RIOMETER STUDIES AT SOUTH GEORGIA

By R. I. KRESSMAN

ABSTRACT. A riometer at South Georgia, a station affected by the South Atlantic geomagnetic anomaly, has revealed no absorption events during 1971 attributable to *D*-layer ionization caused by particle precipitation. A new technique for separating the *D*-region component of absorption and the *F*-region component in riometer data has been developed using ionosonde *fm2* data. The two components are comparable in summer months. The relation between *foF2* and the *F*-region component is consistent with an electron–ion collision absorption mechanism in the *F*-region.

A PROGRAMME of vertical incidence sounding has been in operation at the British Antarctic Survey's geophysical observatory at South Georgia (Table I) since June 1970, and data are now published. This programme was supplemented in June 1971 by the addition of a riometer to monitor the ionospheric absorption of cosmic noise.

TABLE I. GEOGRAPHICAL AND MAGNETIC COORDINATES AT SOUTH GEORGIA

Geographical coordinates	54° 17′ S.	36° 30′ W.
Geomagnetic coordinates	−44° 00′	25° 54′
Dip	−52° 18′	
Declination	− 7°	
L-shell	1·86	

The riometer technique is well established for the continuous monitoring of ionospheric absorption, particularly for the study of solar flare and auroral events. A review by Hultqvist (1966) detailed the results which have been obtained in this field. The method is not as effective for the study of normal *D*- and *E*-region absorption, whose amplitude is generally small at the normal operating frequencies. Useful results may be obtained by statistical methods, however, if sufficient data are employed.

This paper presents results obtained between June and December 1971. Special efforts have been made to detect any phenomena which may be attributed to particle precipitation.

DATA AND ANALYSIS

The equipment used was a commercially produced version of the riometer described by Little and Leinbach (1959), operating on 27·6 MHz. A modification was made to include a minimum-signal detector, giving time constants of 10 sec. for a falling signal and 45 sec. for a rising signal. A three-element Yagi antenna was directed at the zenith, the electric plane lying east–west. The main lobe had a half-angle of approximately 35° at the half-power points. The output current, which is proportional to received noise power, was recorded on a chart recorder, which allowed an average scaling accuracy equivalent to 0·05 dB in absorption, with timing to the nearest minute.

Values of the current were abstracted from the continuous record at half-hourly intervals of local time using a pencil-following digitizer. On occasions when the instantaneous value was unavailable for any reason (e.g. interference), the average value was taken over a maximum period of ± 5 min. from the correct time. Number distributions for each half-hour of sidereal time were produced from these data for those night-time periods ($\chi > 100°$) for which the critical frequency, *foF2*, was less than 5 MHz. As will be shown later, this is a safe limit for negligible *F2*-layer absorption ($L < 0{\cdot}01$ dB). The current, I_0, corresponding to the peaks of these distributions was used to construct a curve representing unabsorbed noise power in sidereal time. The equivalent absorption, L dB, for each half-hourly measurement of current, I, could then be deduced using the expression:

$$L = 10 \log_{10}(I_0/I). \qquad (1)$$

A table of monthly median values of absorption is given in the Appendix. Examination of winter night-time values, when absorption is expected to be negligible, shows a standard deviation of 0·03 dB on the median, equivalent to about 0·12 dB on individual values.

The charts were also carefully examined by eye for departures from a smooth curve, and all events detected in this way were noted for future correlation with other measurements.

A major limitation to the accuracy of the data arises from changes in antenna sensitivity with meteorological precipitation—particularly melting snow—on the antenna. To withstand the high wind speeds encountered in this location, the antenna was constructed with additional supporting insulators along the length of each element. Dry snow accumulating on these supports had no detectable effect, but wet snow caused leakage and loss of signal. This loss generally amounted to between 0·5 and 2·0 dB, occasionally rising to 15 dB. These conditions occur only when the temperature is rising, so that the signal returns to normal within a short time of the precipitation ceasing. Rain, unmixed with snow, had no recognizable effect.

Using precipitation records covering the period (personal communication from J. C. Farman), all periods which could be affected by the phenomenon were identified and the corresponding data rejected. In the majority of cases, the presence of the effect on the records is readily observable, but some accurate data may also have been rejected. Approximately one-third of the total data, evenly distributed throughout the 24 hr. for all months, has been rejected in this way.

The sensitivity of the equipment to *D*-region absorption events has been checked using absorption due to small solar flares, and by comparisons with the ionosonde absorption-sensitive parameters, $f_{\min}$ and $fm2$ (the minimum frequencies of the first- and second-order echoes, respectively).

A considerable number of $f_{\min}$ events associated with optically observed solar flares occurred during the period of operation of the riometer. 15 of these events reached absorption values, A, in excess of 80 dB (after correction for deviative absorption in the *E*-layer), where:

$$A = L(f+f_L)^2, \qquad (2)$$

L being the absorption in dB measured at frequency f; f_L is the gyro-frequency about the longitudinal component of the magnetic field. All of these events were detected by the riometer, although solar noise accompanying the flares interfered in some cases.

The riometer is thus shown to be capable of detecting events with an equivalent riometer absorption index, $Ar(=A/2)$ of 40 dB, equivalent to 0·05 dB at 27·6 MHz. For comparison, typical values of Ar at noon in summer for the normal *D*- and *E*-layer lie between 170 and 350 dB in sunspot minimum and maximum, respectively.

An unusual event encountered in the course of this study occurred on 20 November 1971, when a short burst of solar radio noise seen on the riometer preceded a rapid rise in riometer absorption and ionosonde $f_{\min}$. Widespread sudden phase-anomaly events were subsequently reported, and satellite X-ray measurements show a large peak in flux. However, no optical flare was observed. This was the only event of this type observed.

PARTICLE EFFECTS

A feature of the South Atlantic region is the abnormally low value of total geomagnetic field intensity (Cain and Neilon, 1963). Gledhill and van Rooyen (1962) have noted that this might be expected to lead to enhanced charged particle precipitation capable of producing detectable airglow and ionospheric effects. Abnormally high fluxes at low heights were originally observed by early Russian satellites (Kurnosova and others, 1962), and later by the Discoverer and Alouette satellites. Particle-linked ionospheric events have been reported by Gledhill and others (1967).

Greener (1972) has analysed Alouette I data relating to the Southern Hemisphere and he has shown that, at the heights and particle energies recorded (1,000 km. and >40 keV, respectively), precipitated particle fluxes of up to 5×10^5 electrons cm.$^{-2}$ sec.$^{-1}$ ster.$^{-1}$ were observed above South Georgia.

Fluxes of this magnitude have been found in auroral regions to cause 30 MHz riometer absorption events of up to 1 dB (Jelley and others, 1964). No such events have been recorded

APPENDIX

hr.	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
JUNE																								
Count	12	14	19	20	19	20	20	17	17	18	16	17	17	15	18	18	17	19	19	17	20	19	10	10
Median L_{TOT}	−1	−2	0	−1	−1	0	4	4	1	4	14	23	28	29	26	20	10	4	4	3	0	−1	0	5
Median L_D											9	10	11	15	17	9								
$L_F = L_{TOT} - L_D$											5	13	17	14	9	11								
Median *foF2*	023	024	025	025	025	024	024	024	028	046	058	064	071	066	060	062	053	032	026	022	020	019	019	021
JULY																								
Count	21	21	23	24	23	24	24	23	23	23	22	23	24	24	24	24	21	22	18	19	24	24	18	19
Median L_{TOT}	−2	−2	−2	−2	0	0	1	2	4	7	17	20	22	22	20	14	4	−4	−4	−4	−6	−4	−1	1
Median L_D											9	11	19	15	18	16								
$L_F = L_{TOT} - L_D$											8	9	3	7	2	−2								
Median *foF2*	021	023	024	024	024	024	024	024	029	047	055	060	066	065	062	057	054	039	027	024	021	020	019	020
AUGUST																								
Count	18	17	19	20	20	21	21	19	19	18	17	21	17	13	15	14	14	15	14	12	15	17	17	19
Median L_{TOT}	2	5	5	6	2	4	0	1	3	2	3	17	22	23	16	18	14	6	4	4	7	8	5	2
Median L_D										7	10	12	13	13	13	14	16							
$L_F = L_{TOT} - L_D$										−5	−7	5	9	10	3	4	−2							
Median *foF2*	022	024	024	024	024	024	025	026	044	053	060	064	070	069	066	062	061	051	040	028	022	019	020	021
SEPTEMBER																								
Count	20	22	22	22	20	21	20	18	19	17	16	14	15	11	12	13	12	16	17	17	17	19	16	19
Median L_{TOT}	0	2	0	4	8	9	9	10	16	23	28	34	33	32	29	23	19	17	5	1	−2	−1	1	−2
Median L_D									7	9	12	13	14	14	12	11	8	7						
$L_F = L_{TOT} - L_D$									9	14	16	21	19	18	17	12	11	10						
Median *foF2*	031	030	030	031	031	032	035	051	058	064	074	081	086	082	077	075	069	064	058	048	042	034	032	031
OCTOBER																								
Count	21	24	24	24	22	22	23	19	17	14	13	15	15	15	17	18	16	17	18	16	17	16	12	13
Median L_{TOT}	5	8	6	2	2	0	8	14	21	34	46	54	62	66	68	62	50	40	32	20	15	17	14	10
Median L_D								8	11	12		28	24	14	25	16	12	10	7					
$L_F = L_{TOT} - L_D$								6	10	22		26	38	52	43	46	38	30	25					
Median *foF2*	050	048	046	044	044	046	058	067	074	078	084	090	091	096	095	088	080	071	067	064	062	063	056	052
NOVEMBER																								
Count	19	17	17	16	17	17	20	15	16	16	15	18	19	18	19	17	17	16	16	17	21	15	14	16
Median L_{TOT}	17	12	10	8	12	19	27	36	44	53	61	64	67	71	69	64	54	44	37	32	20	20	15	14
Median L_D							8	22	31	29	29	33	38	38	31	32	19	14	13	5				
$L_F = L_{TOT} - L_D$							19	14	13	24	32	31	29	33	38	32	35	30	24	27				
Median *foF2*	065	064	063	062	060	068	076	080	082	084	086	088	088	088	082	079	075	072	070	070	072	072	070	068
DECEMBER																								
Count	11	9	12	11	10	18	19	14	14	12	12	17	18	17	19	19	20	21	18	17	17	15	11	11
Median L_{TOT}	5	6	6	1	7	19	29	30	45	48	54	67	74	72	73	62	48	37	24	13	5	0	2	1
Median L_D						7	9	17	32	30	32	33	33	37	33	31	31	16	18	13	4			
$L_F = L_{TOT} - L_D$						12	20	13	13	18	22	34	41	35	40	31	17	21	6	0	1			
Median *foF2*	070	069	068	066	066	073	079	085	088	089	091	088	086	084	082	076	071	070	070	073	074	072	071	070

Monthly median riometer absorption data, L_{TOT}, at 27·6 MHz, equivalent *D*- and *E*-region absorption from median *fm2* data, L_D, deduced *F*-region absorption, L_F, and median *foF2* data for South Georgia, 1971.

Units L_{TOT}, L_D, L_F: 0·01 dB.
foF2: 0·1 MHz.
Count is number of observations of L_{TOT} used.

at South Georgia, down to the threshold detection sensitivity previously noted. Indeed, a striking feature of the records, particularly during the winter months when *F2*-region effects are absent, is their regularity and freedom from perturbations. This applies also to $f_{\min}$ and *fm2*, which are even more sensitive to small changes in absorption. We may conclude that there is no ionospheric evidence supporting the precipitation of high-energy particles near South Georgia.

Ionosonde measurements show a high incidence of night *E* reflections with a critical frequency exceeding 0·7 MHz, the lower limit of the ionosonde. These are visible for up to 10 per cent of the night hours and are usually found at abnormally great heights (around 150 km.). This is reasonable evidence of particle activity, since the residual normal *E* at night has a critical frequency which is too low to be recorded. The ionization responsible for these reflections would not cause significant absorption since the collision frequency at 150 km. is small. Bailey (1968) has shown that the incoming particle stream must have a very soft energy spectrum to produce ionization at these heights, with *e*-folding energies of less than 5 keV. A peak at this height would be formed by a stream of mono-energetic particles with an energy of 1 keV (Wulff and Gledhill, 1974).

ABSORPTION IN THE *D*- AND *E*-REGIONS

Previous work has shown that both the *D*- and *F*-regions can contribute to the total absorption observed by riometer (Sarma and Mitra, 1972). At the frequency of operation, the absorption due to the *D*- and *E*-regions is essentially non-deviative, and is related to the electron density, N, collision frequency, ν, and operating frequency, f, by:

$$k \propto \frac{1}{\mu} \cdot \frac{N\nu}{\nu^2 + 4\pi^2 (f \pm f_L)^2}, \tag{3}$$

where k is the absorption coefficient per unit length, and the positive and negative signs refer to the ordinary and extraordinary modes, respectively. The refractive index of the medium, μ, lies between 0·99 and 1·0, and may be put equal to unity in the *D*- and *E*-regions. If $2\pi f > \nu$, this simplifies to:

$$k \propto \frac{N\nu}{(f \pm f_L)^2}, \tag{4}$$

an approximation which is adequate for our purposes.

The absorption experienced by a wave of given frequency is thus proportional to $N\nu$, integrated over the thickness of the region. This product for the regular *D*- and *E*-layers has been shown (Appleton and Piggott, 1954) to vary with solar zenith angle χ, so that the absorption A is given by:

$$A = a \cos^n \chi, \tag{5}$$

where a and n are constants.

A riometer is not a good instrument for determining normal *D*- and *E*-region absorption. An attempt has therefore been made to evaluate this absorption indirectly using both ionosonde and riometer data. The analysis has been confirmed by comparison with measured A1 pulse absorption for corresponding solar activity conditions at Port Stanley (lat. 51° 42′ S., long. 57° 51′ W.).

The most suitable ionosonde parameter was found to be *fm2*, which varies more rapidly with absorption than $f_{\min}$. The deduction of absorption from changes in this parameter depends on the changes of ionosonde sensitivity with frequency, and the variations of absorption with frequency. At South Georgia, receiver gain is changed automatically by pre-selected steps in a diurnal cycle, in a manner determined by normal average absorption, so that a large part of the diurnal absorption is measured directly by these gain changes. For the remainder, a semi-empirical approach is adopted, justifying the theoretical approximations made by the observed fit of the data to the empirical relations.

Let the ratio of the amplitude of the second-order reflection at night (assuming no absorption present) to the threshold recording level be S_0 dB, and the pre-set increase in gain at a given time be S dB. In the presence of absorption, the echo amplitude is reduced to threshold at *fm2*, hence the absorption, L dB, at this frequency is:

$$L = S + S_0. \tag{6}$$

Assuming the inverse frequency-squared law of Equation (2), the corresponding absorption index, Ar, for a single penetration of the layer is:

$$Ar = (S + S_0)\,(fm2 + f_L)^2/4. \tag{7}$$

Thus absorption is expected to be proportional to $(fm2 + f_L)^2$ at constant ionosonde sensitivity. This may be tested by a plot of $(fm2 + f_L)^2$ against the riometer absorption index, Ar, at a time when the influence of *foF2* is expected to be small, as in Fig. 1. Since the points are distributed about a straight line, the assumption that *fm2* obeys Equation (7) is shown to be acceptable. Additional tests, in which the ionosonde receiver gain was changed at night, showed that systematic changes in ionosonde sensitivity were small over the normal range of *fm2*. Systematic errors due to deviative absorption around *foE*, incorrect riometer calibration, or residual *F2*-region absorption will affect the intercept in Fig. 1, but not the slope, which gives a value for S_0. Using all available data, this was found to equal 30 dB.

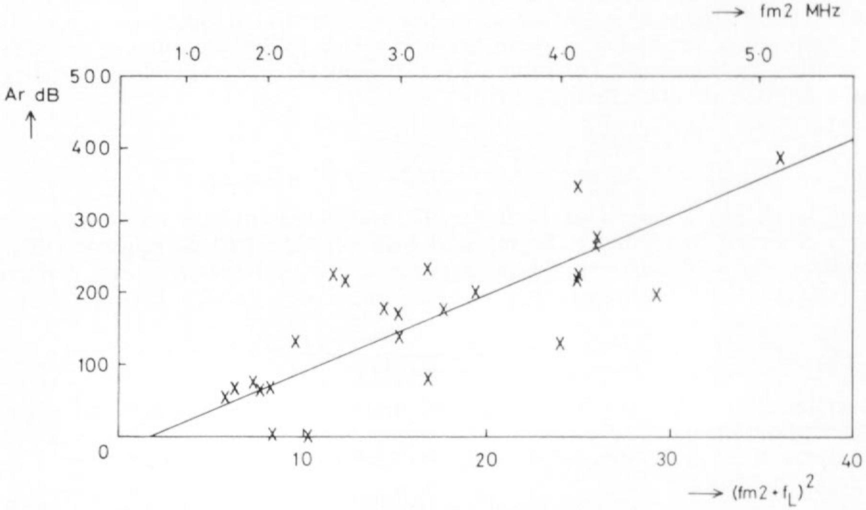

Fig. 1. Relation between riometer absorption, *Ar*, and *fm2*. July, 13.00 L.T.

Hourly values of the absorption at 27·6 MHz, L_D, corrected for *E*-layer deviative losses using George's (1971) function $\phi(f/foE)$, have been calculated from median *fm2* data using this value for S_0, and are shown in the Appendix. The average Ar value for the 4 hr. around noon for each month are plotted against cos χ at noon in Fig. 2. Also shown are noon data obtained at Port Stanley in 1955, a year of lesser solar activity, but for which particularly complete data are available. The detailed correspondance between the two patterns, including the well-known winter anomaly in absorption, confirms that this technique is adequate to evaluate the monthly median absorption.

An estimate of the diurnal variation has been obtained from a plot of South Georgia hourly data against corresponding values of cos χ for the months of October, November and December (Fig. 3). This gives the relation:

$$Ar = 350 \cos^{1\cdot04} \chi. \tag{8}$$

This is consistent, within the expected experimental error (about 40 dB in A), with Port Stanley data for similar solar activity, which gives:

$$Ar = 315 \cos^{1\cdot05} \chi. \tag{9}$$

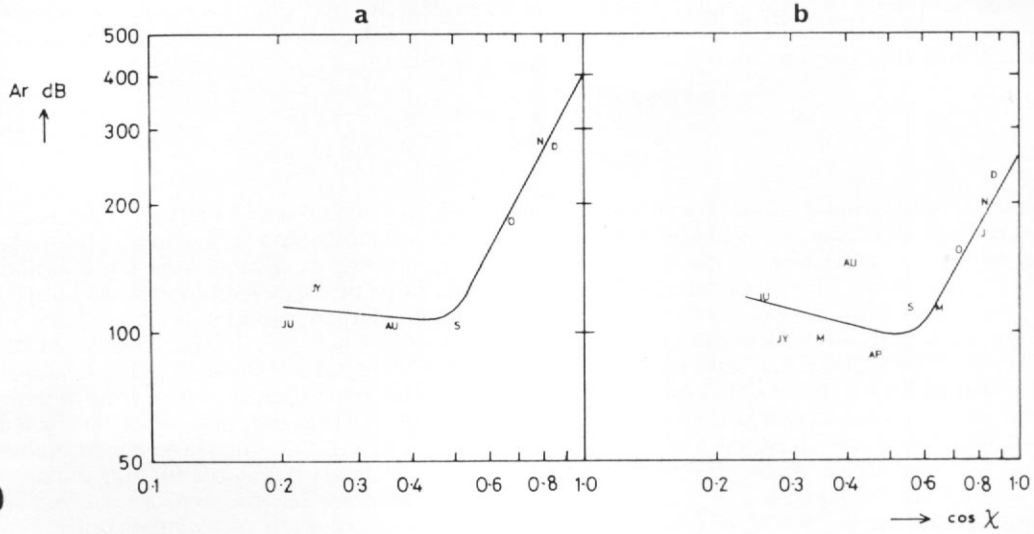

Fig. 2. Monthly median noon absorption index, *Ar*, and cos χ.
a. South Georgia *fm2* data, 1971.
b. Port Stanley pulse data (A1), 1955, reduced to *Ar* ($Ar = A/2$).

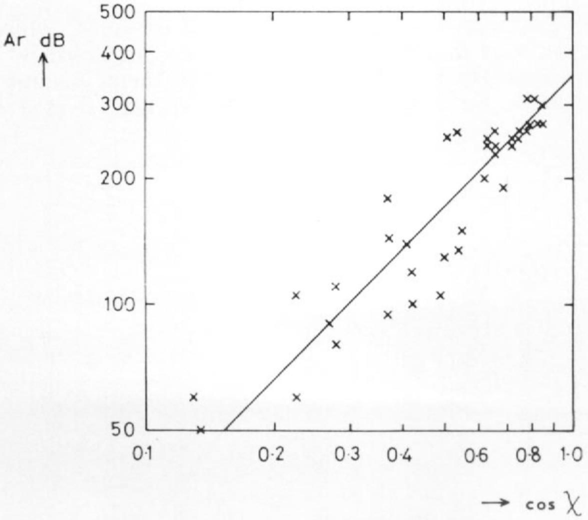

Fig. 3. South Georgia ionosonde absorption index, *Ar*, and cos χ. October–December 1971.
———— Line of best fit to data. $Ar = 350 \cos^{1\cdot 04} \chi$.

Absorption in the *F*-region

The collision frequency in the *F*-region is due to electron–ion collision, ν_{ei}, and was given by Thrane and Piggott (1966) as:

$$\nu_{ei} = [30 + 3\cdot 6 \ln (T_i/N_i)^{\frac{1}{2}}]\, N_i T_e^{-3/2}, \tag{10}$$

where T_e and T_i are the electron and ion temperatures, respectively, and N_i is the ion density.

The *F2*-layer is approximately parabolic in form near its maximum, so that the integral of $N\nu$ can be calculated approximately using a parabolic distribution of N with height having a half-thickness ym. The total *F2*-layer absorption is then:

$$L_F = \int_{-ym}^{+ym} \frac{b}{\mu} \cdot \frac{N^2}{f^2} \cdot T_e^{-3/2} \cdot \mathrm{d}y, \tag{11}$$

where b is a constant. L_F is thus roughly proportional to $ymNm^2/\mu T_e^{3/2}$ or $ym(foF2)^4/\mu T_e^{3/2}$.

Of these quantities, data for *foF2* only are generally available, and it is usual therefore to fit the data to a relation of the form $L_F \propto (foF2)^n$ by plotting L_F against *foF2* on a double logarithmic scale. The exponent n is then given by the slope of the best-fit line to the data.

Deviations from a value for n of 4 would be expected if there are significant changes in μ, ym or T_e with *foF2*. At South Georgia, the highest value of *foF2* encountered was 13 MHz. For $f = 27{\cdot}6$ MHz, μ lies between unity and $\{1 - (foF2)^2/f^2\}^{1/2}$, i.e. 0·88 at 13 MHz. Changes in μ will tend to increase n, but the effect is small. A similar effect may also arise from restriction of the visible sky area as *foF2* increases (Basler, 1963). This becomes significant when $\cos^{-1}(foF2/f)$ is less than the half-angle of the beam width for the antenna used. At South Georgia, this occurs when *foF2* is about 20 MHz, and is clearly negligible for our data.

The effective thickness, ym, may be estimated from ionogram records, but it is subject to considerable error. When *foF2* is changing due to a re-distribution of existing ionization, $Nmym$ would tend to remain constant, reducing the exponent n to 2. ym may also change with T_e, when the relation becomes $L_F \propto (foF2)^4/T_e^{1/2}$.

Lejeune and Waldteufel (1970) have shown empirically that $T_e - T_i = A - BNm$, where A and B are constants varying with height. This correlation between T_e and Nm would tend to increase the exponent of *foF2*.

The influence of the *F2*-region is clearly demonstrated in Fig. 4, which shows a perturbation involving a rapid increase in *foF2* to a high value, accompanied by a similar increase in riometer absorption. The constancy of $f_{\min}$ shows that there was no abnormal *D*-region absorption during the event. Subtracting the estimated regular *D*- and *E*-region absorption,

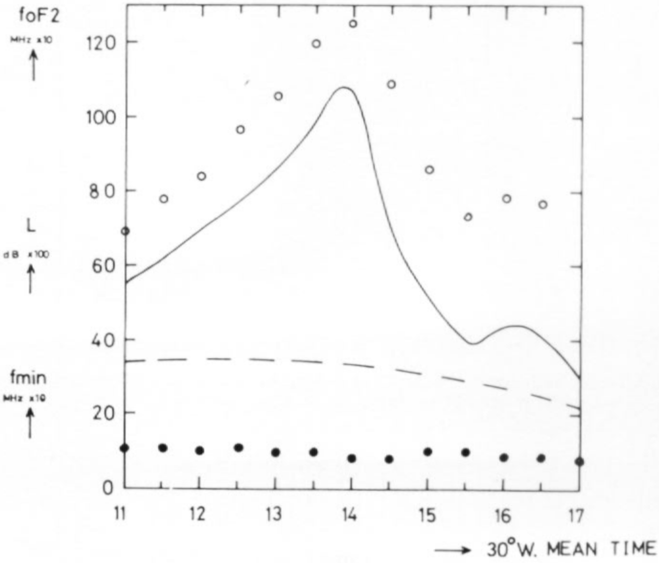

Fig. 4. Riometer absorption event, 9 October 1971.
——— L.
○ ○ ○ ○ *foF2*.
● ● ● ● $f_{\min}$.
– – – – L_D ($= 0{\cdot}43 \cos^{1{\cdot}04} \chi$).

obtained from Equation (8), from the total leaves a remainder attributable to *F*-region absorption, L_F. Fig. 5 shows the relation between L_F and *foF2* on a logarithmic scale, and gives:

$$L_F \propto (foF2)^{3\cdot 1}. \tag{12}$$

Rapid increases in *foF2* of this type are common during summer months, and all were accompanied by readily identifiable riometer absorption events. The low value of the exponent suggests a partial re-distribution mechanism, possibly combined with T_e changes.

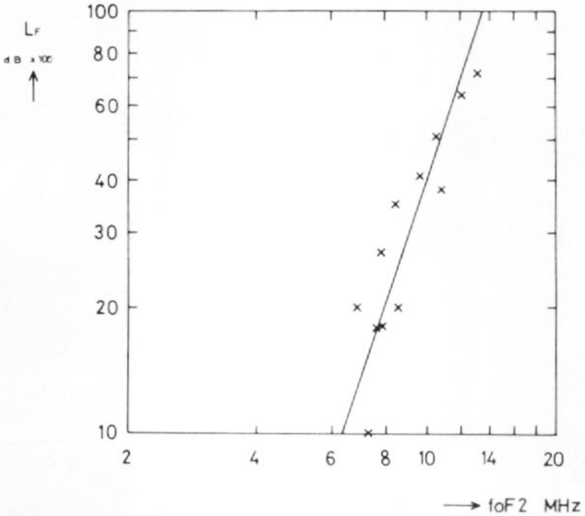

Fig. 5. Relation between L_F and *foF2* for the data in Fig. 4.

Mass plots of L_F against *foF2* show that *F*-region absorption usually becomes significant ($L_F > 0\cdot 1$ dB) when *foF2* is greater than about 6 MHz. Such a plot is shown in Fig. 6, which gives a value for n of 3·9, very close to the simple case value of 4. The scatter is high, however, the absorption at constant *foF2* varying by a factor of more than 2. A proportion of this scatter will be due to deviations of the regular *D*- and *E*-region absorption from that predicted by Equation (8), but most represents variation in *ym* or T_e uncorrelated with *foF2*. We may note that some points at low values of *foF2* show abnormally high absorption. These low values are necessarily from magnetically disturbed days, of which there were seven during the month when ΣKp exceeded 20. This is consistent with Sarada and Mitra's (1962) findings that *F*-region absorption increased in the presence of spread-*F* (a characteristic of magnetic disturbance).

No seasonal variation in *F*-region absorption was found, although generally low values of *foF2* during winter months limit accuracy at these times.

CONCLUSIONS

A riometer was operated at South Georgia during 1971 with the prime objective of observing absorption events attributable to particle precipitation into this area of weak geomagnetic field. The equipment has been demonstrated to be capable of detecting events down to a magnitude of 0·05 dB at the operating frequency of 27·6 MHz. The fact that no such particle events were observed indicates that any particle fluxes which may have occurred were characterized by exceptionally hard or very soft spectra. The conclusion is confirmed by using ionosonde data.

The riometer data have been used to calibrate simultaneous ionosonde measurements of *fm2*, allowing independent measurement of normal *D*-region absorption. This permitted

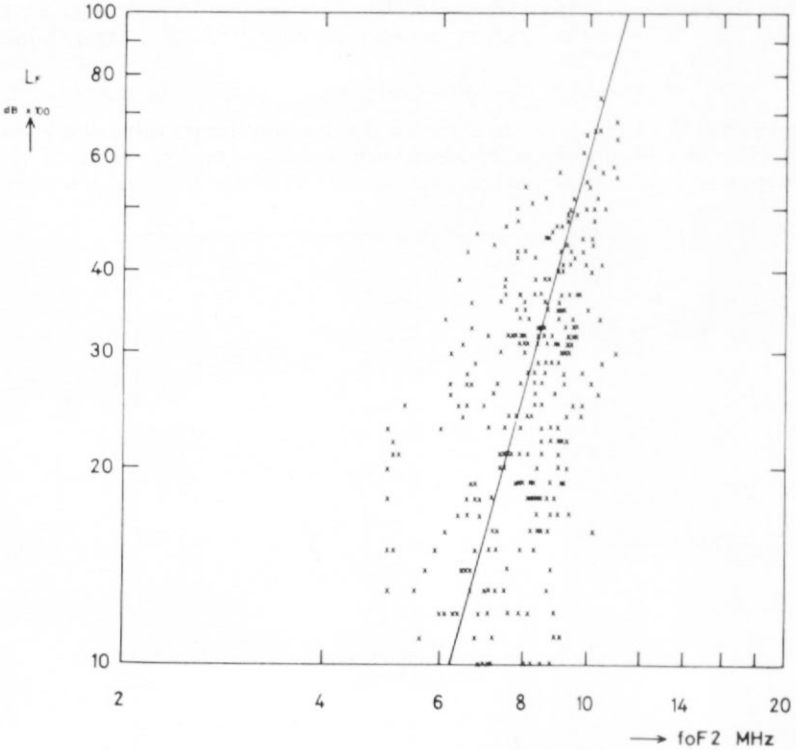

Fig. 6. Relation between L_F and *foF2* for all times during December 1971 when $L_F \geqslant 0 \cdot 1$ dB. ———— Line of best fit to data. $L\text{ (dB)} = 8 \cdot 1 \times 10^{-5}\,(foF2\text{ (MHz)})^{3 \cdot 9}$.

separation of the $(D + E)$- and *F*-region contributions to riometer absorption, a technique which should be useful at other stations. Absorption in the *F*-region has been shown to be significant when *foF2* is greater than 6 MHz, rising rapidly with *foF2* in a manner consistent with an electron–ion collision mechanism. Some occasions were found when *F*-region effects were significant at values of *foF2* down to 4 MHz. The probability that *F*-region absorption has sometimes been ascribed to the *D*- or *E*-regions is significant, and adequate precautions should be taken in future to establish the distinction whenever *foF2* is greater than about one-seventh of the riometer frequency. This point will need attention in the International Magnetospheric Study when riometers will be widely used.

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