261/

261

Journal of Atmospheric and Terrestrial Physics, Vol. 44, No. 11, pp. 973–984, 1982.
Printed in Great Britain.

0021–9169/82/110973–11 $03.00/0

Echoing mixed-path whistlers near the dawn plasmapause, observed by direction-finding receivers at two Antarctic stations

A. J. SMITH*
British Antarctic Survey (NERC), Madingley Road, Cambridge, U.K.

and

D. L. CARPENTER
Radioscience Laboratory, Stanford University, Stanford, CA 94305, U.S.A.

(*Received in final form* 25 *June* 1982)

Abstract—Duct coupling, in which part of the energy of a downcoming whistler-mode wave becomes trapped in a different duct after upward reflection in the ionosphere, manifests itself in the phenomenon of the mixed-path whistler. Using VLF data from direction-finding receivers at Halley and Palmer stations, Antarctica, we analyse a case near dawn in which the path structure was particularly simple. One-hop and three-hop whistlers observed at both stations implied the existence of two ducts inside the plasmasphere (at $L \sim 3$) and of wave coupling between them. The most intense of the three-hop echoes was a mixed-path rather than a single-path component; this is explained in terms of bi-directional coupling between the ducts in both northern and southern conjugate ionospheres. The locations of the ionospheric exit points for signals leaving the ducts were found from whistler arrival bearings measured at the two stations (the first results of crossed bearings from the IMS Antarctic VLF observing programme); these points were about 300 km apart. An echo trace seen only on the Halley record implied coupling to a third path outside the plasmapause (at $L_{pp} \cong 3.3$). We discuss the significance of such path coupling in relation to the spreading of ducted and unducted wave energy in the magnetosphere, and to the triggering of chorus.

1. INTRODUCTION

The spreading of ducted whistler-mode wave energy away from field lines of magnetospheric amplification is important for the understanding of both ducted and unducted wave characteristics of the magnetosphere. Consideration of such processes may be crucial for the correct interpretation of satellite wave observations, particularly in correlative studies with magnetospheric signals observed at ground stations. This paper is concerned with a particular aspect of this spreading, namely the low altitude coupling between field-aligned ducts.

It has long been known that such coupling can occur, resulting in the so-called mixed-path whistler (e.g. HELLIWELL, 1965). It is apparently one aspect of a more general process of reflection of downcoming ducted waves at ionospheric heights and their further propagation. To date little work has been done, either observationally or by modelling, to establish the importance of the phenomenon in influencing the overall excitation and distribution of ducted and unducted waves in the magnetosphere. Satellite observations of whistler-mode signals in the upper ionosphere, and ray tracing studies (JAMES, 1972; THOMSON and DOWDEN, 1978; GORNEY and THORNE, 1980) suggest that downcoming ducted waves become unducted at altitudes of the order of 1000 km, and after reflection back to the same altitude the wave energy flux may be spread over a larger area, perhaps having a diameter ten times that of the duct.

It is clear that ducted propagation is important for wave growth since coherent signals—whistlers, man-made transmissions, power line radiation—can remain in resonance with trapped energetic particles over long distances along the field line (HELLIWELL, 1967). The accessibility of the duct is important; if waves efficiently re-enter a duct or couple to it from elsewhere, the output spectrum of the ducted radiation may become progressively more broad-band and diffuse as time passes from the moment of wave injection. Duct–duct coupling may be expected to cause 'superposition' in time of waves of nearly the same frequency, thus reducing their coherence and causing suppression of wave growth (RAGHURAM *et al.*, 1977). On the other hand narrow band signals that are relatively isolated in frequency-time space might be amplified and produce triggered emissions.

---

* Present address: Department of Physics, University of Sheffield, Sheffield S3 7RH, U.K.

2. GENERAL CHARACTERISTICS OF MIXED-PATH WHISTLER ECHOING

Through the recent work of Strangeways (1981) we now have a clearer understanding of the factors affecting the trapping and untrapping of whistlers in ducts, but we do not know how frequently whistlers can emerge from one duct and become retrapped in another. The usual characteristics of echoing whistlers lead us to believe that path coupling happens most of the time, though only rarely may the duct structure be simple enough for us to analyse it clearly. One-hop whistlers received at medium latitude ground stations generally have a fine structure consisting of several closely spaced and sharply defined components, each corresponding to a different field-aligned path through the magnetosphere with a slightly different travel time. If each component merely echoed back along the same path with no path coupling, then the two-hop whistler would resemble the one-hop, but with corresponding components twice as dispersed and with twice the time separation. In fact two-hop whistlers are usually very diffuse and lack the well-defined fine structure characteristic of one-hop whistlers, as illustrated schematically in Fig. 1(a). Third-hop and higher order echoes are equally or more diffuse. This diffuseness makes them difficult to analyse, and is one reason that most recent research using whistler diagnostics to investigate the distribution and drifts of magnetospheric plasma has been based on data from Antarctic stations where one-hop whistlers predominate owing to high levels of lightning source activity in the conjugate region and to a lack of local lightning sources.

One role of mixed-path propagation may be discussed by considering a simple case involving only two ducts, A and B. A lightning flash excites them both (Fig. 1b), and corresponding one-hop whistlers are seen in the opposite hemisphere. A pair of third-hop components is observed (as shown in the schematic spectrogram of Fig. 1c) but their separation in arrival time is equal to that of the one-hop pair, rather than three times larger. If further odd-hop echoes are received, the dispersion of the two components continues to increase, but their time separation remains constant, with the result that the two traces tend to merge. Situations approximating to that described are indeed observed on occasions. In a more complicated case, however, with many closely spaced components, this merging effect leads to the overall diffuseness of the echoes, as described above.

The interpretation of Fig. 1(c) is that there is effective echoing on one duct only, the B duct, and that the first of the echoing components becomes trapped in the B duct

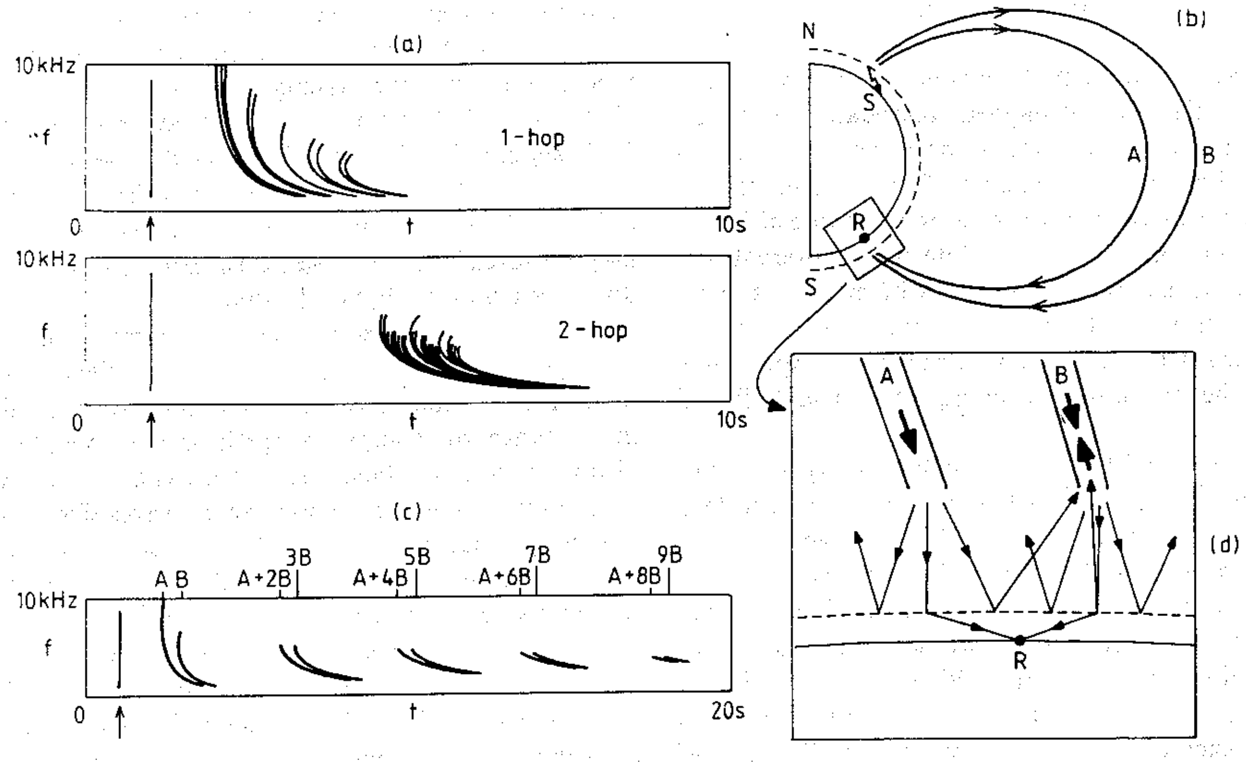

Fig. 1. (a) Schematic spectrograms showing typical characteristics of one-hop whistlers (many discrete components) and two-hop whistlers (usually diffuse) observed on the ground. (b) Sketch showing a simple case of only two whistler paths (A and B) both excited by the same flash. (c) Schematic spectrograms showing two echoing components corresponding to paths A and B (see text). (d) Interpretation of Fig. 1(c). Waves couple from A to B after the first hop and thereafter echo on path B.

after making one hop on the A path (Fig. 1d); the second component travels only on the B path. This is indicated by the labelling of the components A + 2B, 3B, etc.

Whistler-mode echoing observed at a medium latitude ground station normally occurs on just one path even though other paths are present. Periodic emissions, often triggered by whistlers, are frequently observed propagating in the same duct. The dominance of one path for echoing presumably arises because it is statistically more probable that conditions for strong echoing, i.e. wave amplification per hop exceeding total attenuation, exist on one path than on two or more. In disturbed times, when strong amplification might be expected on many paths, the data may be too complex to interpret or else ionospheric absorption may prevent magnetospherically propagated signals from being observed on the ground.

In this paper we investigate a particularly clear case of mixed-path propagation, and by using multi-station observations and direction-finding methods we study the range of duct separation over which coupling takes place. We report that coupling is observed to take place from a path inside the plasmasphere to a nearby path just outside.

3. OBSERVATIONS

The observations reported here were made during the period 0910–0930 UT on 3 June 1978 at Palmer (64.8°S, 64.1°W, $L = 2.4$) and Halley (75.5°S, 26.9°W, $L = 4.3$) stations, Antarctica. At Palmer the data were obtained using the Stanford DF-tracker system (LEAVITT *et al.*, 1978), while at Halley a broad-band VLF goniometer receiver was used (BULLOUGH and SAGREDO, 1973). Although separate results from the two systems have appeared in the literature (e.g. CARPENTER, 1980; MATTHEWS *et al.*, 1979), the present paper describes their first use at different stations to obtain crossed bearings on whistler paths. The two stations are about 1800 km apart, and their locations are shown in the map of Fig. 2.

The spectrogram of Fig. 3(a) shows an example of the whistler data received at Palmer. There are two dominant whistler-mode paths represented by the two prominent one-hop components at ~0.8 and ~1.2 s (at a frequency of 5 kHz). Three distinct three-hop components are also clearly visible between 3 and 5 s. The same pattern of two one-hop traces and three three-hop echoes is repeated many times per minute, without measurable change throughout the 20-min period studied, though only the more intense one-hop whistlers are accompanied by echoes. The causative spheric was readily identified by overlaying the spectra of successive events; it is marked by an arrow in the figures. Knowing the spheric, it was possible to measure whistler-mode travel times for all five components. This showed, to within the accuracy of the measurements (20 ms), (see Table 1 for some typical results) that the first and second three-hop components were mixed-path whistlers propagating on the A and B paths; they are

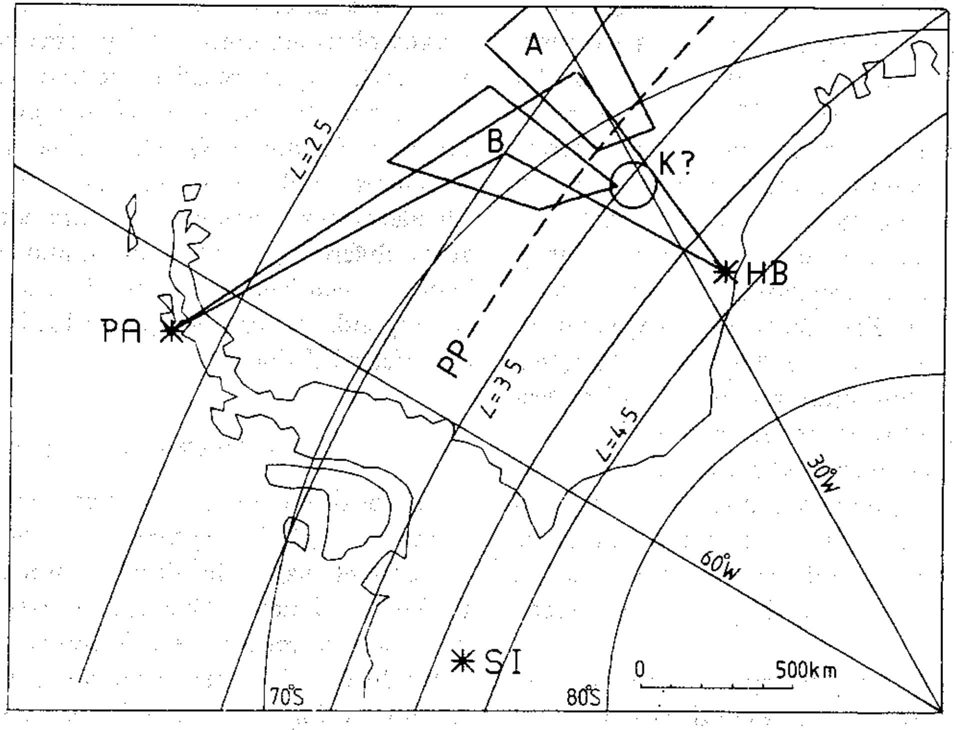

Fig. 2. Map showing the location of the Antarctic stations used in this study. The two boxes labelled A and B show the regions within which one-hop whistlers propagating on the A and B paths exit from the ionosphere, as determined by direction-finding measurements from Halley and Palmer.

Table 1. Typical measured propagation times (in seconds; error ±0.02 s)*

Frequency (kHz)	K	X	A	B	2B+K	2A+B	A+2B	3B
5.0	—	—	0.86	1.24	—	2.94 (2.96)	3.34 (3.34)	3.74 (3.72)
4.0	(0.37)	0.69	0.89	1.31	2.99	—	—	—

* A correction of 0.03 s has been applied to correct for the propagation time of the spheric from its source to the receiver. Times shown in brackets are calculated assuming the mixed-path propagation described in the text.

marked 2A+B and A+2B in the figures. The last component, marked 3B, had made three hops on the B path. Occasionally part of a very faint 3A trace could just be detected (for example near 2 s at 8 kHz in Fig. 3a) but since it was so weak it has been neglected in the following analysis. MORGAN *et al.* (1959) reported a similar event in which only the A+2B and 3B echoes were seen.

The A and B one-hop components were also observed at Halley. It can be confirmed that the same whistlers were being seen at the two stations by noting that they were received at exactly the same times. Precise comparisons of occurrence times, to within 20 ms or better, are made relatively easily by matching spheric patterns, which are normally almost identical at even quite widely separated Antarctic stations (SMITH *et al.*, 1981), owing to the lack of any local thunderstorm activity.

The low frequency part (< 5 kHz) of all three third-hop components observed at Palmer can also be detected occasionally at Halley. Of more interest, however, is a fourth trace which triggers chorus-like noise similar to the chorus which occurs spontaneously throughout the period. An example is shown in the middle panel of Fig. 4 at 0925:09 UT. Neither the whistler trace, the triggered noise, nor the spontaneous chorus are seen at Palmer. In Fig. 4 we also show the data from Siple (75.9°S, 84.2°W, $L = 4.2$), for comparison. The A and B traces are seen there but they are noticeably fainter compared to the spheric background than at Halley, implying that the ends of the whistler paths are closer to Halley than to Siple; this is confirmed by direction-finding analysis as discussed later. No third-hop whistlers or triggering are observed at Siple. There is some chorus but it is different in detail from that at Halley implying that it is being generated on a different field line. The only northern conjugate data available for this period are from Roberval, the conjugate point to Siple; no two-hop whistlers are seen there.

More examples of the triggering trace at Halley are shown in Fig. 5. Its constant delay relative to the A and B components shows that it originates in the same source. However, detailed measurements of its time delay relative to the spheric at various frequencies (see Table 1) cannot be explained in terms of combinations of hops on the A and B paths, as was done for the Palmer echo traces; in particular three hops on the A path would have produced a trace with a measurably shorter time delay. We therefore conclude that a third path is involved. The triggered noise, which is typical of that generated outside the plasmasphere, suggests that this third path may lie beyond the plasmapause and contain the generation region of the simultaneously observed chorus.

A one-hop whistler propagating on the inferred path would be a knee whistler (CARPENTER, 1963), and so we denote the path by K. No K component is observed in any of the available ground data, but we can infer the one-hop travel time from the observed traces. This turns out to be typical for a knee whistler (the one-hop travel time at the nose-frequency $t_n \sim 0.4$ s), assuming that two hops on the B path are combined with one hop on the K path, resulting in the observed three-hop trace. Any other assumption, e.g. travel on the A path, or more than one traverse of the K path implies a travel time, and hence an electron density, much larger than is usually observed outside the plasmasphere. A diffuse one-hop trace just preceding the A trace is visible in Fig. 5; this corresponds to a different propagation path (which we denote by X) well outside the plasmapause.

Figures 3(b)–(d) summarize schematically the whistler traces, triggered and spontaneous chorus seen at the different ground stations, and the relationship between them. The dotted trace (not actually observed) corresponds to a one-hop knee whistler propagated in the inferred K duct.

4. WHISTLER PATH LOCATION

The positions of the whistler ducts are found by triangulating the ionospheric exit point of each whistler component, using the direction-finding receivers at Halley and Palmer. This is supported by analysis of whistler nose frequencies and relative signal intensities at the different stations. As an example of the DF data, we show in Fig. 6 arrival bearings observed at Palmer for the B, 2B+A and 3B components.

The average arrival bearings of the one-hop A and B components for the period 0910–0930 UT, are given in

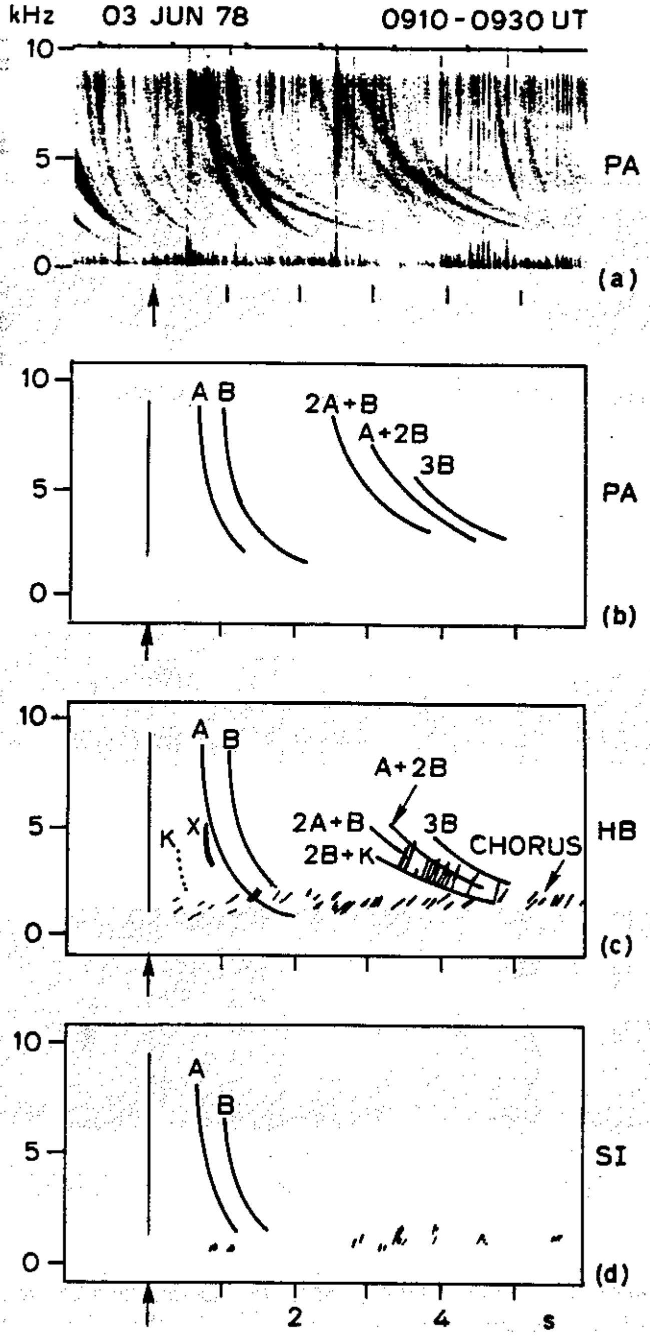

Fig. 3. (a) Spectrogram (for 0928 : 50 UT) showing whistler traces typical of those received at Palmer during the period 0910–0930 UT 3 June 1978. Two strong one-hop traces and three three-hop traces are clearly visible. The spheric is marked by an arrow. (b) Sketch of the Fig. 3(a) spectrogram, showing the relationship between the traces. (c) and (d) Similar to Fig. 3(b) for Halley and Siple. Specific examples of the traces shown are illustrated in Figs 4 and 5.

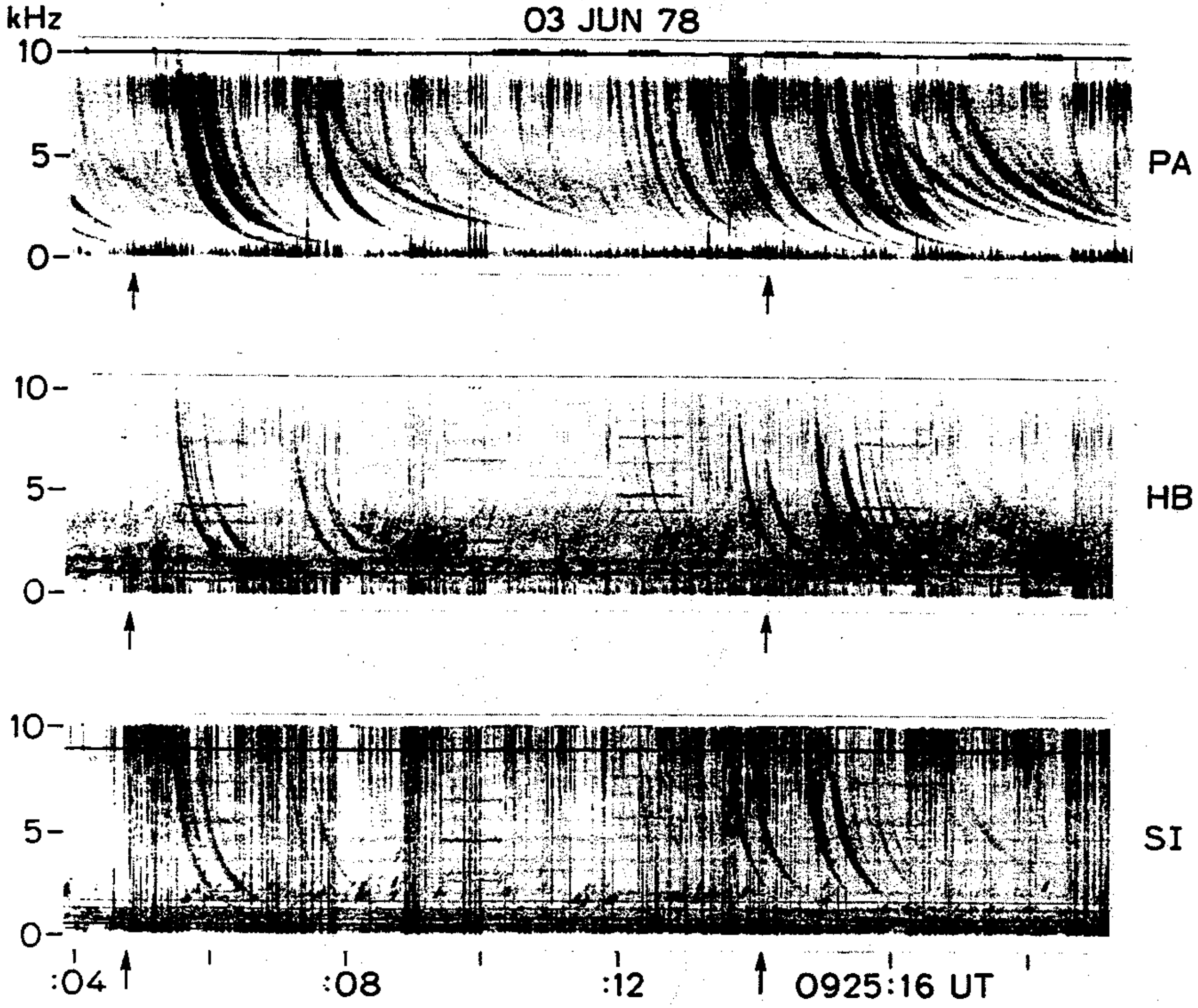

Fig. 4. Simultaneous records from Palmer, Halley, and Siple, showing the relative intensity of the different traces at the different stations, and the unusual echo seen only at Halley which triggers chorus-like noise.

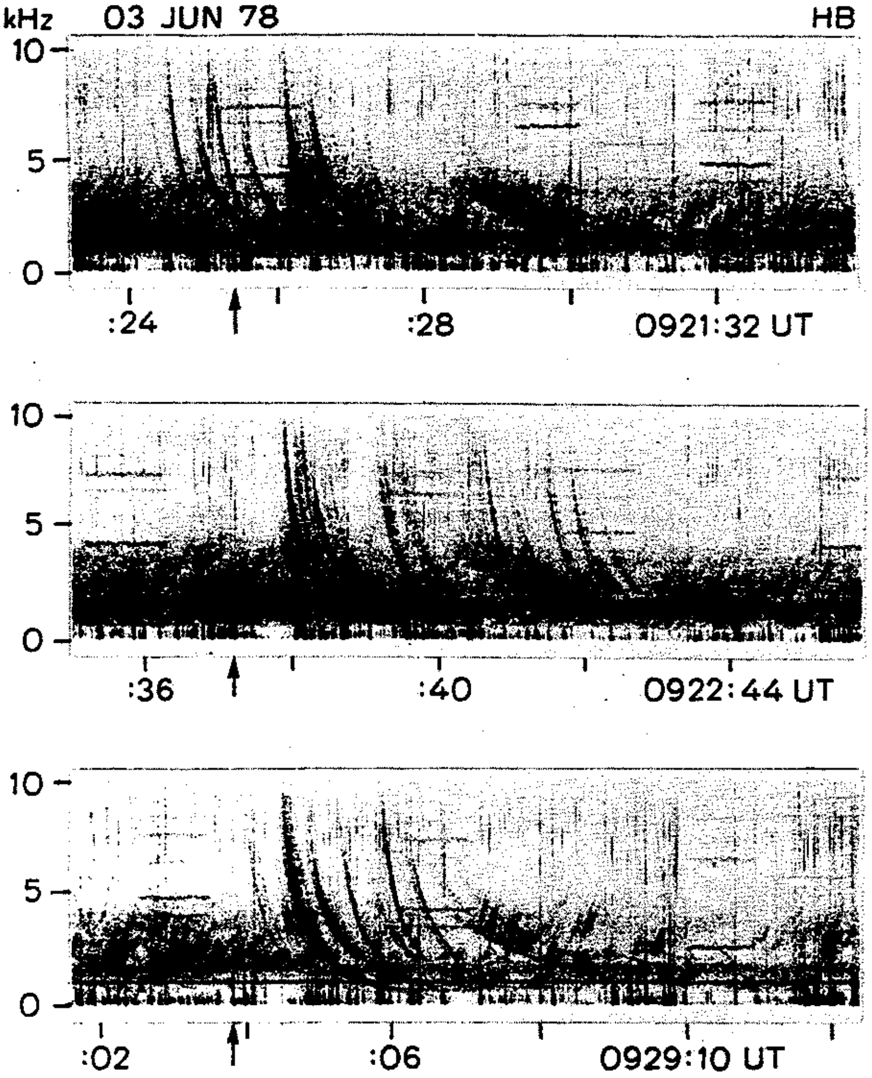

Fig. 5. Three further examples of the triggering three-hop echo trace seen at Halley. (See text and Fig. 7 for interpretation.)

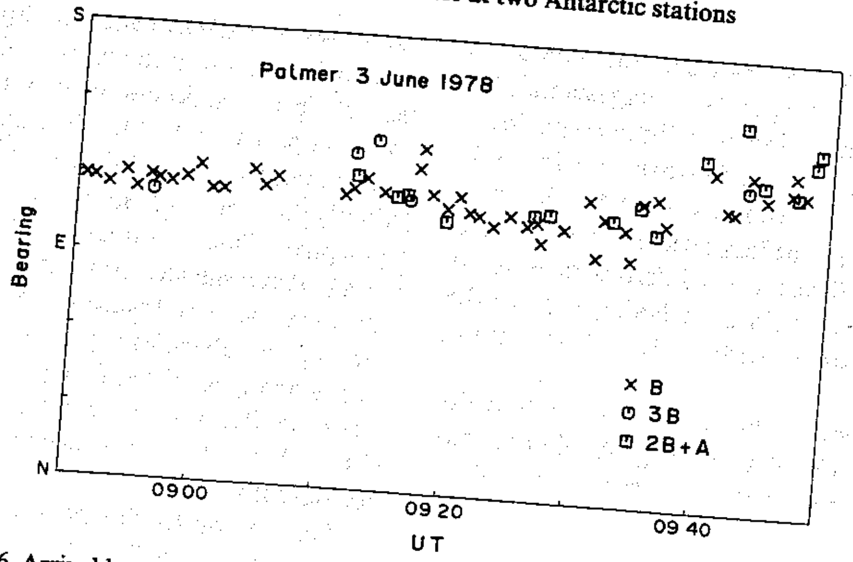

Fig. 6. Arrival bearings for the B, A+2B, and 3B components observed at Palmer.

Table 2. Using these results we deduce that the ionospheric exit points for the A and B paths are located as shown in Fig. 2. The geometry in this case is such that the latitudes of the exit points are determined almost entirely from the Palmer bearings and their longitudes from the Halley bearings. The 180° ambiguity of the Halley goniometer is easily resolved here since the Palmer bearings, for which there is no ambiguity, show that the exit points must lie north rather than south of Halley.

The boxes in Fig. 2 correspond to bearing errors of ±10°, typical of the DF systems used (when direction-finding on whistlers). For B this is consistent with the scatter of observed bearings typified by Fig. 6 and we may be fairly confident that the B exit point lies within the indicated box. In the case of A, however, the bearings observed at both stations were rather more variable, and the presence of fine structure in the A trace suggests that this may be due to the presence of an array of ducts with similar L-values and one-hop propagation times. Thus the A box in Fig. 2 only indicates the average location of the paths contributing to the A trace.

The nose frequencies of the A and B one-hop components, scaled directly from 0–20 kHz spectrograms, were 15.0 and 11.0 kHz, respectively, and assuming a diffusive equilibrium electron density model (PARK, 1972) we compute the L-values of the propagation paths as

$$\begin{array}{ll} \mathrm{A} & L = 2.85 \pm 0.05, \\ \mathrm{B} & L = 3.15 \pm 0.05. \end{array}$$

Table 2. Arrival azimuths (degrees east of true north)

Component	Halley	Palmer
A	350	120
B	325	125

The map of Fig. 2 shows contours of constant L at 100 km altitude and it is seen that the above results are consistent with the direction-finding analysis, assuming field-aligned propagation.

This picture is supported by the signal intensity data. The B component is frequently more intense than the A at Palmer but not at Halley where A is sometimes stronger; see for example Fig. 4. This is in qualitative agreement with the relative distances of the A and B ducts from Halley and Palmer shown in Fig. 2. The weakness of the one-hop components and lack of echoes at Siple is accounted for by the distance of this station from the feet of the field lines of propagation.

Arrival bearings of the third-hop echo components are generally less well determined because of their poorer signal-to-noise ratio. However, the strongest of them, A+2B, has the same direction of arrival as the B component, both at Palmer and at Halley, implying that this component propagates in the B duct on its third hop. The 3B component also arrives at Palmer on the same bearing as B, which would be expected. Evidence from a single DF measurement on the 2A+B echo, made at Palmer at 1018 UT when A and B were more widely separated than in Fig. 2, suggested that it had made its third hop on the A path.

We were not able to measure the nose frequency or direction of arrival for the K path (a one-hop K component was not observed), but estimated its location and that of the plasmapause, as shown in Fig. 2, by the following indirect reasoning. The plasmapause must lie outside the outermost plasmaspheric duct observed (B), and is probably located only slightly beyond it at around $L_{\mathrm{pp}} = 3.3$. This is close to the position which would be expected statistically given the local time (near dawn), the moderate degree of magnetic disturbance ($Kp = 4-$), and the occurrence of a geomagnetic storm on the

$Kp = 7+$) (CARPENTER and PARK, 1973). The short travel time on the K path, $t_n \cong 0.4$ s, suggests that the path length is fairly short, lying only slightly outside the plasmapause—say at $L = 3.5$. Furthermore the B–K separation is probably comparable with the A–B separation since wave coupling occurs between the B duct and both A and K ducts. The inferred location for the K path, considerably closer to Halley than to the other stations, is consistent with the 2B + K trace being seen only at the former.

The nose frequency of the X trace shows that the corresponding path lies at $L = 4.5$, probably near the meridian of Halley since it is not observed from Siple.

5. INTERPRETATION

The sketch of Fig. 7(a) illustrates the four magnetospheric paths A, B, K and X, and the plasmapause, in the magnetic meridian plane of the observing stations. Figs 7(b) and (c) show the north and south conjugate regions drawn to a larger scale. Representative values for the duct diameter (50 km) and duct base altitude (1000 km) are assumed (ANGERAMI, 1970; BERNHARDT and PARK, 1977). The source lightning flash (marked S) is shown at an arbitrary point since no information is available on its location. For the sake of clarity we do not attempt to show all the duct coupling paths implied by the data.

Our interpretation of the observations is as follows. Initially the A, B and X ducts are excited in the northern hemisphere. Duct K is not excited. This may be due to a strong latitudinal electron density gradient associated with the nearby plasmapause preventing wave trapping, or alternatively to ionospheric conditions such as strong localized *D*-region absorption below the duct base. Perhaps ray-tracing in a model ionosphere with realistic ducts and plasmapause would help to elucidate this.

After one hop, the downcoming A and B whistlers are partly transmitted through the southern ionosphere where they are received by ground stations, and partly reflected back upwards. Most of the reflected wave energy undoubtedly propagates in the unducted mode, but a fraction is retrapped in its original ducts. In addition part of the signal which travelled in the A duct couples into the B duct and vice versa.

After two hops the downcoming whistlers, which would be seen as 2A, A + B and 2B by a suitably placed

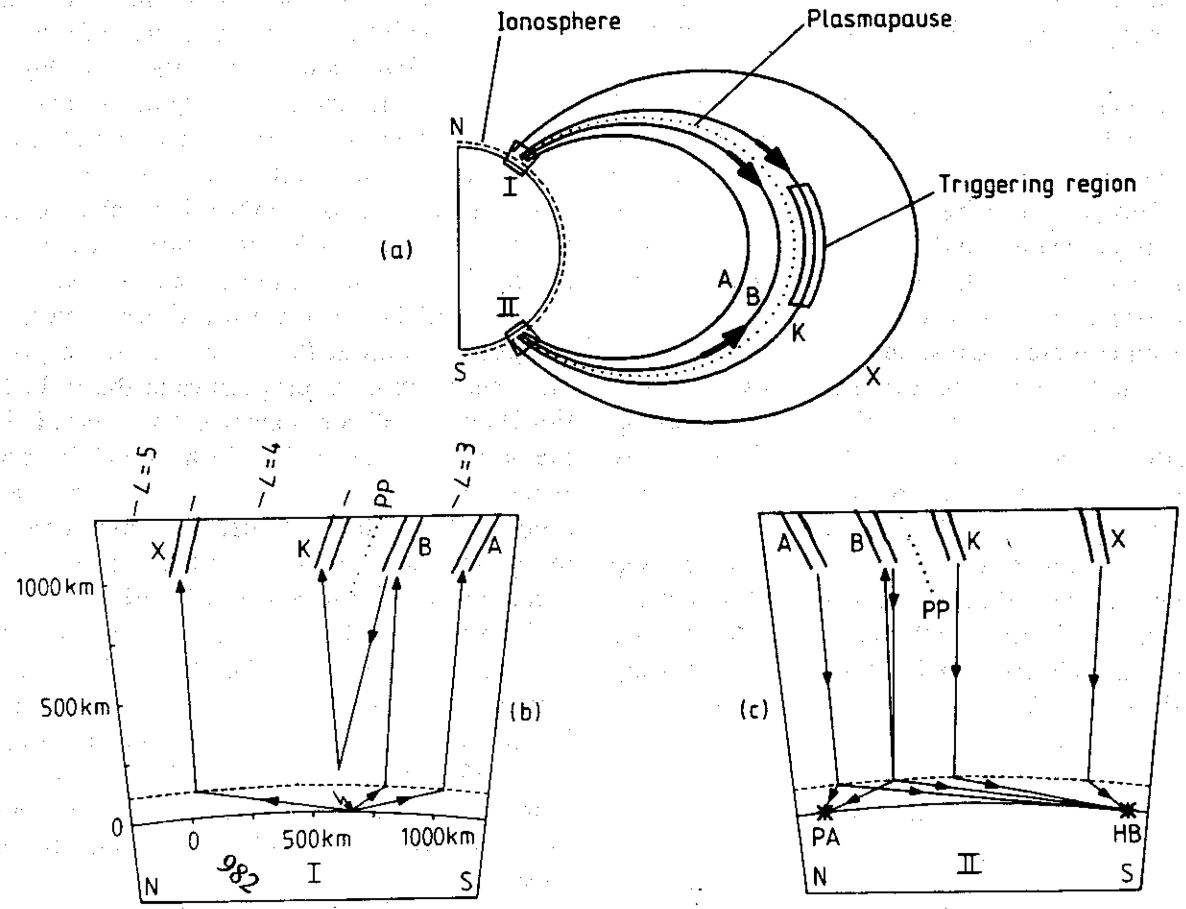

Fig. 7. Interpretation of the data. (a) Sketch showing the approximate locations of the four ducts A, B, K and X and also the plasmapause. There is a generation region for chorus on the K path. (b) and (c) Show the north and south conjugate regions in more detail, with some of the propagation paths into, out of, and between the ducts, which are necessary to explain the observations.

northern hemisphere observer, are again reflected; coupling between the A and B ducts gives rise after a further hop to the 2A+B, A+2B and 3B echoes observed in the south. Reflection also takes place from the B duct into the K duct, across the plasmapause, giving rise to the observed 2B+K echo; the ionospheric gradients or irregularities which permit this may be associated with those which originally prevented the excitation of this path directly from the source. An interesting feature of the data is that the mixed echo A + 2B is more intense than the 'pure' echo 3B. At first sight this may seem surprising but it may be explained using our assumption that coupling between the A and B ducts occurs in both conjugate ionospheres which means that a mixed path echo such as A + 2B can have contributions from three different path combinations—ABB, BAB and BBA. The consequence of this may be examined by using a simple model in which the relative reflection coefficients (on a 1–3 scale) are given in Table 3(a). On this model waves reflect more strongly from A to B than vice versa, which seems physically plausible since the magnetic dip angle will tend to favour transfer from the lower to the higher latitude duct; (this is supported by ray-tracing work: THOMSON and DOWDEN, 1978). Nevertheless the self-reflection coefficients are greater than or equal to the cross-reflection coefficients, except for duct A in the south.

Assuming equal excitation of the ducts from the ground we estimate the relative intensities of the three-hop echoes by adding the products of the three appropriate coefficients for each path combination, as shown in Table 3(b).

The path coupling scheme described accounts for all the observed one-hop and three-hop components. The predicted intensities for the three-hop components match the observations—i.e. A + 2B is most prominent followed by 3B, 2A + B with 3A very much weaker. The final hop of A + 2B is predominantly on path B, whilst that of 2A + B is mainly on path A in agreement with the DF observations (see Section 4). B may be considered the dominant path (see the discussion of Section 2)—from Table 3(b) we can estimate that after three hops the wave intensity in duct B is twice that in duct A.

Table 3(a). Relative reflection coefficients (scale 1–3, small–large)

	A→A	A→B	B→A	B→B
Southern ionosphere	1	3	2	3
Northern ionosphere	2	2	1	3

Table 3(b). Intensities of three-hop echo components assuming reflection coefficient model of Table 3(a)

Component	Contribution	Predicted intensity	Total
3A	AAA	2	2
2A+B	ABA	3	9
	BAA	4	
	AAB	(2)	
A+2B	BAB	4	16
	ABB	9	
	BBA	(3)	
3B	BBB	9	9

The southward travelling wave on the K path passes through a wave-particle interaction region where chorus is being generated, and triggers chorus elements as it does so. At the equator the $2\frac{1}{2}$-hop echo is considerably more dispersed than a half-hop whistler on the same path would have been. This could make triggering more likely by allowing the wave to remain longer in resonance with a given energy of particle.

6. CONCLUSION

We have studied a case of mixed-path whistler propagation near the dawnside plasmapause using multi-station and direction-finding techniques. An echoing whistler can exit from one duct near its base and be trapped in a different one for its next hop. This coupling between different ducts can take place when their exit points are of order 300 km apart horizontally, and there is a tendency for it to occur from the lower to the higher latitude path. The effect is such that even though several paths may be present, and give rise to a corresponding set of one-hop whistlers, subsequent echoing tends to be confined to one dominant path.

Mixed-path echoes can be more intense than 'pure' echoes (involving only one duct) if coupling takes place in both hemispheres, due to multiple contributions to the same whistler component.

Path coupling can occur from inside the plasmasphere to outside. It is known that knee whistlers, corresponding to the excitation of whistler ducts just outside the plasmapause, occur relatively rarely (CARPENTER, 1978; LESTER and SMITH, 1980); perhaps this is due to the difficulty of exciting such a path directly from the ground. In the present paper we demonstrate that a knee path, not accessible to a ground source, can be excited by path-coupling from a whistler echoing inside the plasmasphere, and the resulting echo can trigger chorus. This mechanism may even play a significant role in the triggering of chorus, since echoing whistler activity is relatively common within the plasmasphere. Controlled experiments on wave growth in the magnetosphere (Helliwell and Katsufrakis, 1974) have shown that a triggered wave can be 30 dB stronger than the coherent input signal. The latter may therefore be undetectable, and thus in a case where the path structure was more complicated, the whistler connection might not be as clear as in the situation studied here; the chorus would then appear to be spontaneous. Carpenter (1978) gives examples of triggering just outside the plasmapause in which the causative whistler trace is barely visible on the record. Power line harmonics, which can be amplified within the plasmasphere by whistler-mode echoing (Park and Helliwell, 1981; Matthews and Yearby, 1981), may couple to a path outside the plasmasphere and trigger chorus in a similar way.

Acknowledgements—This work was carried out during a visit by one of us (A.J.S.) to the Radioscience Laboratory and he wishes to thank Prof. Helliwell for the use of the laboratory's facilities. We are grateful to J. Yarborough for preparing the spectrographic records, to J. Green for scaling some of the Palmer DF records, and to D. Thomas for assistance in analysing the Halley goniometric data. The VLF project at Halley is supported by the Science and Engineering Research Council and the Natural Environment Research Council. The work at Stanford was supported by the Division of Polar Programs of the National Science Foundation.

REFERENCES

Angerami J. J. 1970 *J. geophys. Res.* **75**, 6115.

Bernhardt P. A. and Park C. G. 1977 *J. geophys. Res.* **82**, 5222.

Bullough K. and Sagredo J. L. 1973 *Planet. Space Sci.* **21**, 899.

Carpenter D. L. 1963 *J. geophys. Res.* **68**, 1675.

Carpenter D. L. 1978 *J. geophys. Res.* **83**, 45.

Carpenter D. L. 1980 *J. geophys. Res.* **85**, 4157.

Carpenter D. L. and Park C. G. 1973 *Rev. Geophys. Space Phys.* **11**, 133.

Gorney D. J. and Thorne R. M. 1980 *Geophys. Res. Lett.* **7**, 133.

Helliwell R. A. 1965 *Whistlers and Related Ionospheric Phenomena.* Stanford University Press, Stanford, California.

Helliwell R. A. 1967 *J. geophys. Res.* **72**, 4773.

Helliwell R. A. and Katsufrakis J. P. 1974 *J. geophys. Res.* **79**, 2511.

James H. G. 1972 *Annls Géophys.* **28**, 301.

Leavitt M. K., Carpenter D. L., Seely N. T., Padden R. R. and Doolittle J. H. 1978 *J. geophys. Res.* **83**, 1601.

Lester M. and Smith A. J. 1980 *IMS in Antarctica*, pp. 113–127. National Institute of Polar Research, Tokyo.

Matthews J. P., Smith A. J. and Smith I. D. 1979 *Planet. Space Sci.* **27**, 1391.

Matthews J. P. and Yearby K. H. 1981 *Planet. Space Sci.* **29**, 97.

Morgan M. G., Curtis H. W. and Johnson W. C. 1959 *Proc. IRE* **47**, 328.

Park C. G. and Helliwell R. A. 1981 *Adv. Space Res.* **1**, 423.

Raghuram R., Bell T. F., Helliwell R. A. and Katsufrakis J. P. 1977 *Geophys. Res. Lett.* **4**, 199.

Smith A. J., Carpenter D. L. and Lester M. 1981 *Geophys. Res. Lett.* **8**, 980.

Strangeways H. J. 1981 *J. atmos. terr. Phys.* **43**, 231.

Thomson R. J. and Dowden R. L. 1978 *J. atmos. terr. Phys.* **40**, 215.

Reference is also made to the following unpublished material:

Park C. G. 1972 Methods of determining electron concentrations in the magnetosphere from nose whistlers. Stanford Electronics Labs. Tech. Rept., 3454–1.