THE REFLECTION COEFFICIENT OF THE NIGHT-TIME IONOSPHERIC F REGION

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Summary

Night-time records of F_2 reflections at normal incidence have been made at three frequencies, 2·28, 3·84, and 5·8 Mc/s, using a swept-gain technique. The reflection coefficient of the F region has been measured from these records. The reflection coefficient is appreciably less than unity at all frequencies for a large part of the recording period. Resolved trace measurements show the absorption to occur in the deviative region. There is some suggestion of the reflection coefficient, measured at 2·28 and 3·84 Mc/s, depending on season, monthly K_p sum, and true height of reflection. The reflection coefficient measured at 5·8 Mc/s appears to be independent of these parameters. There is a suggestion that the reflection coefficient is related directly to f_bE_s for K indices $\geqslant 5$, and inversely to the operating frequency.

I. Introduction

This work is the outcome of a program of recording in Brisbane (27·5°S., 152·9°E.) on three frequencies, 2·28, 3·84, and 5·8 Mc/s. The temporal, frequency, and height variations of the reflection coefficient have been investigated between the hours 1800 and 0600 (local time) from June 1956 to December 1958. In addition, possible relationships between the reflection coefficient and other geophysical parameters have been investigated.

II. Equipment

The method of recording used was a modification of the normal pulse method described by Appleton and Piggott (1942). Basically, the equipment consisted of a fixed-frequency pulsed transmitter of 500 W peak power, a receiver, and a cathode-ray oscilloscope display, together with a 35-mm camera for recording. This apparatus was duplicated for each other frequency with the exception of the receivers; the original receiver was modified by adding two r.f. heads, tuned to the recording frequencies, and the outputs of the r.f. heads were fed, in turn, into the common i.f. strip.

The aerial systems, for each frequency, consisted of half-wave dipoles, one for transmission and one for reception. As the downcoming waves were roughly circularly polarized, the aerial systems could not discriminate between the two components, and a resultant wave compounded of the extraordinary and ordinary waves was recorded, except when the two components were resolved in range. However, Piggott (1953) has shown that the mean amplitude of a combination of ordinary and extraordinary waves is almost exactly equal to the mean amplitude of the stronger one, although the type of fading is altered.

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In the i.f. strip, a swept-gain technique (McNicol, Webster, and Bowman 1956) was incorporated. This enabled the gain of the receiver to be decreased periodically, in a regular manner from a maximum to 80 dB below the maximum, in discrete steps of 2 dB. The sudden increase in gain (80 dB) at the start of a run resulted in the records appearing as frames, with the echo amplitude measurable by the length of the echo trace on each frame. The transmitters and display units were phased, and the time-base durations adjusted, so that the records obtained on one frequency were not confused by those from the other two frequencies.

Piggott (1953) discussed the way in which ionospheric effects alter the shape of the modulation envelope of echoes and described steps for overcoming this effect. In particular, he showed how these effects depended on pulse length. In the measurements discussed here the pulse length of the transmitters was fixed at 100 μs (as the transmitters were used for other experiments), and it was therefore necessary to determine the highest order of multiple which would not show pulse shape distortion at this pulse width. Values of ρ, derived from the 1st to 4th multiple echoes, were compared and it was found that results obtained using the 1st, 2nd, and 3rd multiples were in agreement. Consequently the analysis was limited to an examination of these multiples.

Since the method of photographic recording gave some measure of integration, the effects of short-period fading could, to a large extent, be overcome by adjusting the rate of change of gain. The rate finally adopted was 2 dB each 12 s. This rate gave results which showed consistency from frame to frame.

III. Reduction of Records

The film records (for sample, see Plate 1) enable one to measure the range and amplitude of the echo, as well as the time of occurrence. With the aid of routine local ionograms one can decide whether the echo arose from an ordinary, an extraordinary, or a compound wave.

The simple ray theory of propagation indicates that the amplitude, E_r of the rth multiple, reflected at vertical incidence from a level at an apparent height of h', is given by (Piggott 1953)

$$E_r = (\rho\rho_g)^r E_0 h_0 / rh', \tag{1}$$

where ρ, ρ_g are the apparent reflection coefficients of the ionosphere and ground respectively, for one ionospheric component (i.e. ordinary or extraordinary), E_0 is a parameter depending on ρ_g and the equipment characteristics, and h_0 is a convenient reference height. E_r and $\rho\rho_g$ can be deduced from equation (1) when two or more multiple reflections are present; and when E_0 is known $\rho\rho_g$ can be deduced using the quantities measured from a single reflection.

Because of the occurrence of long-period fading at night, it is necessary to average E_0 over a time of the order of at least one fading period. For each frequency and for each week of recording a mean value of E_0 was obtained and used to determine $\rho\rho_g$. The mean E_0 was derived from a number of individual values large enough to smooth out the effects of long-period fading.

It is possible to estimate the approximate value of ρ_g. If the value of $\rho\rho_g$ is near unity on all frequencies for a considerable time it is likely that the ionospheric absorption is negligible; focusing effects are unlikely to occur on all frequencies for a long period. Thus the value of $\rho\rho_g$ under such conditions is a fair indication of ρ_g. In October 1958, $\rho\rho_g$ is very nearly unity for all three frequencies. Baird (1954) reported records, on $2 \cdot 28$ Mc/s, of multiples up to the 30th order, consistent with a value of unity for ρ_g. On the basis of this information measured values of $\rho\rho_g$ are taken as being values of ρ.

IV. Results

(*a*) *Temporal Variation*

Values of the reflection coefficient derived from individual frames were averaged to give hourly mean values, and all hourly mean values for a particular month averaged to give a nocturnal plot. These are shown in Figure 1, where ρ is plotted against local time for each month.

The reflection coefficient shows no systematic nocturnal or seasonal variation. There is a suggestion that the variation in ρ increases with time, and a closer examination reveals a tendency for the variation to increase as the sunspot number increases.

The increase in variation in ρ could be due to either an increase in focusing variation or in absorption variation. To determine which, values of ρ, derived from different multiples, were compared during periods of marked variation. If the variation was due to an increase in focusing variation then one would expect to find marked differences in the values of ρ. No such differences were found, suggesting that there is an increase in absorption variation.

It is apparent from Figure 1 that ρ is appreciably less than unity for a considerable part of the recording period, indicating that some absorption is present. The maximum and minimum values of the absorption for one month in each season are given in Table 1.

Because of the marked variation in ρ, there is a possibility that systematic temporal variations could be masked. To investigate this the hourly mean values of ρ, for the whole recording period, were averaged to give seasonal and annual nocturnal plots (Figs. 2 (*a*), 2 (*b*), 2 (*c*)). Examination of these plots shows a seasonal variation for ρ_4 ($3 \cdot 84$ Mc/s); the variation is confused for ρ_2 ($2 \cdot 28$ Mc/s), but ρ_2 (summer)$>\rho_2$ (autumn), and, except for early morning, ρ_6 ($5 \cdot 8$ Mc/s) appears independent of season. The same relationships are seen if a monthly mean value of ρ (2300–0000 hr) is plotted against month (Figs. 3 (*a*), 3 (*b*), 3 (*c*)). The nocturnal variation of ρ in the seasonal plots (Figs. 2 (*a*), 2 (*b*), 2 (*c*)), shows no regularity; this is borne out by the relatively small nocturnal variation evident in the annual plot (Fig. 2 (*d*)).

(*b*) *Resolved Trace Observation*

On quite a few occasions the ordinary and extraordinary components were resolved for lengthy periods. This presented an opportunity for determining the type of absorption occurring. Values of the ratio ($\log \rho_x/\log \rho_0$), when compared with theory, showed that the absorption was mainly deviative. Figure 4 shows a

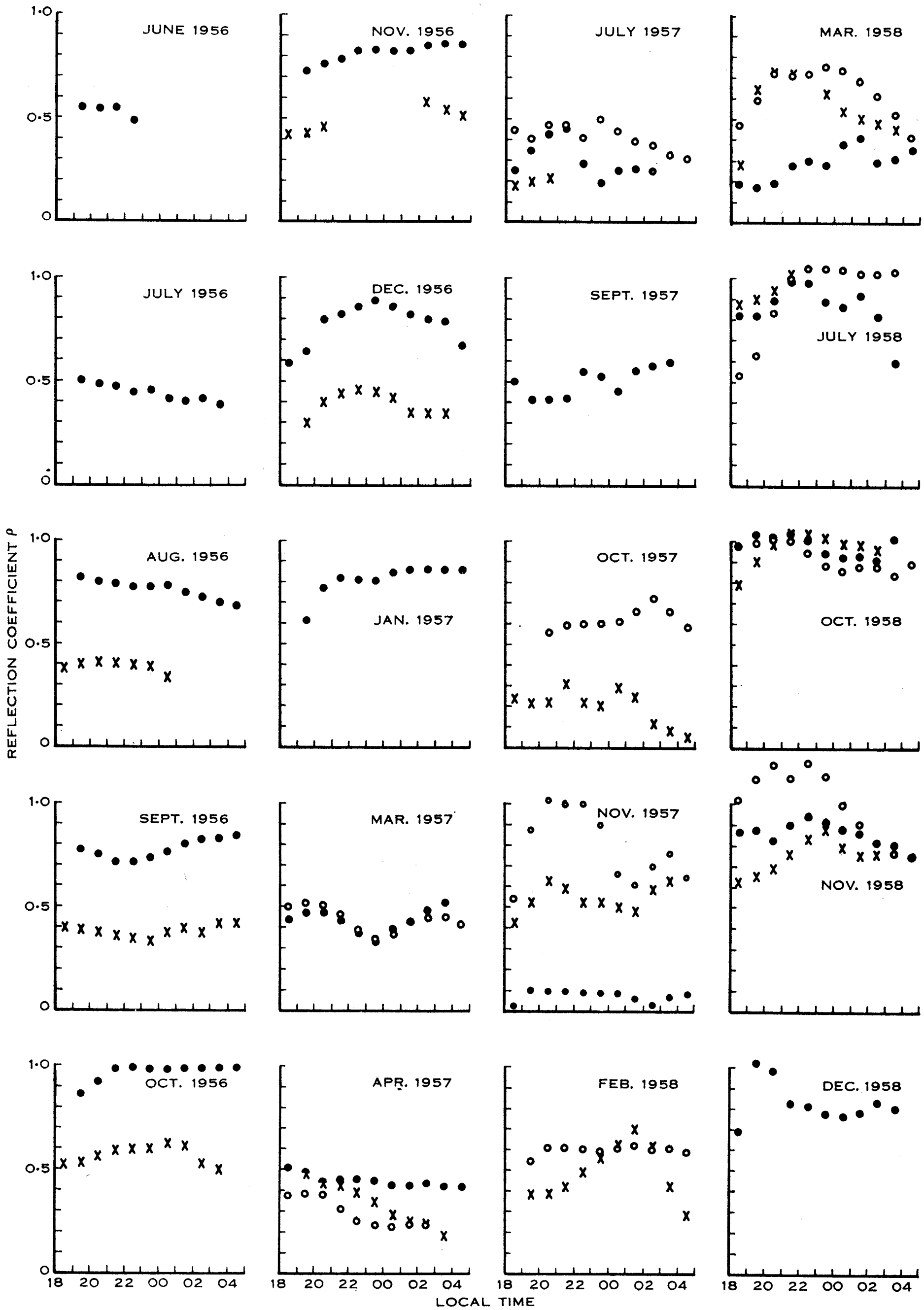

Fig. 1.—Monthly mean nocturnal variation of reflection coefficient. ○ 2·28 Mc/s, ● 3·84 Mc/s, × 5·8 Mc/s.

plot of the values of ($\log \rho_x/\log \rho_0$) for the night August 18–19, 1956, together with the critical frequency variation.

(c) *Magnetic Correlation*

Correlations were looked for between ρ and hourly mean values of the horizontal component (H_{av}) of the Earth's magnetic field. Since no magnetic data are available for Brisbane before 1957, values of H_{av} for Watheroo (30·3°S., 115·9°E.) were used prior to 1957 and local magnetic data when they became available. The results showed no significant correlation between individual values of ρ and H_{av}, even when lags of up to 6 hr were introduced.

Some suggestion of a correlation appeared when the relationship between the monthly mean value of ρ (2300–0000 hr) and monthly K_p sum was investigated. A statistical analysis is given in Table 2. Figure 3 (*d*) suggests that the seasonal variation of K_p correlates inversely with the variation of ρ_2 (Fig. 3 (*a*)) and ρ_4 (Fig. 3 (*b*)).

TABLE 1

MAXIMUM AND MINIMUM VALUES OF ABSORPTION FOR SOME TYPICAL MONTHS

Month	Absorption (dB)					
	2·28 Mc/s		3·84 Mc/s		5·8 Mc/s	
	Min.	Max.	Min.	Max.	Min.	Max.
Oct. 1956	—	—	0·1	0·7	4·2	6·0
Dec. 1956	—	—	1·1	3·9	6·7	9·2
Mar. 1957	5·7	9·7	5·3	9·2	—	—
July 1957	6·0	9·7	6·9	14·3	13·5	13·8
Oct. 1957	2·7	5·2	—	—	10·0	22·0
Dec. 1957	0	4·3	2·0	3·0	4·0	6·3
Mar. 1958	2·3	5·7	7·7	15·5	2·7	6·9
July 1958	0	2·8	0	4·6	0	0·9
Oct. 1958	0	1·6	0	0·8	0	0·9
Dec. 1958	0	2·3	0·5	1·9	1·1	3·8

(d) *Other Correlations*

Mitra and Shain (1953) and Bhonsle and Ramanathan (1958) found a correlation between absorption and spread-*F*. Consequently, possible correlations of ρ (*F* region) with occurrence of range spreading and frequency spreading (McNicol, Webster, and Bowman 1956) were investigated. No correlation was found, whether range and frequency spreading were considered separately or together.

A correlation was sought between the appearance of E_s clouds above Brisbane and the *F*-region reflection coefficient. The existence of E_s clouds was deduced from the appearance of E_s reflections for a limited period on the local ionograms (1·5–16 Mc/s). The E_s occurring at Brisbane has been classified as either "sequential" or "constant height" type (McNicol and Gipps 1951). No correlation was found between the F-region reflection coefficient and the presence of either of the two types of E_s clouds considered separately or together; neither was any correlation found between the seasonal variation of E_s occurrence (the two types together, or separately) and that of the F-region reflection coefficient.

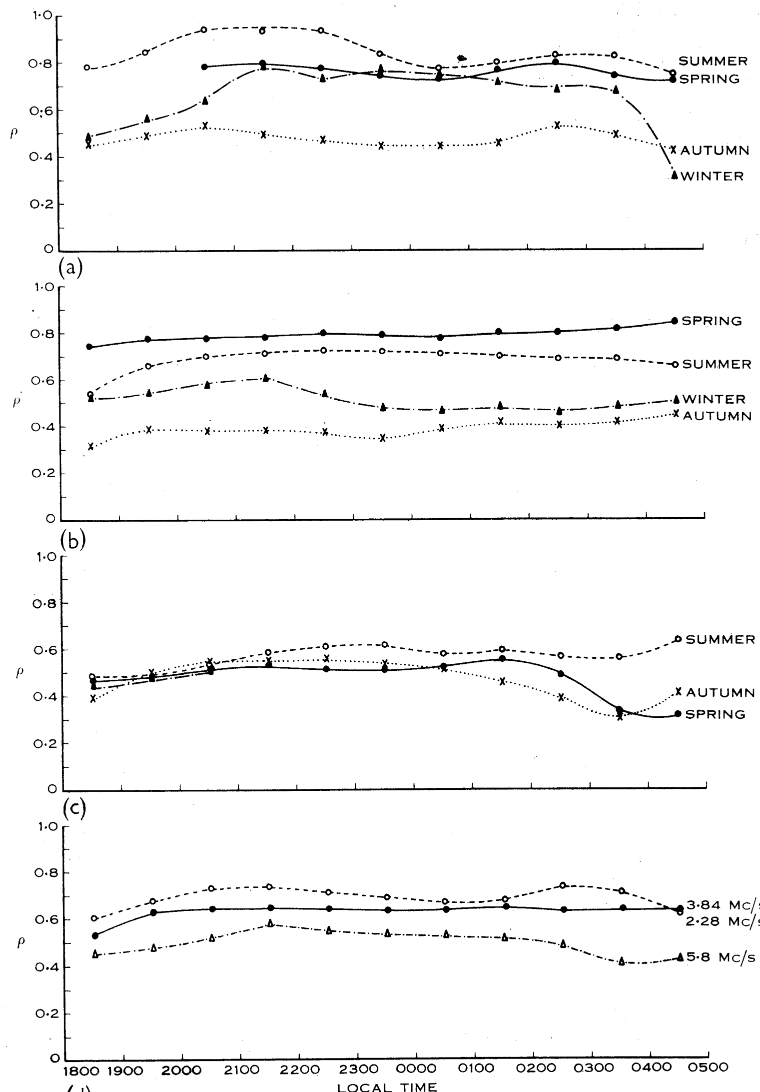

Fig. 2.—Average nocturnal variation of reflection coefficient. (*a*) Seasonal for 2·28 Mc/s, (*b*) seasonal for 3·84 Mc/s, (*c*) seasonal for 5·8 Mc/s, (*d*) annual for all frequencies.

Finally, a possible correlation between the F-region reflection coefficient and E_s blanketing frequency (f_bE_s) was investigated. No correlation was found for low K indices. However, when restricted to values observed when the K index$\geqslant$5, a correlation was obtained. As these high K indices occurred infrequently, very few values were available, and in fact, for 2·28 Mc/s, insufficient values were available to test the correlation. A statistical analysis is given in Table 3.

TABLE 2

RELATIONSHIP BETWEEN MONTHLY MEAN VALUE OF ρ (2300–0000 HR) AND MONTHLY K_p SUM

Frequency (Mc/s)	Correlation Coefficient	Significance
2·28	−0·59	Significant at 10% level
3·84	−0·56	Significant at 3% level
5·8	−0·15	Insignificant

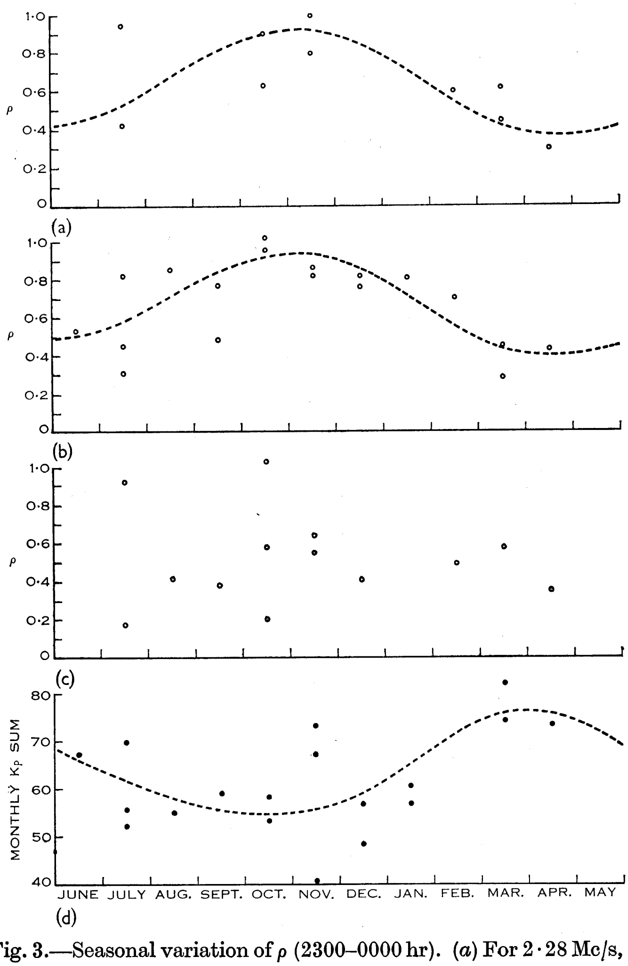

Fig. 3.—Seasonal variation of ρ (2300–0000 hr). (*a*) For 2·28 Mc/s, (*b*) for 3·84 Mc/s, (*c*) for 5·8 Mc/s, (*d*) seasonal variation of monthly K_p sum.

TABLE 3

RELATIONSHIP BETWEEN REFLECTION COEFFICIENT AND E_s BLANKETING FREQUENCY FOR K INDICES $\geqslant 5$

Frequency (Mc/s)	Correlation Coefficient	Significance
2·28	—	Insufficient values
3·84	−0·51	Significant at 0·1% level
5·8	+0·48	Significant at 7% level

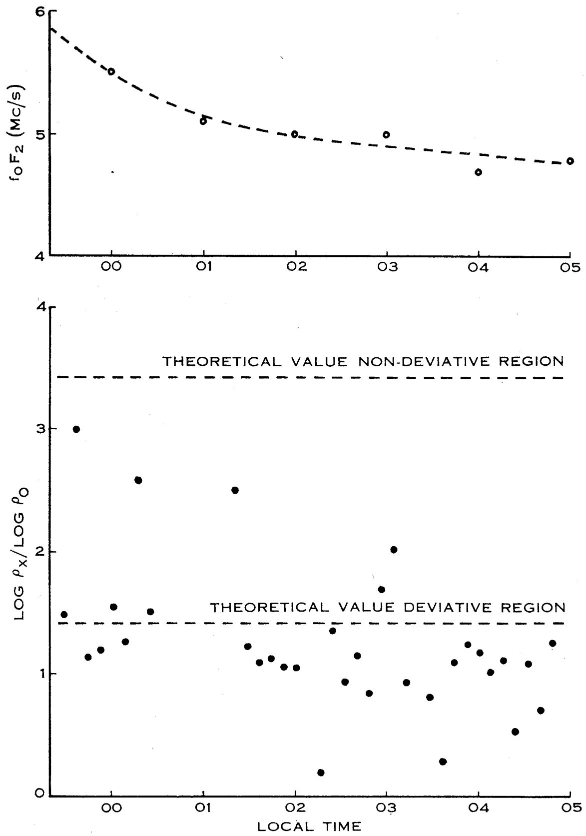

Fig. 4.—Variation of log ρ_x/log ρ_0 for 3·84 Mc/s records and f_0F_2 on August 19, 1956.

(e) *Variation of ρ with Reflection Height*

To check on the possible dependence of ρ on reflection height, true heights (h) for all records were calculated using the Schmerling and Ventrice (1959) five-point method. Hourly mean values of ρ and h were averaged over a month and the relationship between them investigated.

There is a tendency for ρ_2 and ρ_4 to increase as the true height of reflection increases; ρ_6 appears to be independent of height of reflection. A statistical analysis of these results is given in Table 4.

TABLE 4
RELATIONSHIP BETWEEN REFLECTION COEFFICIENT AND TRUE HEIGHT OF REFLECTION

Frequency (Mc/s)	Correlation Coefficient	Significance
2·28	+0·23	Significant at 5% level
3·84	+0·49	Significant at better than 0·1% level
5·8	+0·14	Insignificant

(*f*) *Frequency Dependence of* ρ

This can be examined best by rearranging the data in Figure 2. This is done in Figure 5, where the seasonal and annual nocturnal plots are regrouped so as to show the frequency dependence of ρ in each season. An inverse relationship between ρ and frequency is suggested in the annual, summer, and winter plots, but the relationship is confused in the equinoxes.

V. DISCUSSION

The main points of interest arising out of this work are:

(i) the relatively small range of nocturnal variation of ρ at any one season and frequency,

(ii) the indications of a seasonal variation of ρ,

(iii) the suggestion of an inverse relationship between ρ and frequency.

The ionospheric reflection coefficient ρ is related to the ionospheric absorption $\int \kappa \, ds$ and the discussion below will be in terms of absorption.

(*a*) *Determination of the Type of Absorbing Region*

The results obtained from resolved trace records, discussed in Section IV (*b*), support Whitehead's (1956) suggestion that most of the absorption, for the ordinary wave, at a given time, must occur near the level of reflection, and accordingly be deviative. Therefore it appears reasonable to assume that, to a first approximation, the region where most of the absorption occurs is quite a small fraction of the ionosphere, and is situated very near the height of reflection. Assuming ν to be constant in this small region where most of the absorption occurs, Mitra (1952) gives for the *o*-ray

$$-\log \rho_D = (\mathrm{P}'-\mathrm{P})\nu/2c,$$

where P' = group path, P = optical path, ν = collisional frequency, c = velocity of light. Thus the absorption may vary either because ν varies or because $(P'-P)$ varies.

(*b*) *Variation of Absorption with Reflection Height*

The observed variation of absorption at 2·28 and 3·84 Mc/s with reflection height (Section IV(*c*)) implies that ν and/or $(P'-P)$ decreases as the height of reflec-

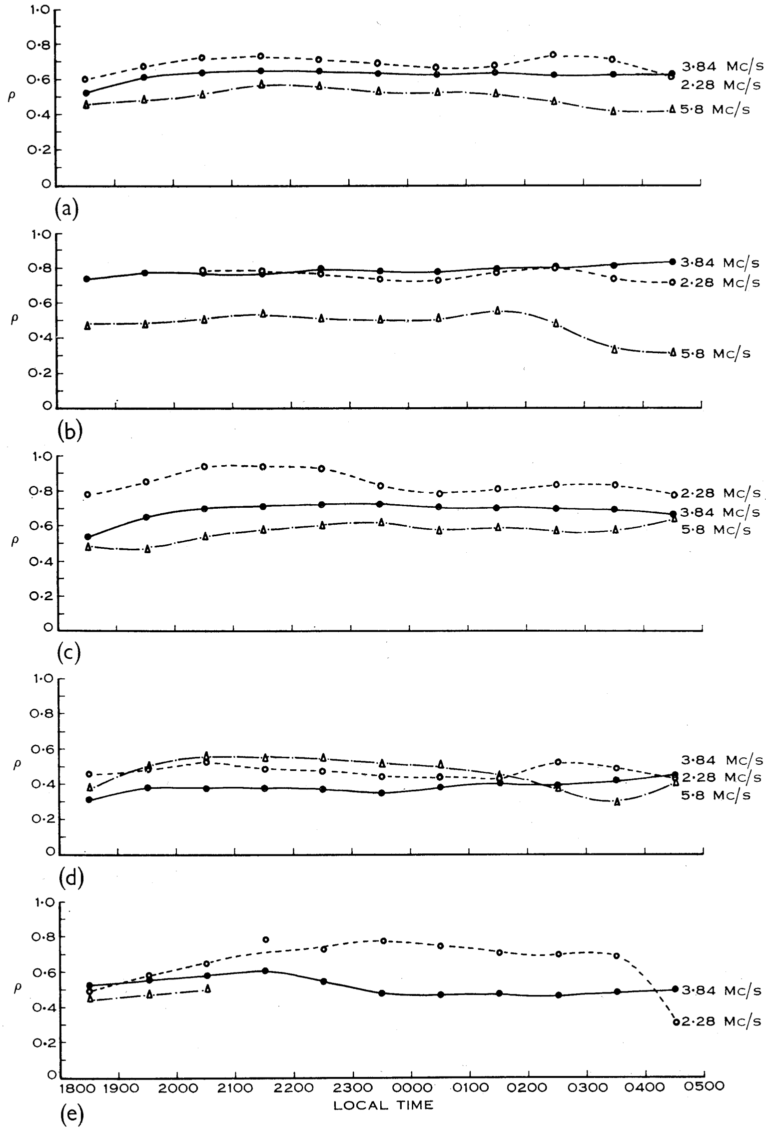

Fig. 5.—Average nocturnal variation of reflection coefficient. (*a*) Annual, (*b*) spring, (*c*) summer, (*d*) autumn, (*e*) winter.

tion increases. If ν is assumed to decrease as height increases then the absorption would be expected to decrease with increasing reflection height, since most of the absorption occurs close to the reflection point. As the height increases are associated, on a seasonal basis, with decreases in f_0F_2, one would expect $(P'-P)$ to increase, tending to counteract the effect of change in ν on absorption. However, at 2·28 and 3·84 Mc/s the magnitude of the change in $(P'-P)$ is too small to counteract the effect of change in ν, and the absorption should thus decrease as the height of reflection increases; this is in agreement with the observed results.

The absorption at 5·8 Mc/s appears to be independent of change in reflection height. As this recording frequency is much closer to the critical frequency, the magnitude of the change in $(P'-P)$ will be much greater than is the case at 2·28 and 3·84 Mc/s. To explain the observed independence of absorption on height changes at 5·8 Mc/s the contribution to the absorption due to an increase in $(P'-P)$ as the reflection height increases must be sufficient to almost balance the decrease in absorption as ν decreases.

(c) *Variation of Absorption with Frequency*

There is a tendency for the absorption to increase as the frequency increases (Section IV (*f*)). This can be attributed to an increase in $(P'-P)$ as the operating frequency approaches the critical frequency of the F_2 region. The collisional frequency will decrease as the height of reflection increases (i.e. as the operating frequency increases) but, to explain the observed results it is necessary that

$$\nu_6(P'-P)_6>\nu_4(P'-P)_4>\nu_2(P'-P)_2$$

in winter and summer. However, this does not explain the confused relationship in the equinoxes.

(d) *Seasonal Variation of Absorption*

Nicolet (1959) showed that ν in the F_2 region depends only on collisions with positive ions, and that

$$\nu_{e,+}\propto n^+T^{-3/2},$$

where n^+ = positive ion density, $\nu_{e,+}$ = frequency of collisions between electrons and positive ions, and T = temperature.

Assuming that the positive ion density n^+ equals the electron density N in the F_2 region at night (Martyn 1956), then, for fixed frequency results, n^+ at the level of reflection remains constant and $\nu_{e,+}$, at that level, must depend only upon the temperature. The temperature in the upper atmosphere increases with height and so $\nu_{e,+}$ must decrease with height.

Published satellite data indicate diurnal and seasonal variations in density and in temperature. Martin and Priestler (1960) report a seasonal effect with a density maximum in summer. This indicates a seasonal variation in temperature, at constant height, with a maximum in summer. This suggests a seasonal variation in ν and in absorption at 2·28 and 3·84 Mc/s (since change in $(P'-P)$ is not so marked at lower frequencies), with a minimum in summer. This effect would explain the seasonal variation in absorption at 3·84 Mc/s. The lack of a clear seasonal variation at 2·28 Mc/s can be explained by the smaller variations in temperature and ν expected at lower heights. Martin and Priestler (1960), Paetzold (1959), and King-Hele and Walker (1960), using satellite data, report density fluctuations which are very small at about 200 km, but may be as large as 10–100 : 1 at 1000 km. Thus the seasonal variation in temperature may be too small at the reflection height of 2·28 Mc/s to have any marked effect on the absorption.

This does not explain the apparent seasonal independence of absorption at 5·8 Mc/s. It is possible that the overriding effect of changes in $(P'-P)$ at 5·8 Mc/s, suggested in Section V (*b*), masks the seasonal variability expected from the variation in temperature.

(*e*) *Correlations with Other Geophysical Parameters*

The correlation found between magnetic activity and absorption (Section IV(*c*)) was much less definite for 5·8 Mc/s. It is known that the diurnal density (and temperature) fluctuations increase with height, and these, together with variations in $(P'-P)$, may be sufficient to mask the magnetic control at the level of 5·8 Mc/s signal reflection.

In the case of the correlation between absorption and E_s blanketing frequency (Section IV(*d*)) it is found that no correlation shows up for $K<5$. It may be significant that certain density variations derived from Sputnik II (1957 β) and Sputnik III (1958 δ_1), are associated with $K\geqslant 5$ (Nicolet 1961). The fact that, while the absorption at 3·84 Mc/s increases with increasing blanketing frequency, the absorption at 5·8 Mc/s decreases with increasing blanketing frequency is difficult to explain. It may be remarked that the correlation coefficient for the 5·8 Mc/s results is not highly significant statistically.

The lack of correlation between spread-*F* and absorption is possibly due to the selective rejection of records, as unreadable, in the present investigation. Finally, the lack of correlation between absorption and the occurrence of sporadic-*E* clouds does not contradict a suggestion made by Davies and Hagg (1955) that the particular type of sporadic *E*, which they report as associated with a marked increase in absorption, occurs only in or near auroral regions.

VI. Acknowledgments

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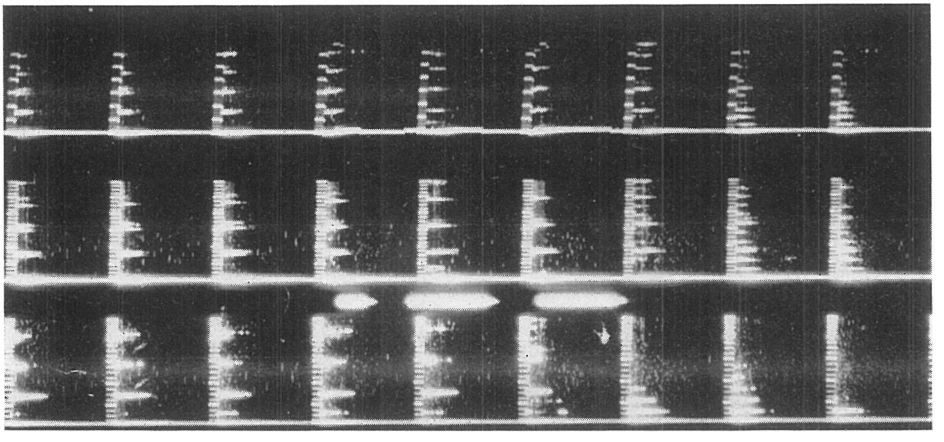

A typical swept-gain record showing recordings on three operating frequencies.

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