LT. Between 1900 and 1945 hrs LT the spread-F irregularities seem to be situated almost at the base of the F-region. Strong VHF scintillations were recorded at Huancayo beginning at 1845 hrs LT. From a height of 350 km at 2000 hrs LT, the irregularities descended to 315 km at 2015 hrs LT and continued to descend later. At 2115 hrs LT the irregularities were about 200 km lower than the base of the F-layer. This shows that the vertical movement of the irregularities and the main F-layer may be completely different.

The radio wave of a particular frequency is reflected from the level of the ionosphere where the exploring frequency equals the plasma frequency of the medium which depends on the density of ionization at that level. The plasma frequency of the equatorial ionosphere rarely exceeds 20 MHz. Thus the echoes of VHF radio waves from the ionosphere are due to the scattering mechanism and do not depend on the background ionization density. The echoes of HF radio waves used in vertical ionosonde in normal conditions are due to reflection mechanism. The range type of spread-F structure on the ionogram seems to be formed by the scattering mechanism.

4 Discussion

In the original paper on equatorial spread-F at Huancayo, Booker and Wells[3] had shown the two different examples of diffuse echoes, one occurring at lower frequencies with critical frequencies clearly defined and the other when diffuse echoes were absent at lower frequencies but strong at frequencies close to the critical frequencies. Meek[16] described different nature of diffused and complex echoes on the ionogram at high latitudes and used for the first time the word "spread". An extensive work on the spread-F at midlatitude station Brisbane was undertaken by Australian workers and the classification of "range spreading" and "frequency spreading" were first used in a series of papers by McNichol *et al.*[17] and Singleton[18]. A new dimension to the equatorial spread F studies was provided by the forward scatter propagation experiment in Peru during IGY. Cohen and Bowles[19] found that the trans-equatorial F-scatter propagation was associated with the range type equatorial spread on the Hunacayo ionograms. The scattering layer corresponds to the bottom of the F-layer or as much as 100 km below it. Rastogi[20] has clarified the difference in the configuration range and frequency spread at equatorial and tropical latitudes. McNicol *et al.*[17] had undertaken an extensive set of experiments to determine the exact nature of spread-F at Brisbane. Besides the normal ionograms, they obtained range time records of 2.28 MHz signal at the corners of a 95 km triangle. The observations were supplemented by swept gain recordings, phase path recordings and the observations of the direction of echo arrival. They concluded that the spread-F at Brisbane was due to the presence of a large number of individual traces. The VHF forward scatter results by Cohen and Bowles[19] had motivated Calvert and Cohen[21] to model the equatorial spread-F configurations observed at Huancayo. They concluded that certain spread-F configurations observed at the magnetic equator arise from the scattering in the vertical east-west plane from thin, field-aligned irregularities. Later observations of HF backscatter[22] and VHF backscatter[8] from the equatorial spread-F do support the mechanism suggested by Calvert and Cohen[21].

King[23] suggested that the spread-F echoes are not due to partial reflection from small irregularities; rather, they are due to total reflection from large tilted surfaces of ionization. The observation of very strong echoes on HF (on ionogram) and VHF (MRTI backscatter records) described here does not lend any support for total reflection theory of King[23] for the equatorial range spread. The improvement of the ionosonde recordings at Huancayo with expanded frequency scale has enabled the finer resolution of echoes on the ionograms. This has revealed multiple heights of spread-F irregularities. This would mean the extension of Cohen and Calvert interpretation which was based on a single scattering layer or patch.

The occurrence of equatorial spread-F has been known to be associated with the rapid rise of the minimum virtual height of the F-region following sunset[3,6,24-26]. The iso-electron density contours at Jicamarca by Woodman and La Hoz[10] (their Fig. 2) shows the rise of F-layer at all altitudes up to the peak electron density region. Using the electron density profile data derived from the ionograms at Huancayo, Rastogi[26] showed that the whole of the F-region from

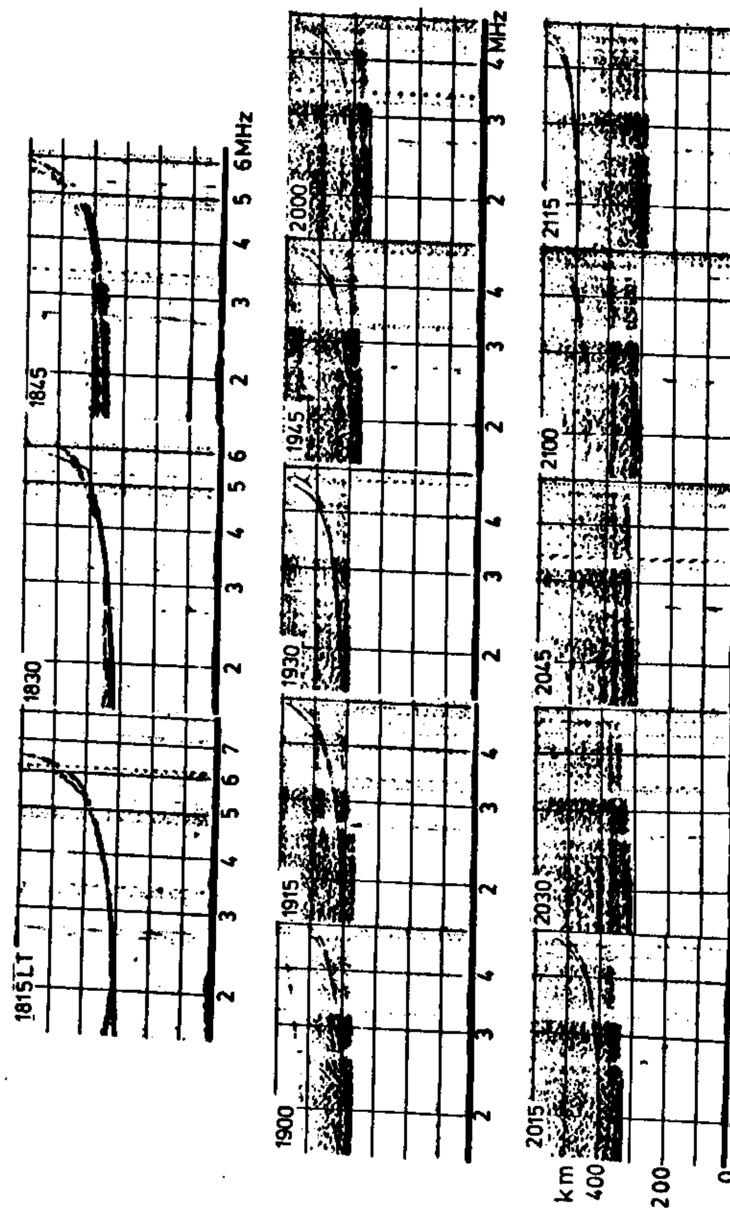

Fig. 12—Development of spread-F at Huancayo on 4 May 1975 showing the downward movement of the irregularities while the main F-layer was moving up

the base to the height of the peak ionization rises during the post-evening hours with little change in the semi-thickness of the layer. It was also stressed that a strong peak in the vertical drift velocity (eastward electric field) seems to be a necessary condition for the generation of equatorial spread-F. This idea was further supported when Rastogi and Woodman[29] showed that a reversal of F-region vertical drift at Jicamarca to positive (upward) value during any time of the night is followed by the generation of range type of spread-F in the ionograms at Huancayo with a time delay of 0.5-1 hr. Thus abnormal reversal of the electric field to eastward direction is an essential condition for producing spread-F at late night when no spread-F had occurred early during early part of the night. Rastogi[30] suggested that the necessary conditions for the generation of spread-F irregularities are: (i) the existence of region of strong plasma density gradient, which is always present at the base of the F-region at night, (ii) the existence of eastward electric field in the F-region, i.e. the continuation of normal daytime *Sq* field even after the layer sunset, (iii) the continuance of the above conditions for a period large enough for the irregularities to grow sufficiently strong. The seeding of the irregularities may thus be due to gradient instability mechanism and later these irregularities may develop throughout the F-layer or even above it by Rayleigh Taylor instability mechanism. The role of eastward electric field has been incorporated in the development of irregularities by the Rayleigh Taylor mechanism by Anderson and Haerendel[31] and by Ossakow[32]. It is recommended that a detailed study of HF and VHF records due to spread-F would greatly help in understanding the equatorial F-region irregularities near the magnetic equator.

5 Conclusions

(i) During the condition of range equatorial spread-F, the altitude of the scattering layers observed on the normal HF ionosonde (2-5 MHz) correspond remarkably well with the level of strong backscattering of VHF radio waves as observed on MRTI records.

(ii) The range spread-F echoes on the ionogram from the base, inside or above the F-region do not show group retardation effects; the virtual height is independent of frequency.

(iii) the range spread-F echoes on the ionograms are due to scattering process and not due to normal reflection process.

(iv) Equatorial spread-F echoes are absent on the nights with early reversal of F-region electric field.

(v) The vertical movement of the general F-layer and the irregularity may be independent or at times opposite to each other.

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