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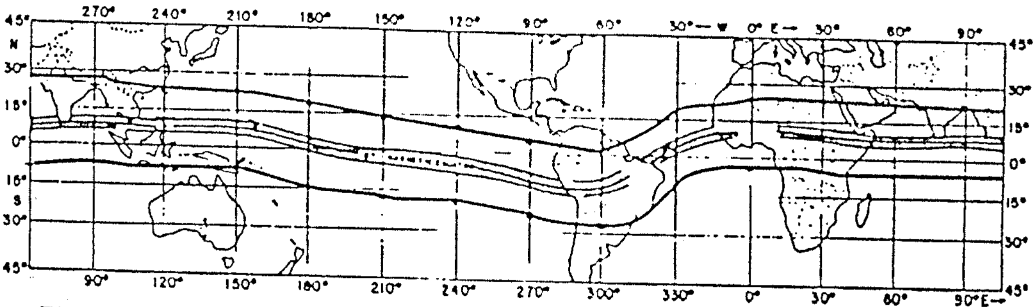

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Equatorial E and F Region Scattering Structures over Jicamarca.

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Abstract

During the IGY, from December 1957 to November 1958, Trans-equatorial, 50 MHz forward scatter propagation studies were carried out in Perú by the National Bureau of Standards. They had different propagation paths. They included the E and/or F-region altitudes in their common volume. The studies showed that scattering from E and F-region irregularities were responsible for the relatively strong received signals. The strongest signals were identified with the same irregularities responsible for the Esq and Spread-F signatures observed in the ionograms. Shortly after, the Jicamarca Observatory was built. These same irregularities have been studied since, using this facility. One could claim that the present knowledge we have about the nature of these irregularities has come out from the backscattering observations made with its powerful radars. The space-time morphological characteristics of these irregularities are presented. A short account of the current theories proposed to explain the physical processes responsible for them is included.

Introduction

The subject related to E and F region scattering irregularities in the equatorial ionosphere is very broad and extensive (see Fejer and Kelly [1980], for a review). To reduce the scope of the present paper to the allocated time, we will restrict ourselves to discuss the matters that are relevant to trans-equatorial propagation via scattering from these irregularities, satellite scintillation and radar clutter. We will also limit ourselves to observations made with VHF scattering systems, namely the Jicamarca (1° Dip) and Piura (14° Dip) VHF radars, and forward scattering bi-static experiments, all made in Perú. Although reducing the scope of the paper to these subjects is convenient to us because of our familiarity with this work, we are not limiting the subject artificially, since most of what is known about equatorial ionospheric irregularities has resulted from work done in Perú, specially from research done at the Jicamarca Radio Observatory.

Trans-equatorial Forward Scattering Experiments

The first equatorial ionospheric scattering experiments were carried out in Perú during the IGY by the National Bureau of Standards [e.g., Cohen and Bowles, 1963, and references therein]. The observations were made using several VHF Forward Scatter links, of which we will discuss only the Antofagasta-Guayaquil, Arequipa-Trujillo, Antofagasta-Huancayo, Huancayo-Guayaquil. The geometry is shown in figure 1. Note that Huancayo (2°N Dip) is marking the magnetic equator. The first two links are symmetric with respect to the equator, with common volumes in the lower F-region and in the E-region respectively. The other two have their common volumes in the E-region, 5° south and north of the equator respectively.

Figure 2 shows the signal intensity for the three short paths and for a temperate latitude one, for different months of the year. They all scatter in the E-region. Note the large difference in strength between the center path, Arequipa-Trujillo, and the temperate latitude one. Note also the asymmetry between the north and south path; at certain times the difference in strength between the two is also very large.

The main conclusions for these experiments can be summarized as follows:

-The minimum signal strength in any path any time was stronger that the maximum strength of the ones observed with similar links at temperate latitudes.
-The scattering responsible for the signals received in the shorter three paths came from about 100 km.
-The signals received during daylight hours in the short path symmetric with respect to the equator were much stronger than any other path in any other part of the world. They were associated with the occurrence of Equatorial Sporadic-E echoes ---as observed by the Huancayo ionosonde--- and the strength of the Equatorial Electrojet---as observed by the H trace in the Huancayo Ionograms.
-Although the Antofagasta-Huancayo path showed some diurnal characteristics that could be associated with the electrojet, the corresponding symmetric path to the north, Huancayo-Guayaquil, showed much weaker signals with different diurnal behavior.
-The fading rate of the received signals was roughly
10 fades per second, or less.
-The scattered signals received during the daylight hours in the long trans-equatorial path from Antofagasta to Guayaquil are also associated with the same equatorial E-region irregularities, though their altitude is slightly below the horizon of both sites. Their reception could be explained by refraction effects and by the large scattering cross section of the E-region irregularities.
-The echoes received in this long path, but during the evening hours, were related to the occurrence Spread-F as seen by the Huancayo Ionosonde.
-The scattering region for the F-region experiment, was fairly localized and came mainly from the bottom edge of the Spread-F trace seen by the ionosonde at Huancayo.
-The maximum altitude of the scattering region for the long path was 450 km., coincident with the first cutoff of the antenna beams.

The large difference between the daytime signal strengths received in the northern short path and the short one in the center, and the much lesser difference with respect to the corresponding path to the south, could be taken as evidence that there was a sharp cutoff of E-region irregularities associated with the Electrojet at about ±5• from its center. This is our interpretation. It is not discussed by the authors.

Starting in November 1966 to June 1967, a similar experiment was repeated [Romero et al, 1968] but for a single path and under different solar activity. Although the path was different---more tangential to the Electrojet--- it was concluded that there is little solar activity effect in the equatorial E-region scattering properties.

After Romero's work, there were a few other experiments made by Peruvian researchers, unfortunately unpublished, were different voice modulation schemes were tried. The main conclusion of this work was that it was possible to communicate intelligently during the day time at 50 MHz, with transmitter powers in the 50 kW range, seven element Yagui antennas and distances of the order of 600 to 1000 km. Two modulation schemes were tried: amplitude and

When the electrojet current diminishes, the corresponding velocity of the electrons falls under the ion acoustic velocity and the two stream instability, type I, disappears, gradually merging into the other type, type II. The irregularities in this case are produced by a two dimensional turbulent interchange of plasmas from higher to lower densities produced in turn by a gradient-drift instability. Figure 3b shows a frequency power spectrum of radar echoes obtained under these conditions. In this case the Doppler shift corresponds to the velocity of the drifting electrons projected on the line of sight of the radar.

Note that in both cases the spectral width is of the order of a few tens to about 100 Hz. This width is related to twice the fading rate of the forward scattered signals. The fading is actually slower---even though the radio frequency is the same---due to the longer wavelengths responsible for the forward scattering. The rapid fading is responsible for the fluttering of the voice, when amplitude modulation is used. The medium also produces a frequency modulation on any carrier with comparable audio frequencies. But this modulation is not heard, even if a frequency modulation scheme is used, since it is filtered with all the low frequencies outside the voice frequency band.

An important property of the irregularities for the design and understanding of trans-equatorial propagation at VHF frequencies, as well as radar clutter, is their aspect sensitivity. Both types of irregularities show a very strong aspect sensitivity. Their scattering angle is confined to Bragg wave number vectors within a degree of perpendicular to the magnetic field. Under certain conditions this angle is reduced to one or two tenths of a degree [Kudeki and Farley,1989].

In the plane perpendicular to the magnetic field their scattering cross section is far from isotropic. The scattering cross section of the irregularities is larger when the Bragg wave number vector is parallel or close to parallel to the electrojet current vector, specially during two stream conditions [Ierkic et al,1980].

The depth and structure of the irregularities varies with the time of day and the strength and direction of the electric field that drives the electrojet. This is shown in figure 4. During the day, when the electric field is westward---which is usually the case---only the bottom side of the E-region is unstable, and there is a single layer. If the field reverses, as it some times does in the afternoon, the irregularities disappear. This is to be expected, since the same bottom density gradient is stable. During the night several electron density peaks are formed. They produce a complicated multi-layer structure, specially during type II conditions, covering from 95 to 135 km. Each layer is associated with the positive or negative gradient, above or below the electron density peaks, depending on the sign of the electric field.

The depth of the layer determines the maximum bandwidth one can communicate by scattering and using conventional modulation, since the modulation would actually be convolved by the shape of the scattering layer. The frequency coherence will also fall beyond this bandwidth for the same reason. Coherence bandwidth and depth of the layer expressed in time units are inverse of each other.

Back-scattering work has been limited to magnetic latitudes close to the magnetic equator. The lateral extend of the irregularity belt can be determined by the behavior of the two short forward scattering links north and south of the magnetic equator mentioned before and by the width of the

FM modulation.

The quality of the amplitude modulated voice signals was clean, as far as signal to noise ratios was concerned, but distorted with a very conspicuous flutter, produced by the very fast (10-20 HZ) fading of the signal. The flutter did not affect the intelligibility of the messages by much. The FM-modulated voice signals were free of flutter and much more pleasant, but with sporadic (every few seconds) short burst of noise. The bursts occurred more frequently as the signal became weaker.

Valladares and Woodman [1975] have made a computer simulation of the sound quality for both types of modulation . They assumed a time changing scattering medium that would produce a widening of 20 HZ to all the components of the modulated spectrum. The similarity of the signal quality of both the simulated and the real signal was very good. This should allow the design and testing of non conventional modulation schemes ,without having to actually perform the propagation experiment.

Apart of above-mentioned work, no other experiments have been made using equatorial forward scattering schemes. Nevertheless, we have made very significant progress in understanding the nature, morphology and physics of the scattering irregularities. Since then, most of the work has been done using back-scattering radar techniques at the Jicamarca Radio Observatory, including the use of the large antenna and powerful incoherent scatter radar of this facility.

<u>Scattering properties of equatorial E-region irregularities</u>

As mentioned in the introduction, the subject of this subtitle is too extensive to be treated or reviewed in general. We have to limit ourselves to the most important scattering properties of these irregularities.

The electron density irregularities at the equatorial E-region present the largest scattering cross-sections---at VHF frequencies---of any other in the ionosphere. They are produced in the region of enhanced Cowling conductivities responsible for the equatorial electrojet. They are confined to an altitude range between 95 and 115 km. of altitude during the day, with a maximum at about 105 km.. This range extends to about 135 km. , with a multiple peak structure, during the night.

The irregularities are produced by two different types (I and II) of plasma instabilities depending on the strength of the electrojet current. Type I occurs when the drifting velocities of the electrons, responsible for the electrojet current reach the acoustic velocity of the ions, a two stream instability takes place [Farley, 1963; Buneman, 1963] producing a fan of unstable waves confined in a direction perpendicular to the magnetic field and strongly peaked in the direction of the electrojet current. They all propagate with a phase velocity close to the acoustic velocity of the ions.

Figure 3a, shows a typical power frequency spectrum of the back-scattered signals of a 50 MHz radar under type I conditions. Note that the frequency of the peak is Doppler shifted by an amount that corresponds to the ion acoustic velocity, and is independent of the elevation angle of the antenna beam. Although not shown here, as the intensity of the electrojet increases, the amplitude of the peak increases, but stays at the same Doppler shift.

equatorial electrojet as determined by magnetometers. One should not expect strong scattering beyond about ±5o from the magnetic equator. Recently Woodman, Rodriguez and Balsley [Personal communication] have performed a back-scattering experiment using the Piura wind profiler [Gage et al,], 7.5o north of the magnetic equator, and did not see any echoes during the daytime hours corresponding to strong electrojet conditions. They did see some significant echoes during the night. A digital RTI record of one of the nights of observations is shown in figure 5.

Equatorial 150 km irregularities

Apart of the now well known Equatorial E-region irregularities associated with the electrojet, there is a less known and less understood irregularity structure, also observed at the magnetic equator, at about 150-170 km of altitude. Their existence have been known at the Jicamarca observatory for many years, but there have been only a few systematic studies made of their characteristics [Royrvik and Miller ,1981]. Recently, Kudeki and Fawcet [1993] has reported very interesting observations using the new high resolution capabilities of the Jicamarca radar. Also new are the temporal extent of the observations. Color RTI plots of the irregularities show a multi-layer necklace-like structure extending from sunrise to sunset. The irregularities are very aspect sensitive and produce slow fading with an spectral width of the order of a few Hz. A black and white reproduction of one of these records is shown in figure 6.

These irregularities should also be capable of supporting forward scattering and could very well be responsible for some of the signals received during the day in the long Antofagasta-Guayaquil path. As we mentioned before, the electrojet altitudes were below the horizon for this path, and the 150 km. irregularities were at an advantage.

Equatorial F-Region irregularities

Perhaps the most spectacular type of irregularities as seen by a back-scatter radar are the F-region irregularities. If we could see them with our bare eyes I am sure they would compete beauty and variety with the polar aurora. The radar echo strength they produce, although not as strong as the ones produced by the daytime electrojet, are about 50 db over the noise level for the typical Jicamarca radar parameters. Their large radar back-scatter cross section definitely confirms the interpretation of Cohen and Bowles that they were responsible for the night time enhancement of the forward scatter signals observed in the long trans-equatorial path from Antofagasta to Guayaquil.

It has been established that the occurrence of coherent echoes in the jicamarca radar are highly correlated with the occurrence of Spread-F as seen in ionograms and with satellite scintillations. These are in fact different manifestations of the same phenomena. They are all effects of very large fluctuations in electron density produced by plasma instabilities. Any deviation from one hundred percent correlation between the three different manifestations mentioned can be attributed to the fact that each one is sensitive to a different length scales. It is possible, although it does not occur often, that at times one length scale is included in the size spectrum of the irregularities but not the other for which the other manifestation is sensitive to.

Figure 7a nd 7b how two RTI plots of the F-region irregularities. Note that we do not say typical. They differ greatly in appearance from one day to the other. How much they vary can be appreciated in the sequence of RTI's shown by Woodman and La Hoz [1976] in a lapse time of about fifteen consecutive days. One night they may not appear at all; on another they may show only as a very confined layer, a few tens of kilometers deep; yet the next day they may appear covering the whole F-region from the bottom of it to 1200 km or more. In fact we have not established yet how high can they occur since the maximum altitude at which they have been observed at Jicamarca could be explained by their aspect sensitivity and the limitations of the antenna to illuminate the region perpendicular to the magnetic field beyond 1200 km.

The length scales of the fluctuations go from a thousand kilometers, the outer scale of the unstable region, down to the few meters responsible for the back-scattering of the 50 Mhz signals of the Jicamarca radar, to even smaller ones responsible for the echoes obtained by the L band Kwajalein radar [Tsunoda, 1980].

The dynamics of the radar echoes are equally variable. The width of the frequency power spectrum of the radar returns go from one Hz to 200 Hz or more. Figure 8 shows a catalogue of the different spectral signatures observed.

The only thing these irregularities have in common, to deserve a single name, is that they occur in the F-region of the equatorial ionosphere and that they occur at night. But, they occur in such a variety of conditions---neutral densities, electric fields, gradients---involving such a large range of length scales, and having such a different dynamic behavior, that we can not expect to find a single physical mechanism responsible for their existence. There is consensus, though, that the primary mechanism, responsible for the largest length scales, is produced by a non-linear development of a gravitational Raleigh-Taylor instability in which a "bubble" of low density plasma rises beyond the peak of the F-region [Woodman and La Hoz, 1976]. Figure 9a shows the original sketch of Woodman and La Hoz[1976] and figure 9b a later computer simulation by Osakow et al [1979] showing how the bubbles are formed and propagate upwards beyond the F-region peak. Smaller scales of the order of a few kilometers or less are also Raleigh- Taylor unstable given the right background conditions. Gravity can be replaced or helped by electric fields (or, equivalently, by neutral winds) as a driving force. What is not very clear is how the meter scale irregularities, responsible for the scattering of VHF waves are produced. No single theory could explain the more than 2 orders of magnitude in their spectral width.

Another property of interest of the F-region irregularities is their very pronounced aspect sensitivity. Experiments at Jicamarca have determined that at times their aspect sensitivity is smaller than a tenth of a degree. How much smaller is difficult to measure.

No systematic statistical studies have been made of the different properties of the irregularities as seen by the Jicamarca radar. But the high correlation of their occurrence with that of Spread-F in ionograms and satellite scintillations allow us to make use of the statistics of these latter manifestations, not only in the Peruvian sector but in other parts of the world as well.

As far as the communication potential of the F-region irregularities, it has been established by the Antofagasta-Guayaquil path, but I am not aware of their use or study for voice or other type of communications. Unless very narrow vertical beams are used, the large vertical extend of the scattering region would reduce the frequency coherence below the bandwidth required for voice communications. The large broadening of spectral lines should also present difficulties when it occurs.

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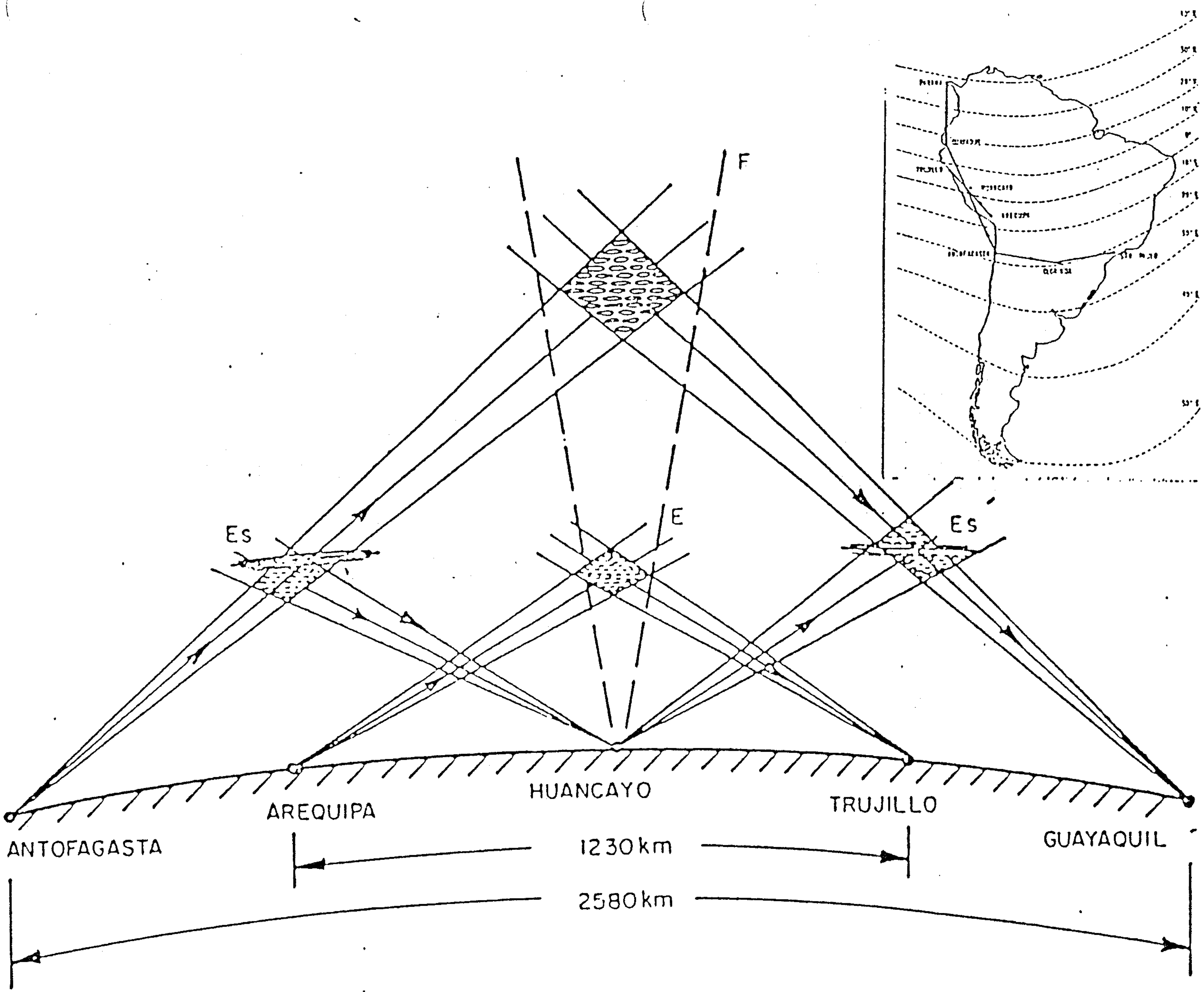

FIGURE 1 Schematic diagram of the vertical cross sections of antenna beam intersections along the west coast of South America, indicating four of the propagation paths referred to in this paper. After Cohen + Bowles, 1963

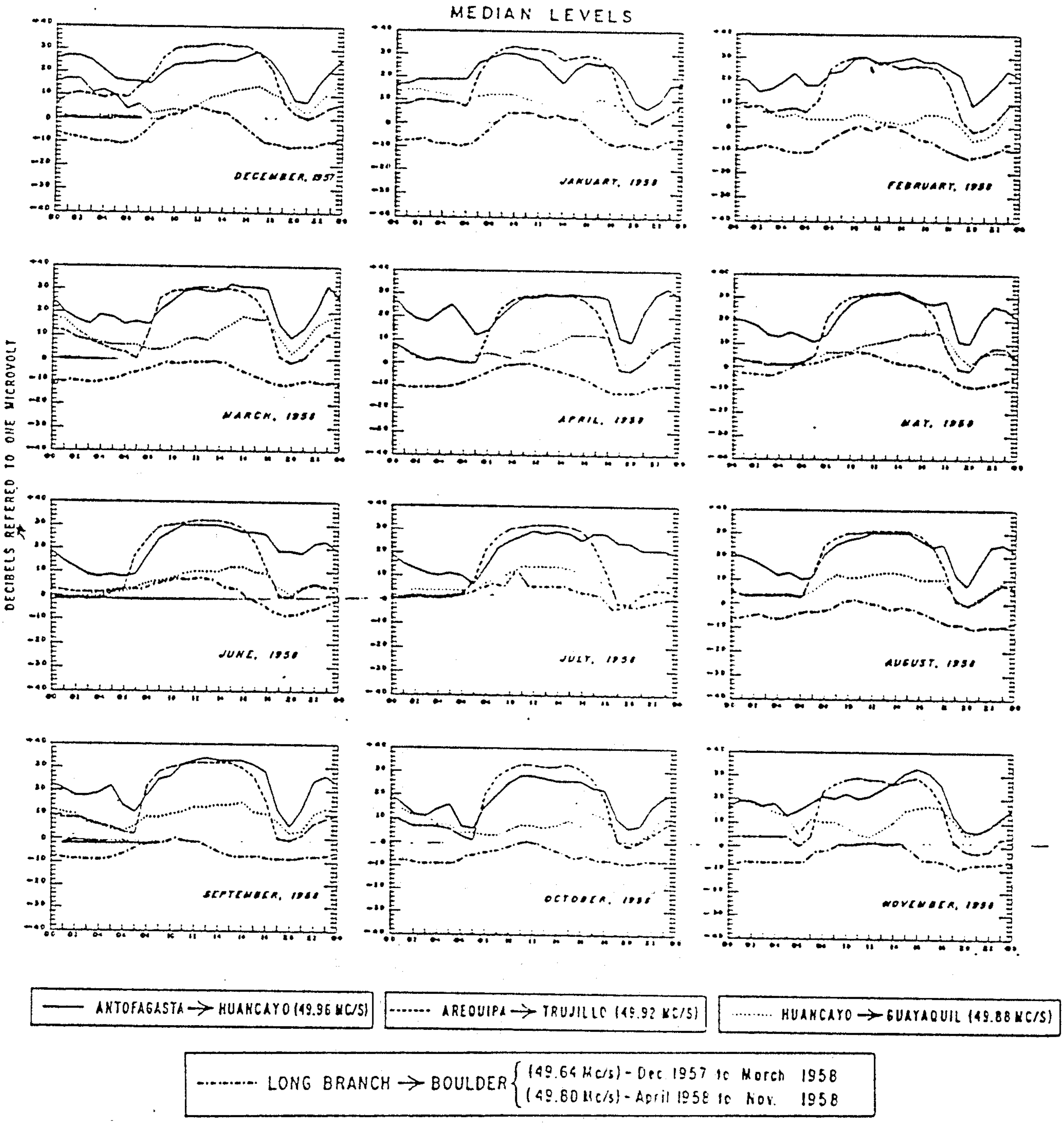

FIGURE 1.2 *The diurnal variation of monthly median signals (of all classes) propagated over the south, central and north paths, along with the corresponding statistics for all signals propagated over a temperate latitude path.*

After Cohen + Bowles, 63

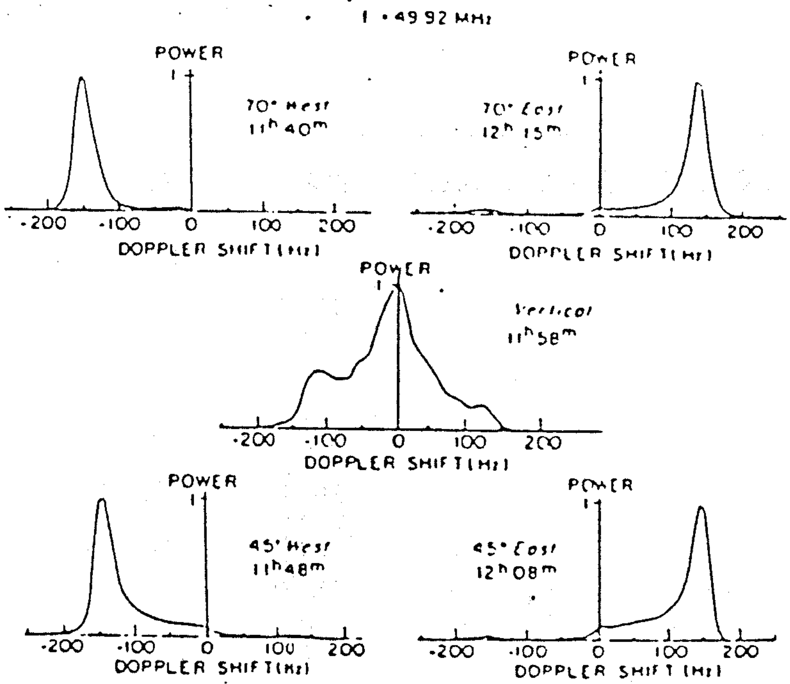

Fig. 3a. A series of Doppler spectra from the equatorial electrojet irregularities at different elevation angles obtained at Jicamarca during a period of relatively strong scattering. The spectra are normalized to a fixed peak value [after *Cohen and Bowles*, 1967].

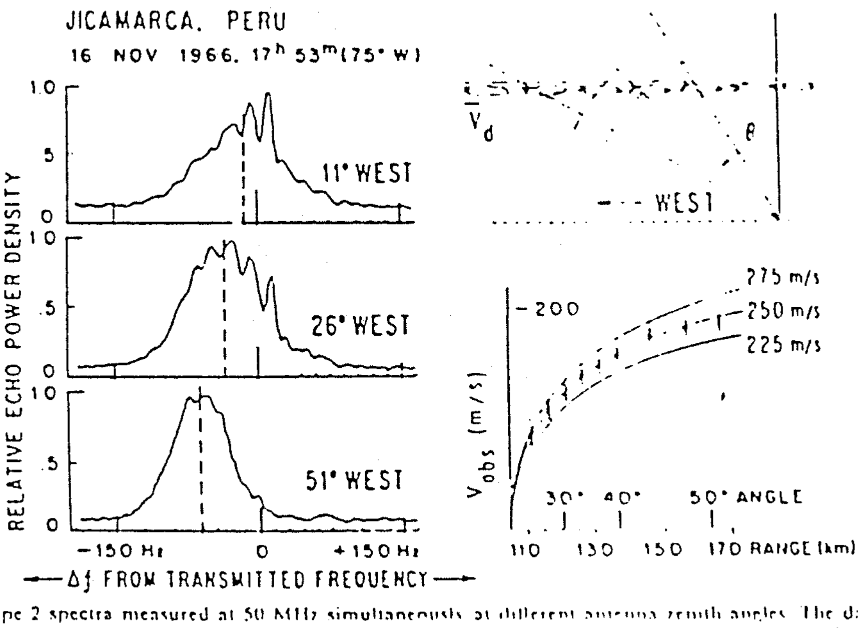

Fig. 3b Type 2 spectra measured at 50 MHz simultaneously at different antenna zenith angles. The dashed lines indicate the average Doppler shifts. The geometry of the experiment is shown in the top right-hand panel. The results of the experiment, together with three theoretical curves for which a sine dependence of the average phase velocity with zenith angle was assumed, are shown in the bottom right-hand panel [after *Balsley*, 1969].

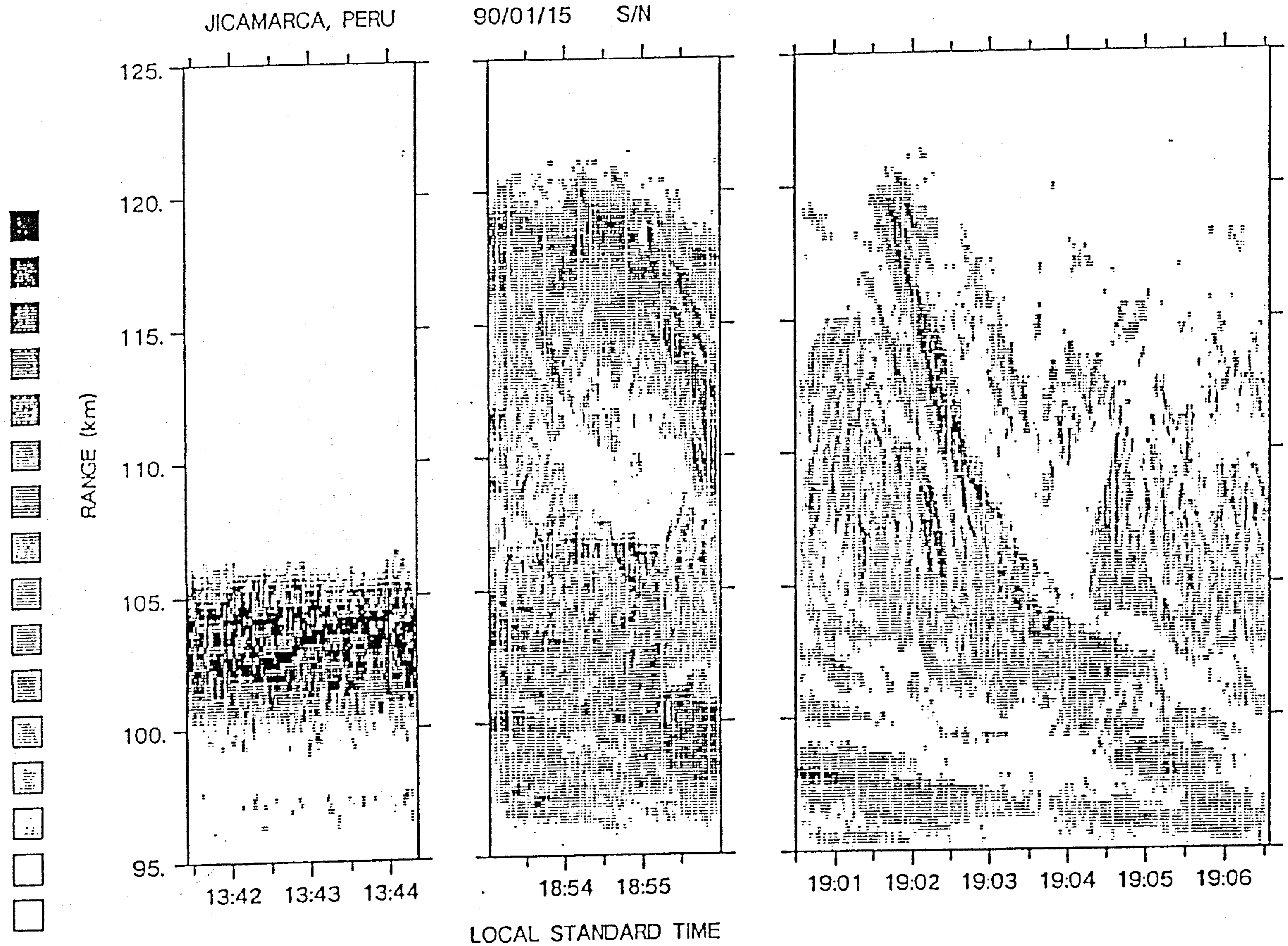

Fig 4'

After Swartz and Farley, 1993

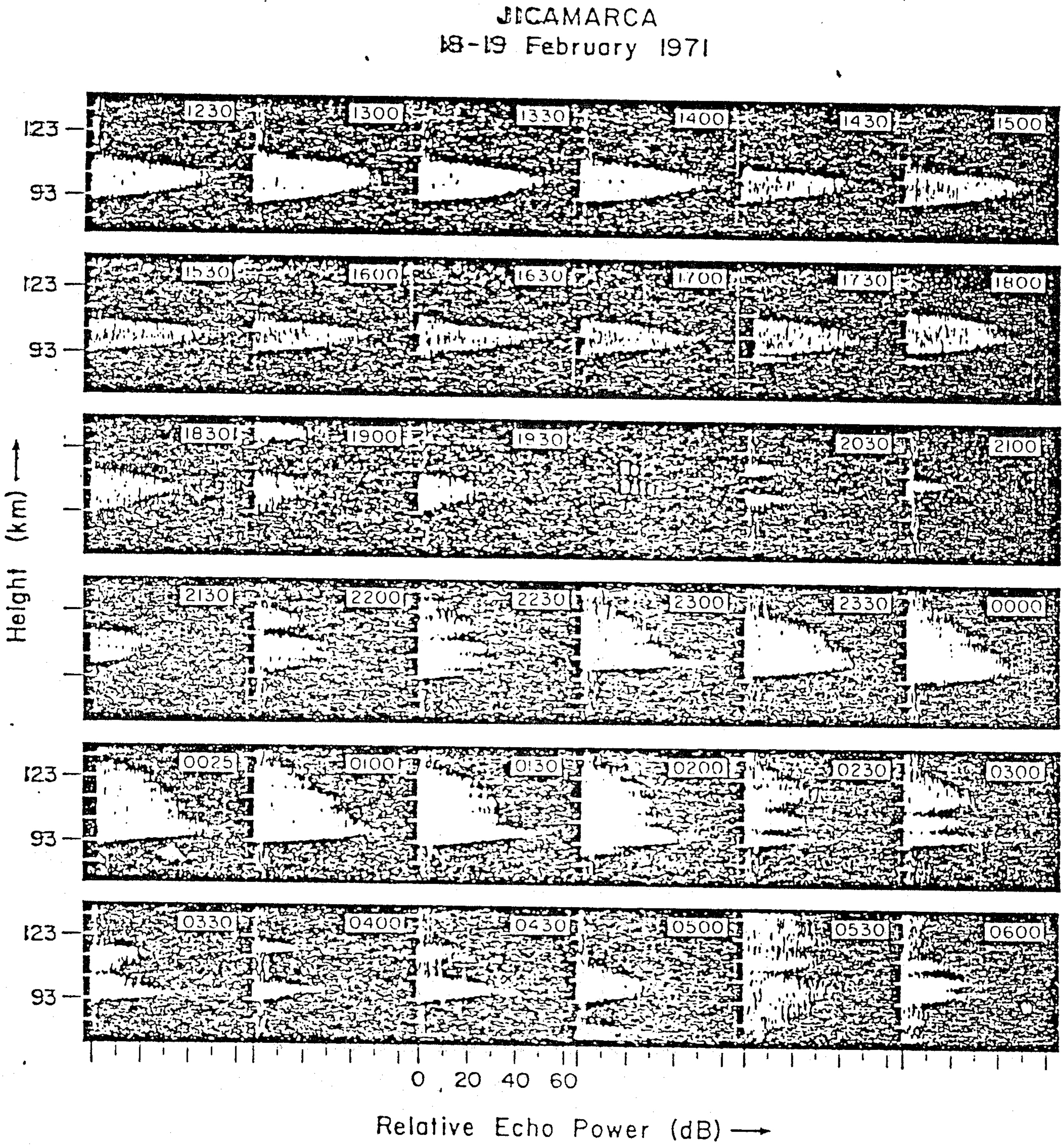

Figure ~~6.1~~ 4 A sample of the power profiles backscattered by vertically travelling irregularities. Equatorial spread-F echoes contaminated the data between 0405 and 0550 hours and perhaps at 1900 hours.

After Fejer et al, 1975

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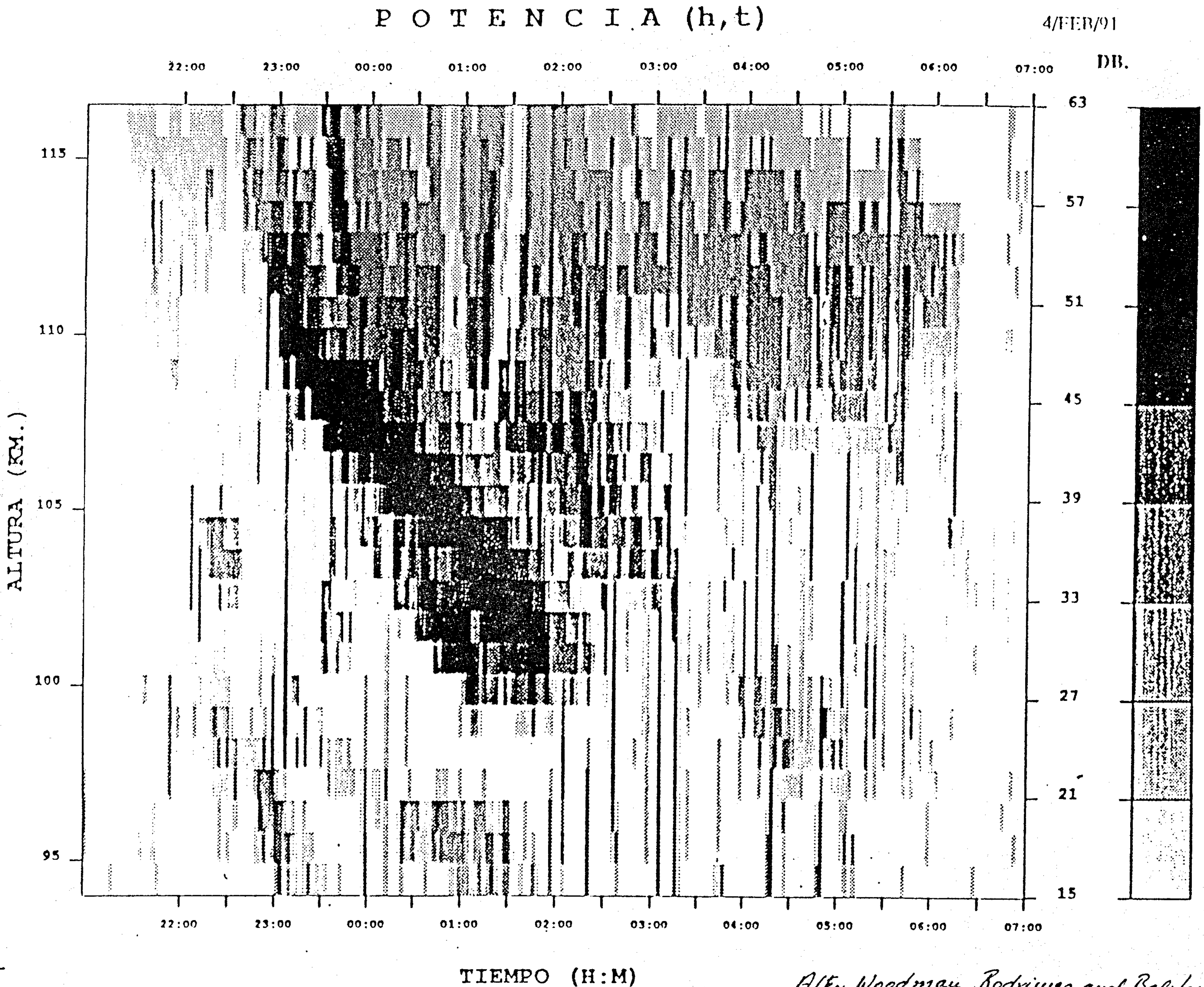
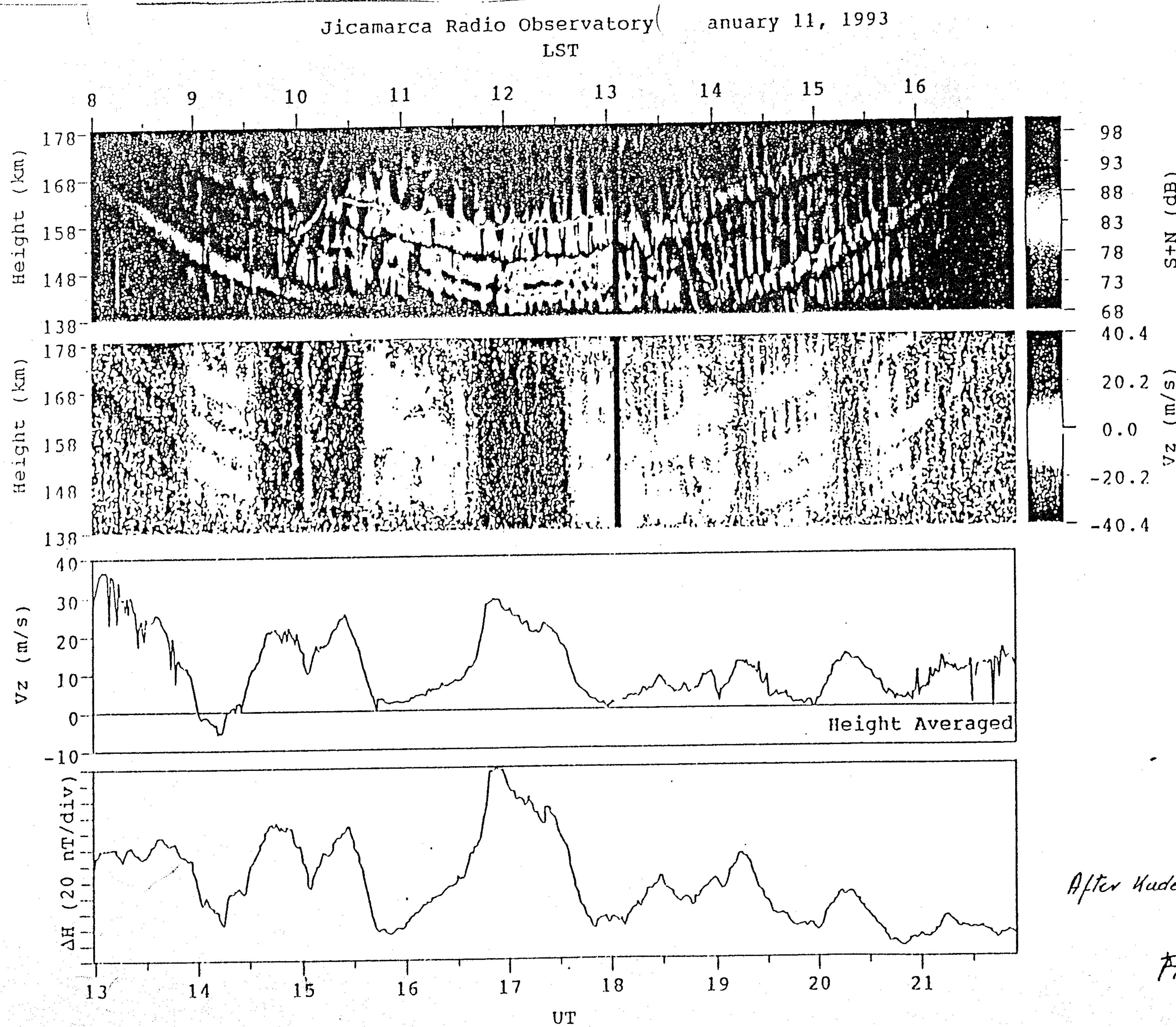


Fig 5

After Woodman, Rodriguez and Ratley, 93



After Kudeki + Fawcet, 1993

Fig 6

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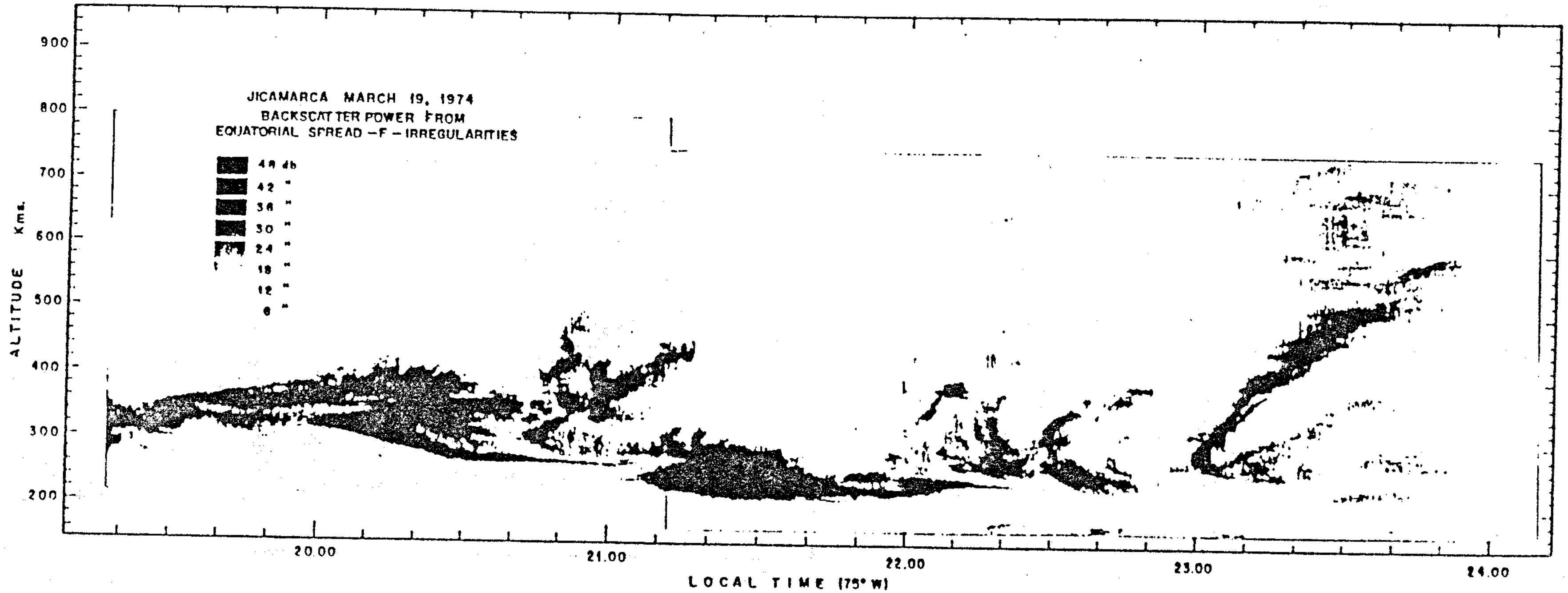

Fig 7a - Sp-F RTI, after Woodman + La Hoz, 1976

Fig 7b - Spread-F RTI.

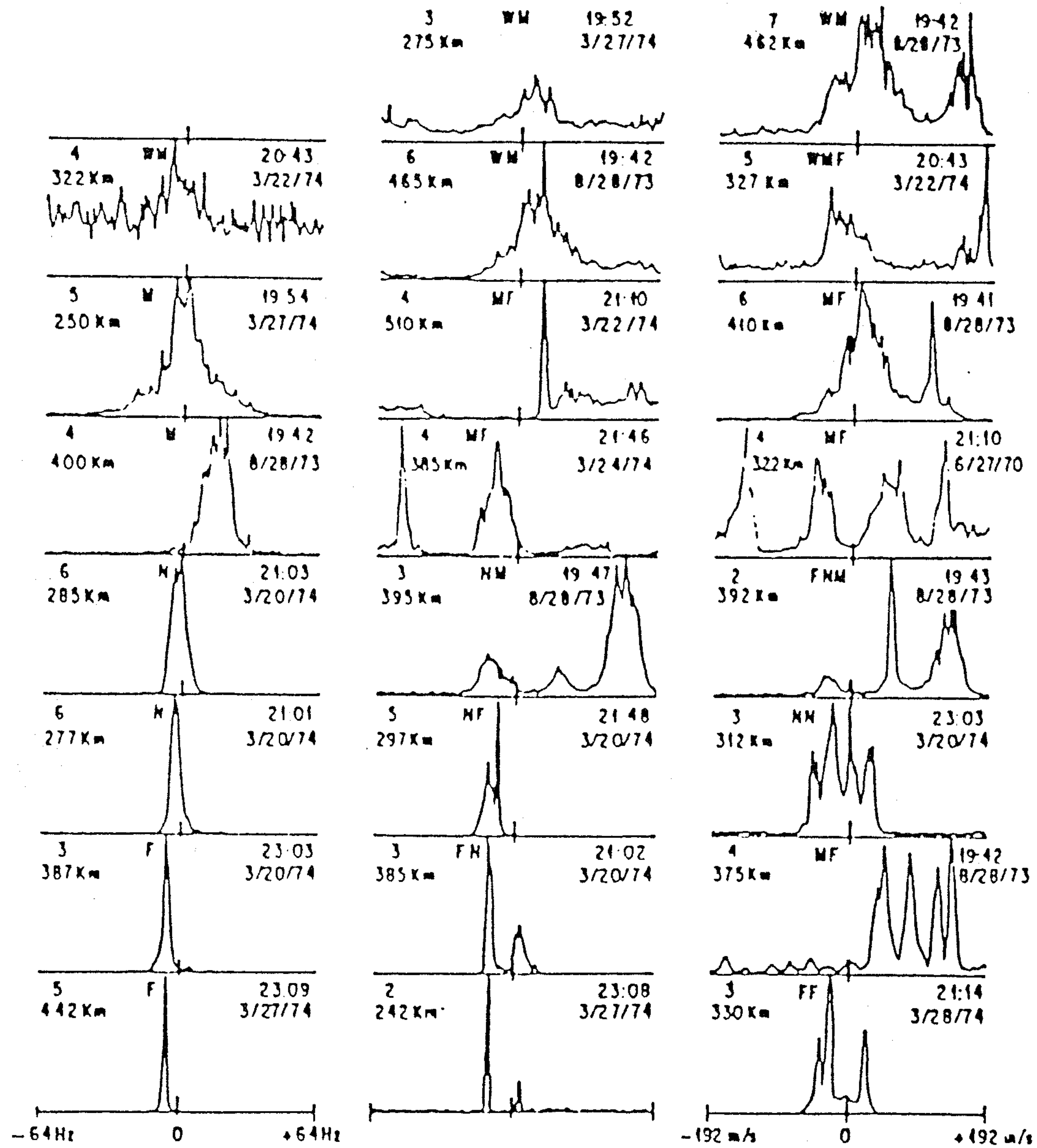

Fig. 4. Selected set of frequency spectra of backscatter echoes from F region irregularities showing the large variety of spectral shapes and illustrating the classification scheme introduced in the text.

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After Woodman + La Hoz

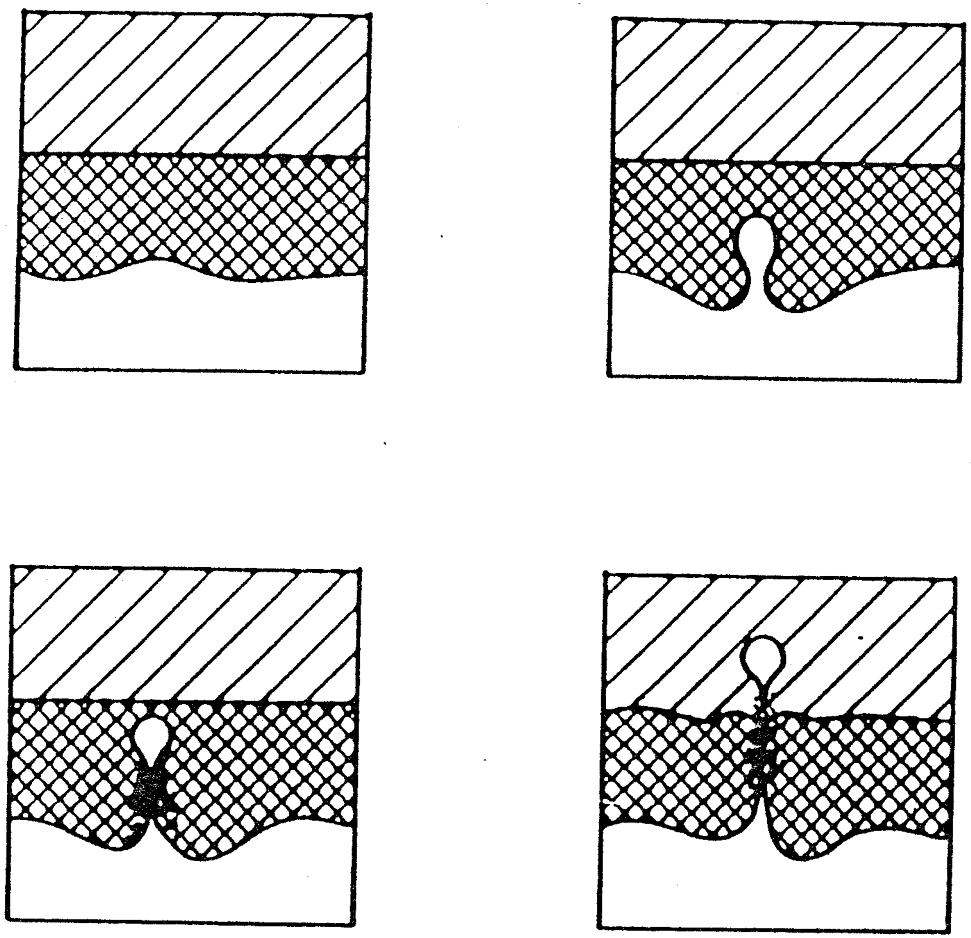

Fig 9a - Proposed mechanism for the formation of F-region "bubbles" or "plumes", After Woodman + La Hoz, 1976

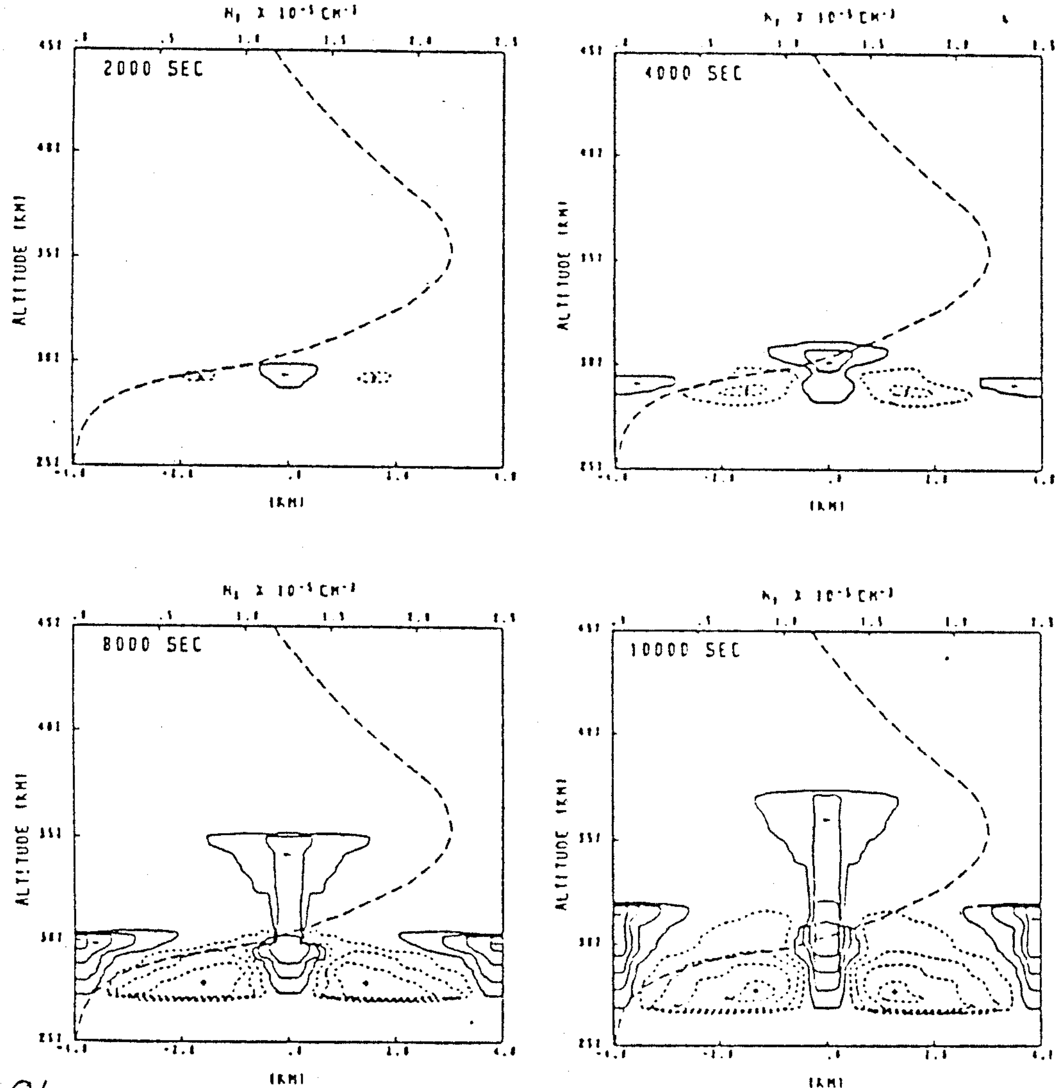

Fig. 9b. Contour plots of constant n_i/n_a for the simulation ESF 1 at t = 2000, 4000, 8000, and 10,000 s. The small dashed contours with a plus sign inside and the solid contours with a minus sign inside indicate enhancement and depletions over the ambient electron number density. The large dashed curve depicts the ambient electron number density (values on upper horizontal axis) n_a as a function of altitude. The vertical y axis represents altitude, the lower horizontal x axis is east-west range, and the ambient magnetic field is along the z axis, out of the figure. After Ossakow et al, 1979