Indian Journal of Radio & Space Physics
Vol. 3, March 1974, pp. 70-75

Study of Field-Aligned Ionospheric E-Region Irregularities & Sporadic E at hf

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Received 4 *August* 1973

A continuous series of oblique backscatter observations at 19 MHz made at Plum Island, Massachusetts, (56°N invariant) over nearly half a solar cycle is utilized to derive the occurrence characteristics of aspect sensitive field-aligned irregularities in the E-layer and their association with ground backscattered echoes which are propagated via sporadic E(E_s) reflection. Under quiet magnetic conditions, it is found that the field-aligned echo from E-layer heights [FAE(E)] displays a summer evening maximum in conjunction with the E_s echo. A weak secondary maximum is observed in the winter with no detectable field-aligned structures being evident in the day-time E_s. During disturbed magnetic conditions, the E_s ground back-scattered echo is greatly suppressed together with a simultaneous increase of the FAE(E) which also appear in the day-time; no seasonal control is evident. These observations are discussed from the point of view of current plasma instability theories.

1. Introduction

THE OBJECT of this paper is to discuss some results of a series of hf oblique backscatter observations that were conducted at Plum Island, Massachusetts, situated at an invariant latitude of 56°N. The observations were made from 1961 to 1965. Only one aspect of these observations, namely, the occurrence of field-aligned irregularities in the temperate latitude E_s layer will be presented here. With continuous hf oblique backscatter data over nearly half a solar cycle we were able to study, on a statistical basis, the diurnal, seasonal and magnetic control of the occurrence of field-aligned irregularities in E_s layers. An extensive study of this type involving E_s has not been attempted so far. Simultaneous vhf oblique backscatter data available for a period of 1 year, provided useful information regarding the echo type and scale sizes of the field-aligned irregularities in the E_s layers and, these results have been presented elsewhere[1].

The equipment is very similar in nature to the fixed frequency IGY sounders. The hf observations were made at 19·4 MHz with a low-powered 1 kW peak-power radar using a pulse length of 1 msec and a pulse repetition frequency of 10 sec^{-1}. The pulses were transmitted by a horizontal three-element Yagi antenna rotating at the rate of one revolution every 8 min. The resulting data were recorded on compressed time-scale film as well as on the Plan Position Indicator (PPI) type frames. The maximum range on the sweep was 3600 km. A preliminary report utilizing part of this data has been made earlier[2].

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2. Geometry of Radar

It is well known that the geometrical requirement for obtaining radar echoes from field-aligned irregularities is that the probing radar ray intersect the earth's magnetic field lines orthogonally at ionospheric heights. Fig. 1 illustrates the geometry for the Plum Island radar. The map shows the loci of points of 0° and 5° aspect angles (i. e. angle between the radar ray and a normal to the earth's magnetic field) for a height of 110 km where most of the field-aligned echoes are found to occur[3]. It has been assumed here that the radar ray travels along the line of sight although, at 19 MHz, this may not always be the case. However, any departure from this line of sight direc-

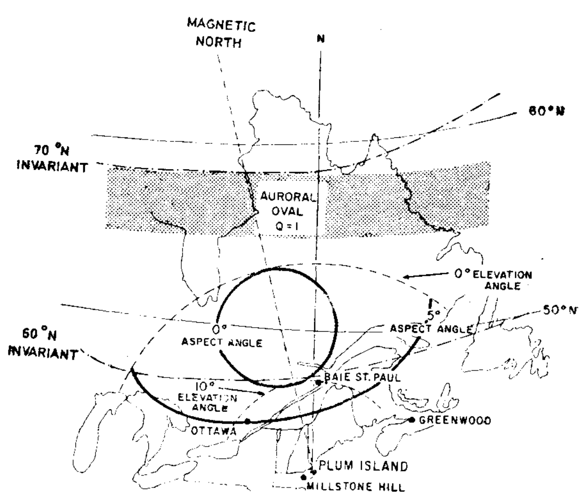

Fig. 1—Map showing loci of 0° and 5° aspect angles as well as 0° and 10° elevation angles at 110 km height for the Plum Island radar (Invariant coordinates and the midnight position of the auroral oval when $Q = 1$ are also shown)

tion due to refraction at E-layer heights will be small. Elevation angle circles of 0° and 10° are also shown, which correspond to slant ranges of 1180 km and 520 km respectively. Aspect angles within the 0° contour are everywhere less than 2°, and hence, theoretically, we should be able to get field-aligned echoes from the horizon up to elevation angles somewhat greater than 10°. However, the antenna system used for this study discriminates against low elevation angles, and aspect-sensitive echoes are obtained in the 8-12° elevation range only, corresponding to an invariant latitude range of 59-61°N. The directions of true north and magnetic north and the midnight position of the Feldstein auroral oval for $Q = 1$ are shown[4].

From Plum Island it is also possible to get field-aligned echoes at hf from the F layer if sufficient ionospheric refraction is available. However, in this paper we shall confine our attention to the aspect-sensitive echoes obtained at group delays of $\leqslant 6$ msec and denote them as field-aligned echoes from the E layer, using the notation FAE(E). Considering the magnetic field geometry, it is obvious that the NW quadrant will show more FAE(E) activity. The other type of echo to be discussed in this paper is the ground backscatter echo which is propagated via sporadic-E reflection[5] and will be hereafter referred to as 'E_s propagation'.

3. Correlation of FAE(E) and E_s Propagation

A typical example of simultaneous E_s propagation and FAE(E) is shown in Fig. 2. The top of the diagram points north, and the antenna rotates clockwise once every 8 min. The innermost range circle represents a delay of 4 msec with each succeeding range circle representing an additional delay of 5 msec. The E_s ground backscatter echoes are seen at all azimuths except NE at ranges varying between 7 and 11 msec. A very well defined FAE(E) is seen to the NW with an inner range of 4 msec. This PPI shows a rather typical situation that occurs on any summer evening. This particular evening event of 12 July 1965 will be described in some detail to give the reader an idea of the sequence in which these two types of echoes occur. At approximately 1500 EST a ground backscatter echo appeared to the south. By about 1730 EST this type of echo was seen at all azimuths. The field-aligned echoes appear at 1915 EST, are quite intense at 1942 EST, as seen in Fig. 2, and decay at 2012 EST. The magnetic index throughout this period was 1.

The occurrence of E_s propagation at 19 MHz over the 5 year period of observation for quiet magnetic conditions ($K_{Fr} = 0 - 3$) are presented in Fig. 3 for the NW quadrant. K_{Fr} is the 3-hourly magnetic index reported by the magnetic observatory at Fredricksburg, Virginia. The contours show that there is no systematic variation of the E_s propagation with the solar cycle. The only prominent feature is the presence of E_s propagation during the summer months (May to August) of each year. The diurnal variation during these months shows the occurrence of morning and evening peaks. The evening peak is usually more marked when E_s propagation is observed for as much as 50% of the time. Some E_s propagation is seen during the winter months in the evening hours, but it is usually present for less than 10% of the time.

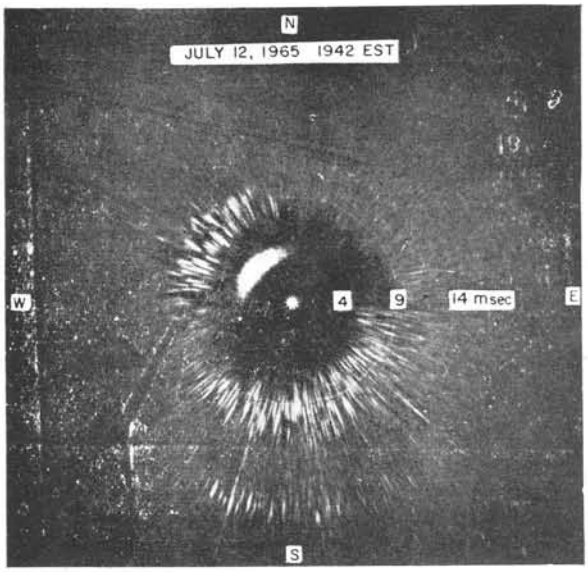

Fig. 2—Typical summer evening PPI showing simultaneous E_s propagation and field-aligned E-echoes at 19 MHz (The E_s propagation with ranges varying between 7 and 11 msec is seen at all azimuths except NE. The field-aligned echo is seen in the NW with inner range of 4 msec)

To determine whether this type of propagation is indeed a reflection from E_s clouds to the north, fE_s occurrence contours from Ottawa were studied. These ionosondings are very well suited for this comparison since Ottawa is at a slant range of approximately 500 km (E-layer heights) at an azimuth of 310° to Plum Island; this range corresponds to median slant ranges observed if elevation angles are assumed to be about 10°. Thus, maximum vertical frequencies of 4·5 – 5 MHz for the E_s clouds should be able to reflect the observing frequency. Fig. 4 shows percentage occurrence contours of $fE_s \geqslant 5$ MHz as observed at Ottawa for the period 1961-1965. The overall similarity of oblique E_s propagation presented in Fig. 3 and E_s occurrence at Ottawa are proofs for the conclusion that what we observe is probably oblique propagation via E_s.

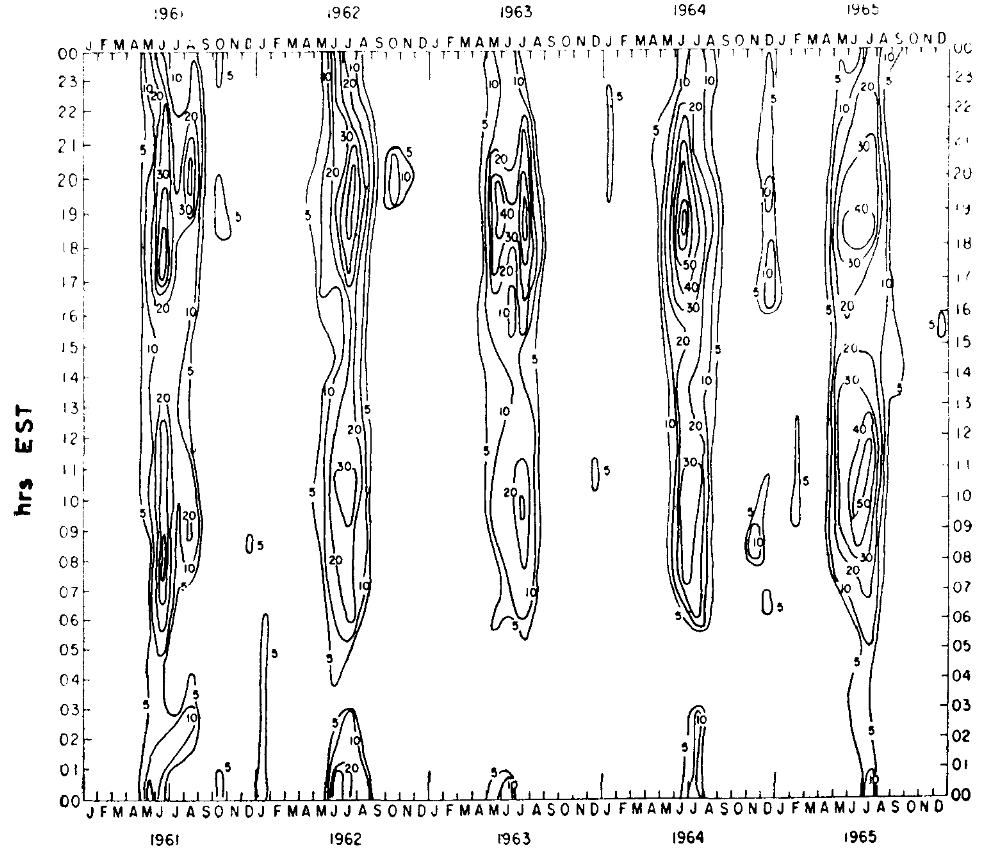

Fig. 3 — Percentage occurrence contours of Es propagation at 19 MHz in the NW, during 1961-1965 (KF_r = 0-3)

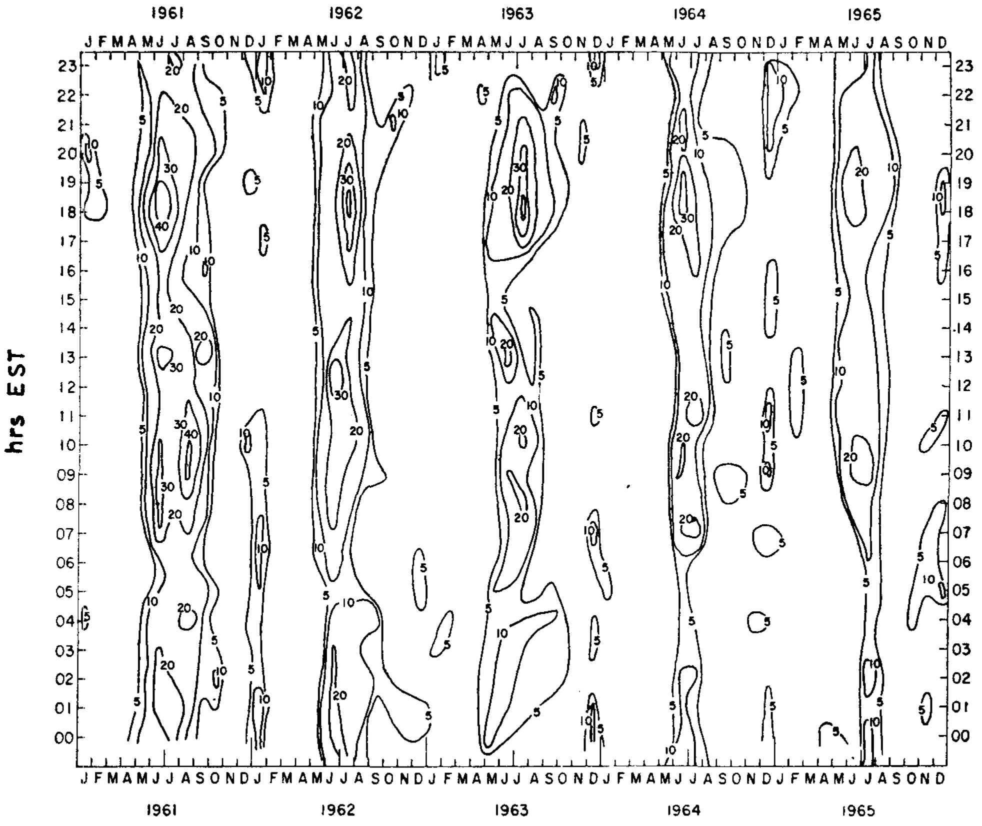

Fig. 4 — Percentage occurrence contours of fEs ⩾ 5 MHz for Ottawa, during 1961 1953

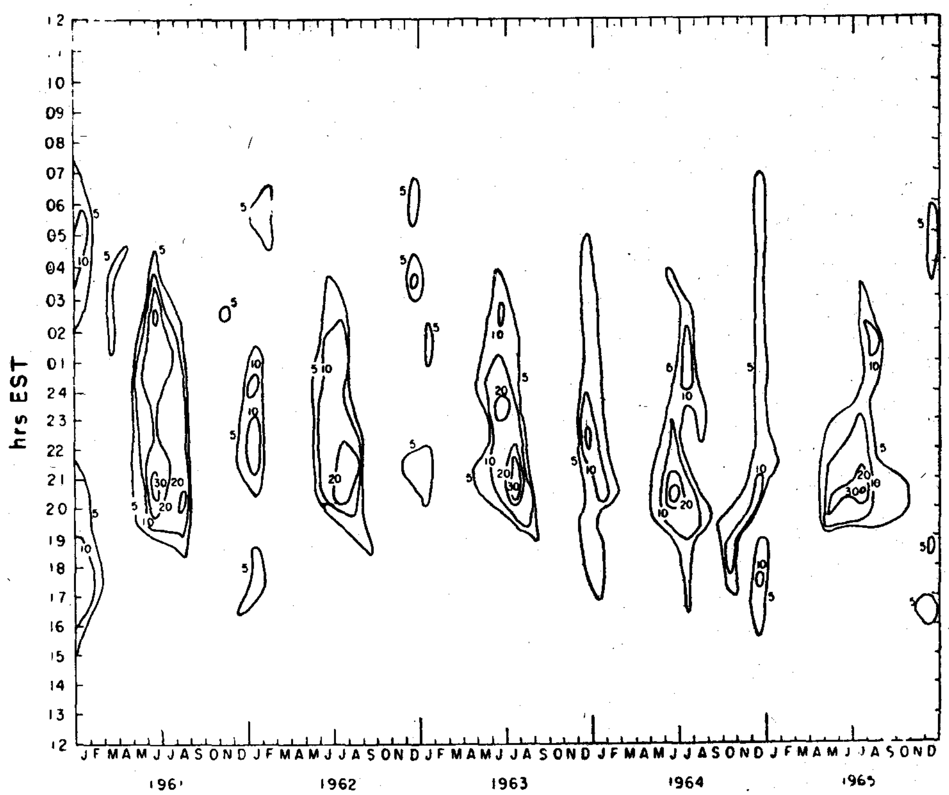

Fig. 5—Percentage occurrence contours of field-aligned E-echo at 19 MHz from the NW quadrant during 1961-1965 (K_{Fr} = 0-3)

To determine whether the occurrence pattern of Es over Ottawa is typical of a mid-latitude stations, Es propagation contours for latitudes to the south of Plum Island were drawn by utilizing the backscatter data from the SE and SW quadrants. Although the percentage occurrences were greater to the south, comparison of these contours with Figs. 3 and 4 showed similar diurnal and seasonal occurrence characteristics. These Es data demonstrate that Ottawa behaves like a mid-latitude rather than an auroral station. At an auroral station, on the other hand, the occurrence of Es would be predominantly a night-time phenomenon, positively correlated with magnetic activity, with little or no seasonal variation.

3.1 Quiet Magnetic Conditions

The total occurrence statistics of FAE(E) in the NW quadrant at 19 MHz during quiet magnetic periods (K_{Fr} = 0-3) over the years 1961-1965 are presented in Fig. 5. A very pronounced evening peak of occurrence in the summer is noted with a smaller peak after local midnight. FAE(E) occurrence of 5-10 % is also noted near the winter solstice with almost no activity in the equinoxes. No evidence of any solar cycle variation is noticeable.

We thus find that the definite summer evening maximum in FAE(E) is extremely well correlated with the evening maxima of both Es propagation and

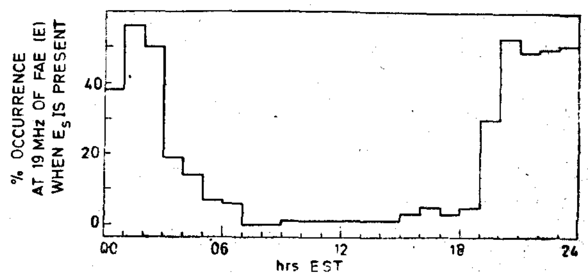

Fig. 6—Percentage occurrence of Es-associated, field-aligned E-echo at 19 MHz from the NW quadrant during 1961-1965 (K_{Fr} = 0-3)

*f*Es at Ottawa. The other diurnal peak in Es during the forenoon hours has no detectable accompanying FAE(E) activity. The high association of Es with FAE(E) during evening hours is further illustrated in Fig. 6, which shows the percentage occurrence of Es-associated FAE(E) from the NW quadrant for the 5 years of observation during quiet magnetic periods. During 2000 and 0300 hrs Es propagation is accompanied almost 50% of the time by FAE(E). Thus, the high occurrence of FAE(E) in association with summer evening Es under quiet magnetic conditions is a prominent feature of the backscatter data.

3. 2 Comparison between Quiet and Disturbed Conditions

To study the differences in simultaneous occurrence characteristics of Es and FAE(E) under different degrees of magnetic disturbance, we constructed a diagram (Fig. 7) which shows the seasonal behaviour of these two types of echoes for very quiet (K_{Fr} = 0, 1), moderate (K_{Fr} = 2, 3), and disturbed conditions (K_{Fr} 4 = 9). Each seasonal histogram shows the mean percentage occurrenc of FAE(E) at 19 MHz over the 5 years of observations.

The most notable features of Fig. 7 are (i) the presence of the predominant summer maximum of FAE(E) under both very quiet and moderately disturbed magnetic conditions, with a high percentage of simultaneous Es propagation, and (ii) a greatly increased occurrence of FAE(E) during disturbed conditions irrespective of season. Moreover, during the disturbed periods the appearance of day-time FAE(E) is noted with very little simultaneous Es propagation being observed at any time of day. The decrease of simultaneous Es propagation is not caused by the increased absorption that accompanies magnetic disturbances but rather by an actual absence of Es layer near the echoing volume. This could be established from Ottawa ionosonde data.

The very different behaviour of the association of FAE(E) with Es under quiet and disturbed conditions, namely, the failure of FAE(E) and Es to show a positive correlation with magnetic disturbances, has rather important consequences regarding the origin of these echoes. Generally, FAE(E) are considered to be auroral in origin, and the FAE(E) obtained at Plum Island during magnetic disturbances most likely belong to this category. However, it is to be emphasized that for a magnetic index of 1, the southern boundary of the auroral oval at midnight is almost 10° north of the echo region as shown in Fig. 1. The definite seasonal pattern of quiet time FAE(E) and the extremely low level of magnetic disturbance make it highly unlikely that even the hard zone portion of the auroral particle precipitation[6] could be responsible for the formation of these irregularities. It is our contention, therefore, that the occurrence of the quiet time FAE(E) is intimately connected with the simultaneous presence of mid-latitude evening Es and both very likely have a common origin which is other than auroral.

4. Discussion

We wish to examine our results of Es-associated, quiet time FAE(E) in the context of currently postulated plasma instability theories. Many workers[7-9] have suggested that the diffuse non-blanketing type of sporadic-E which frequently occurs at mid-latitudes may be caused by an instability in a weakly ionized

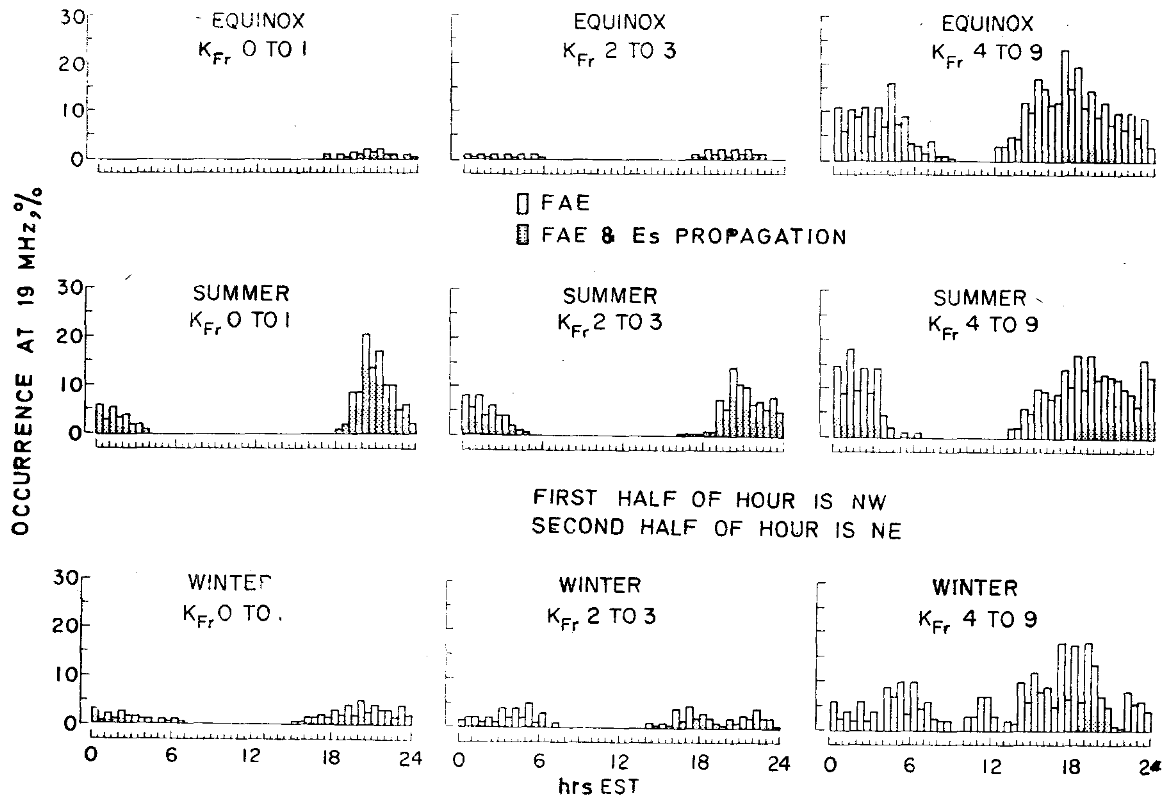

Fig. 7—Average seasonal behaviour of field-aligned E-echo and simultaneous Es propagation for various ranges of magnetic index during 1961-1965 (The histograms represent percentage occurrence of FAE(E), and the shading within the blocks represent simultaneous Es propagation)

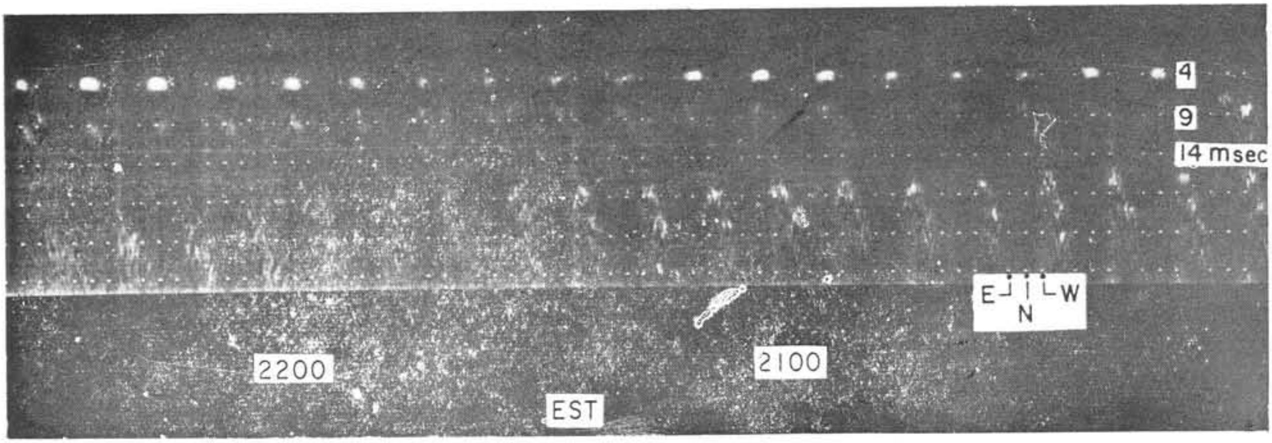

Fig. 8—Typical summer evening compressed time scale film showing simultaneous Es propagation and field-aligned E-echoes at 19 MHz (Note the intensity variation of the field- aligned echo)

plasma. This type of instability, known as the cross-field instability, occurs in the presence of external electric and magnetic fields directed at na angle to each other, provided an appreciable gradient in the plasma density exists.

The theory of ionospheric plasma instability was developed[7-9] on the basis of electric fields of the order of 1 mVm^{-1} which can be accounted for by normal ionospheric winds in the quiet time mid-latitude ionosphere. In particular, Tsuda *et al.*[7], using a two-dimensional, non-linear form of the instability, indicate a cyclical process of growth and decay of the irregularity in a time scale of a few tens of minutes even in the presence of a constant applied electric field. In Fig. 8 we show such a cyclic behaviour of the FAE(E) component in our hf data. This is a compressed time scale representation which allows one to study the fluctuation in FAE(E) intensity with a scale of tens of minutes. The FAE(E) echo amplitude does not vary in conjunction with the ground E_s echo. In fact, the FAE(E) becomes more intense when the E_s echo weakens. At this time the magnetic index was varying between 0 and 1.

Davis[10] has invoked the cyclically recurrent behaviour predicted by this theory for the explanation of a strong 50 sec modulation in the intensity of the direct hf backscattered component from artificial plasma clouds. A longer period (tens of minutes) intensity fluctuation was also observed in his two cases of long-duration release without any corresponding intensity variation in the ground scattered component.

It should be pointed out, however, that without accompanying Doppler measurements we cannot rule out a possible contribution of turbulence in the formation of the irregularities which give rise to FAE(E)[11-13]. Whatever the mechanism, it is nevertheless true that FAE(E) do occur at hf and these are unrelated to magnetic disturbances. It is our feeling that the use of the term 'radio aurora' to describe these events may be somewhat misleading in view of the IAGA (1968) recommendation that this name be confined only to 'aspect-sensitive high-latitude irregularities strongly related to magnetic storms'.

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