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Radio wave Doppler studies of the Antarctic ionosphere

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The occurence of propagating wave-like disturbances in the atmosphere at ionospheric heights is well documented, but their causes and rôle in the energy balance of the atmosphere is poorly understood. This paper describes an experiment deployed in the Antarctic Peninsula region to investigate the morphology of the various classes of disturbance, with particular emphasis on the identification of their sources. Current knowledge of the phenomena is briefly reviewed and the reasons why observations in the peninsula region may be especially valuable are discussed. Some preliminary results from the first 3 months of operation are presented; these indicate the presence of waves with periods ranging from less than 1 min to more than 90 min. The short period waves (1–5 min) are unusually common in these data.

1. Introduction

This paper describes the joint B.A.S.–Leicester University project to study propagating disturbances in the ionosphere over the Antarctic Peninsula. In this project an h.f. Doppler sounder deployed in the peninsula is used to both detect the presence of waves and determine their velocity of propagation.

Section 2 of the paper reviews current knowledge of travelling disturbances in the ionosphere and illustrates why measurements in the Antarctic may prove very valuable. Section 3 discusses the general principles of the Doppler technique and the specific details of the peninsula equipment. Finally, in § 4 some first results from the Antarctic experiment are presented.

2. Waves in the upper atmosphere

A wide range of wave-like disturbances exist in the neutral atmosphere at ionospheric heights. These range in horizontal scale from a few metres to hundreds of kilometres and may occur as events of one or two cycles, or as long wave trains. Horizontal velocities of propagation range from under 100 m s^{-1} to over 1000 m s^{-1}. The propagation of these waves in the ionosphere distorts the iso-ionic contours and such effects are readily detected by a variety of radio techniques (see Vasseur, Reddy & Testud 1972 for a review). The interaction of the long period ($>$ 10 min) atmospheric waves with the ionosphere produces an ionic disturbance usually referred to as a travelling ionospheric disturbance (t.i.d.).

The spectrum of t.i.ds observed in the ionosphere is conveniently divided into two classes of waves, normally labelled 'large scale' and 'medium scale' respectively. The principal difference between the two classes is that the horizontal velocity of the large scale waves is typically in the range 400–1000 m s^{-1}, whilst that of medium scale waves is less than 250 m s^{-1}. The periods of the large scale phenomena fall in the range 30 min to 3 h and their wavelengths are usually greater than 1000 km. The corresponding figures for the medium scale waves are approximately 10 min to 1 h period and 100–400 km wavelength.

The large scale t.i.ds propagate equatorward from the auroral zones and their excitation is related to auroral disturbances which occur during magnetic storms. Both the amplitude of the waves and their frequency of occurrence are strongly related to magnetic index K_p. The medium scale t.i.ds are much more common than large scale events but their origins are still obscure. They are not correlated with magnetic activity and it is possible that both auroral sources and tropospheric weather sources are involved. The direction of propagation for medium scale waves is generally equatorward in local winter but poleward in local summer.

In addition to the t.i.ds, waves of much shorter period are sometimes observed in the ionosphere. These are referred to as 'acoustic' waves since the forces of buoyancy and gravity do not influence their propagation. Their periods range from about 20 s up to about 5 min. The lower limit is set by viscous damping, while the upper limit is fixed by the 'acoustic cut-off' period above which the waves become evanescent and are rapidly attenuated. The acoustic cut-off period depends upon the temperature and molecular mass of the atmosphere resulting in a minimum value at the mesopause. The morphology of occurrence of acoustic waves is not well understood, they are discussed further in § 4*b* below.

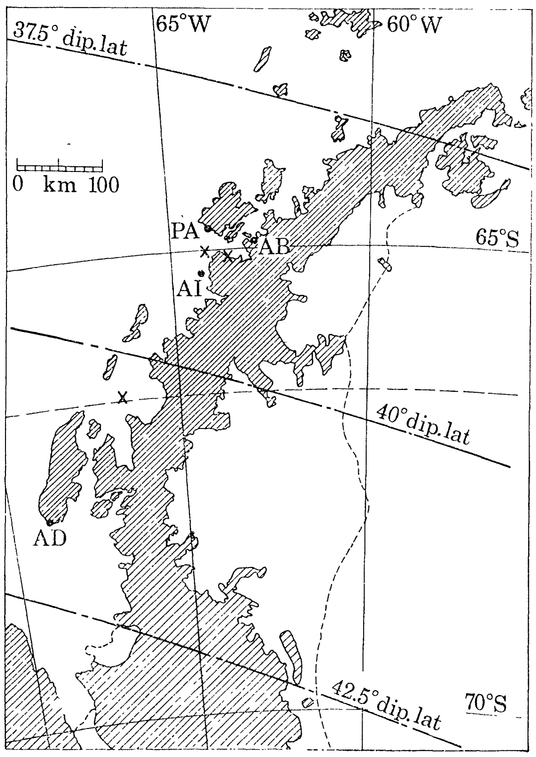

FIGURE 1. Map of the Antarctic Peninsula showing the locations of the stations involved in the experiment (dots) and the corresponding ionospheric reflexion points (crosses). Also shown are contours of constant dip latitude, defined as Arctan ($\frac{1}{2}$ tan dip). AB, Almirante Brown; PA, Palmer Station; AI, Argentine Islands; AD Adelaide Island.

The study of t.i.ds is currently an important area of aeronomic research because the atmospheric waves which produce them represent a potentially significant mechanism for redistributing energy in the atmosphere. In particular, they may play an important rôle in transferring energy deposited in the auroral zones during magnetic storms to lower latitudes, thereby propagating storm effects within the ionosphere. They may also transport significant amounts of energy to the ionosphere from lower atmospheric regions (troposphere and mesosphere). The primary objectives are thus to identify the sources of the waves, study the manner in which these waves propagate through the atmosphere and investigate the processes by which their energy is dissipated. For detailed reviews of both the theoretical and experimental aspects of the subject see Francis (1975) and Vasseur *et al.* (1972).

The zone containing the Antarctic Peninsula and Weddell Sea (i.e. between the 20° W and 80° W meridians approximately) is a particularly interesting region for conducting aeronomical research for two reasons. Firstly, the dip of the Earth's magnetic field is abnormally low compared with any other zone at the same latitude (for example the dip latitude at Argentine Islands is 20° lower than the geographic latitude, see figure 1). The sector is thus normally free from auroral disturbances except during major magnetic storms when the resultant ionospheric events stand out clearly. Also the ionospheric effects of thermospheric winds and electric fields are very pronounced in this area. Secondly, the Antarctic continent as a whole is a pole-centred, flat plateau entirely surrounded by oceans. The development and movement of tropospheric/stratospheric weather systems is therefore not complicated by disturbances due to local topography. (Note, however, that the peninsula itself may induce turbulence, see § 4*b* for further discussion.)

These factors combine to make the Antarctic Peninsula an excellent site for the study of t.i.ds. The British Antarctic Survey geophysical observatory at the Argentine Islands (65° 15′ S, 64° 16′ W) is strategically placed between the auroral zone (about 1000 km to the south), and the zone in which the main Southern Ocean weather systems are centred (about 500 km to the north). A wide range of related experiments (ionosonde, magnetometer, seismometer, surface and upper air meteorological observations) are in routine operation at this location. A study of the morphology of wave-induced disturbances in this vicinity should therefore provide new evidence on the location of the sources.

3. The h.f. Doppler technique

A change in the reflexion height of an h.f. radio signal propagated via the ionosphere produces a change in the phase path (P) of the signal. This produces a Doppler shift (Δf) in the frequency of the reflected signal, the magnitude of which can be expressed as

$$\Delta f = -\frac{1}{\lambda}\frac{\mathrm{d}P}{\mathrm{d}t},$$

where λ is the free space wavelength of the transmitted signal. The passage of a pressure wave through the ionosphere displaces the iso-ionic contours, causing the height of reflexion to vary with the same period as the wave. The changes in reflexion height can be determined from the variations produced in Δf. The horizontal velocity component of the pressure wave may be determined by using three transmitters and a central receiver, spaced so that the reflexion points are arranged in a triangle. The causative disturbance produces a Doppler signature on each transmission in turn, and from measurements of the time displacements of these and the geometry of the triangle, the velocity may be simply determined. The transmitter and receiver ideally should be sited so that the triangle of reflexion points is equilateral with dimensions of the order of half the wavelength of the waves to be studied. The height dependence of the disturbances can be studied by using more than one nominal frequency, each chosen to give triangles of reflexion points suitably spaced in altitude. For more details of the general technique the reader is directed to Davies, Watts & Zacharisen (1962).

It is impractical to set up the ideal configuration of transmitting and receiving sites in a hostile environment such as Antarctica since costs and logistic difficulties limit available sites to the currently manned bases. The peninsula experiment therefore consists of a receiving station at Argentine Islands, and transmitting sites at Palmer Station (64° 46′ S, 64° 05′ W), Almirante Brown (64° 53′ S, 62° 53′ W) and Adelaide Island (67° 46′ S, 68° 56′ W); see figure 1. The system has been designed and deployed so that two operating frequencies can be used simultaneously to give data from two different altitudes.

The configuration of stations is by no means ideal because of the great length of the path from Argentine Islands to Adelaide (346 km) compared with the other two paths (55 km for Palmer, 77 km for Almirante Brown). Theoretical studies using ray tracing techniques in conjunction with representative model ionospheres have shown that there will be occasions when the mode of propagation, and hence the height of reflexion, will be different for the long and short paths. For the current epoch of the solar cycle this problem is most serious near local noon in summer, at which time the long path is always an E mode when the short paths are either F1 or F2 modes. However, for most of the year, careful selection of operating frequencies permits propagation via F2 modes for all the three paths. The analysis has shown that when both short and long paths are F2 modes the difference in reflexion height between them is not significant.

Another consequence of the asymmetrical triangle of reflexion points is that for a particular wave the long path will show slightly smaller Doppler shifts than the short path. Practical and theoretical tests show, however, that provided the propagation is via the same mode the discrepancy is only about 10% and this is not considered important.

The main experiment was deployed in January 1976 and is now operating satisfactorily. Before this a short test experiment was conducted consisting of transmitters at Adelaide Island, Palmer Station and aboard the R.R.S. *Bransfield*, with a receiving station at Argentine Islands. This network was operated from 13 January to 5 April 1975. The experience so gained proved very valuable in the design of equipment for the main experiment and the optimization of operating procedures.

4. First results from the Antarctic Doppler experiment

4(*a*) *Medium and large scale disturbances*

The type of results so far obtained from Antarctica are illustrated by figure 2 which shows a summer local night-time record for a period of moderate magnetic activity. The main feature of this record is a large scale t.i.d. whose apparent horizontal velocity is about 1000 m s^{-1} in a northerly direction (away from the auroral zone). The wave appears to be dispersive, such that its period decreases (frequency increases) with time. Small amplitude medium scale disturbances with periods of about 20–30 min appear to be superimposed on this wave. The traces die away after 05 U.T. as foF2 decreases to, and below, the operating frequency. An increase in frequency spreading is evident just before this, which results from irregularities in the F2 layer.

A statistical analysis of the amplitudes of waves seen on the Adelaide transmission during the trial experiment (summer/equinox 1975) indicates that the most active time is centred on local midnight, with relatively little activity during the day. This result should however be treated cautiously since, although most of the data refers to F2 mode, near noon the propagation will have sometimes been via E or F1 modes, for which the Doppler shifts are smaller. The analysis has also demonstrated a strong positive correlation between the amplitude of Doppler disturbances and magnetic activity (see figures 3 and 4). This implies that large scale phenomena dominate the sample, provided the results of other analyses (see § 2) are applicable to the peninsula area.

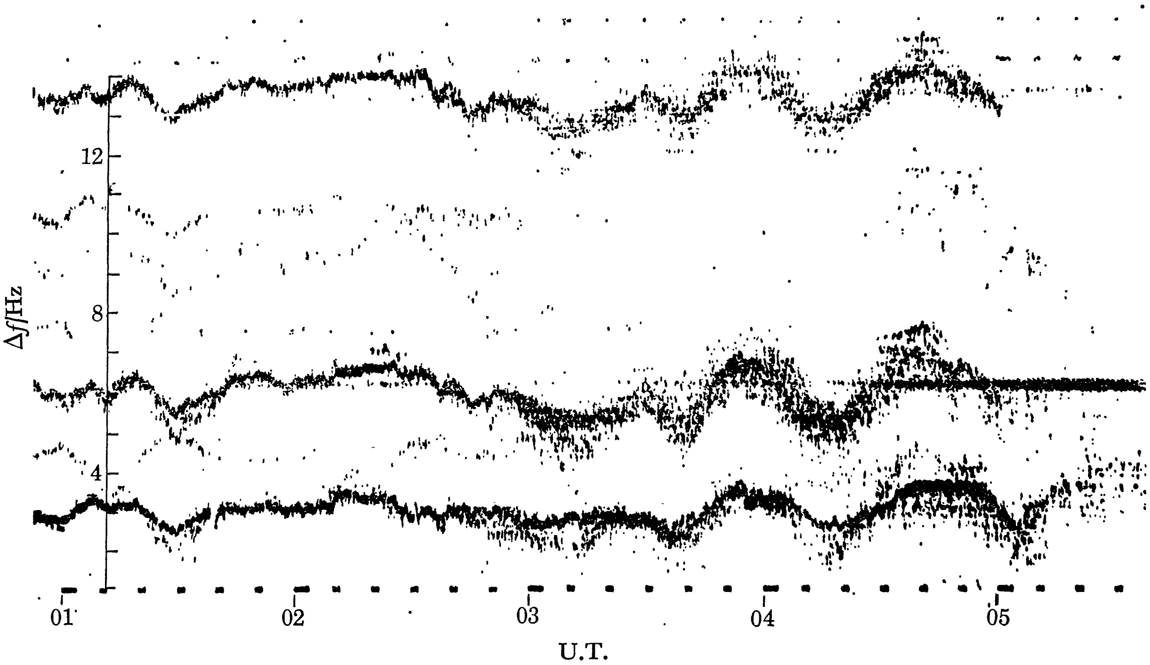

FIGURE 2. Doppler shifts (Δf) recorded on a frequency of 5.417 MHz for the night of 1 February 1976. Top trace is from the Almirante Brown transmission, middle trace is from Palmer and the bottom from Adelaide.

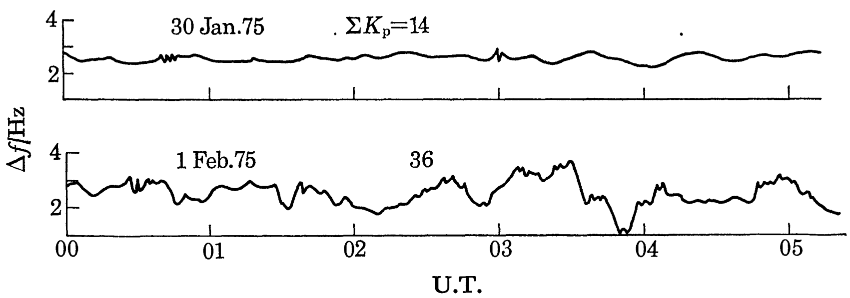

FIGURE 3. Comparison of activity on magnetically quiet and magnetically stormy nights for the Adelaide transmission.

4(*b*) *Short period oscillations*

Many more short period events were recorded in Antarctica than are normally seen by the same techniques in the U.K. (T. B. Jones 1976; personal communication). Two classes of events were observed, one exhibiting periods of about 1 min (shortest observed was ~ 40 s), and the other of about 5 min, just below the predicted acoustic cut-off period. The shorter periods were more common than the longer periods and both normally occurred in bursts lasting about 1 h. Some evidence that the shorter period waves also occur over the polar plateau has been given by Davies & Jones (1968). Typical examples of the two classes are shown in

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figures 5 and 6. A feature of these oscillations, illustrated by the figures, is that the same waveform appears on both transmissions even though the reflexion points (see figure 1, PA and AD propagation paths) are about 200 km apart. Also there is no measurable phase difference between the two waveforms. This implies that the waves producing the disturbances were either travelling horizontally orthogonal to the line joining Palmer and Adelaide, or as is more likely, propagating almost vertically. The horizontal line through the Palmer data is caused by ground wave propagation, and constitutes a useful instrumental check.

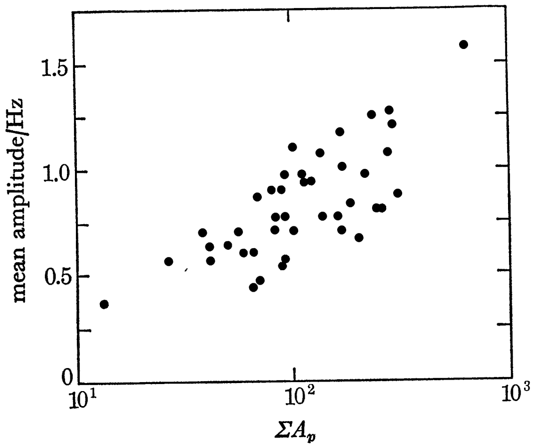

FIGURE 4. Peak-to-peak amplitude of Doppler shift on Adelaide transmission in each hour, averaged for the hours 00–04 U.T. on each day and plotted as a function of magnetic index A_p.

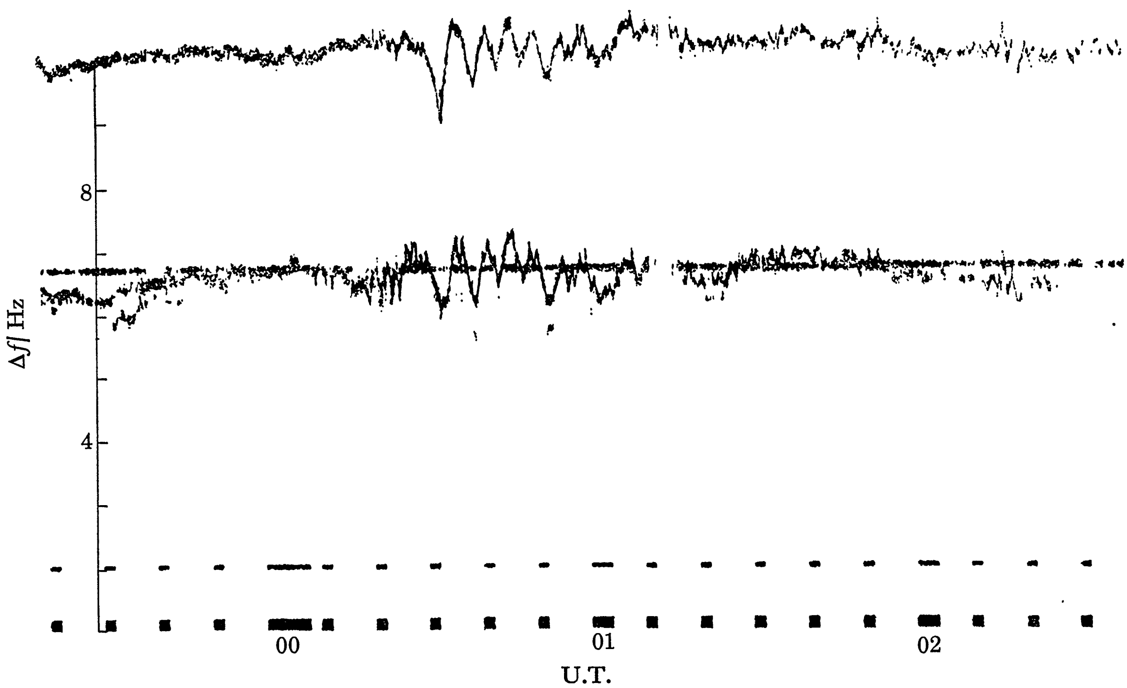

FIGURE 5. Example of ~5 min period oscillations observed on the Palmer (bottom) and Adelaide (top) transmissions for a frequency of 4.642 MHz (on 1–2 April 1975). Note that the Adelaide transmission was in this case made from a separate transmitter on board *Bransfield* in the vicinity of Adelaide base.

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The rate of occurrence and the amplitudes of the disturbances was low during the early part of the period (January–February) but rose to at least one event per day in the latter part (March–April).

Short period oscillations have been observed elsewhere and have been associated with a variety of different geophysical phenomena. There have been a number of reports (Baker & Davies 1969; Davies & Jones 1971; Davies & Jones 1973) of acoustic waves (typical periods 3.5–4.5 min) in the ionosphere apparently associated with severe tropospheric storms, particularly thunderstorms. This appears to be the primary cause of such events in the Midwest of the U.S.A. Similar oscillations have been demonstrated to coincide with storm sudden commencements (Davies 1962; Huang, Najita & Yuen 1973) although true wave trains seem rarely associated with s.s.cs. Evidence has also been presented showing that surface Rayleigh waves,

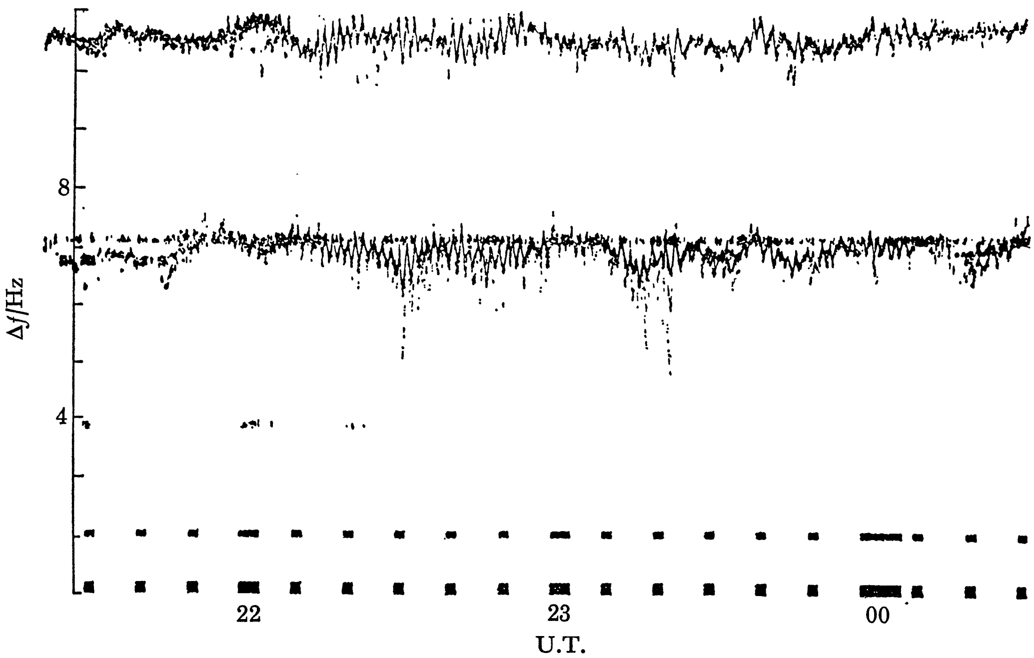

FIGURE 6. Example of ~1 min period oscillations observed on the Palmer (bottom) and Adelaide (top) transmissions for a frequency of 4.642 MHz (on 3–4 April 1975). Note that the Adelaide transmission was in this case made from a separate transmitter on board *Bransfield* in the vicinity of Adelaide base.

with amplitudes of about 1.5 mm, produced by the May 1968 earthquake in Japan (Yuen, Weaver, Suzuki & Furumoto 1969) and the August 1969 earthquake in the Kurile Islands (Weaver, Yuen, Prolss & Furumoto 1970), launched nearly vertically propagating acoustic waves which were subsequently detected in the ionosphere over Hawaii up to heights of about 300 km. In both cases the wave trains consisted of two independent oscillations with periods of ~ 20 s and 2 min respectively.

The acoustic waves observed in the Antarctic do not appear to be associated with any of the above mentioned phenomena. There were no recorded s.s.cs during the period studied (13 January–5 April) and no evidence of correlated storm or seismic activity. Thunderstorms are unknown in the Antarctic Peninsula area.

The thin, steep-sided, high plateau (max. elevation ≈ 2000 m, see figure 1) which constitutes the Antarctic Peninsula can be considered, to a first approximation, as an isolated knife-edge standing in an otherwise unbroken expanse of ocean. Data collected from many years of radar tracking of meteorological balloons at Argentine Islands demonstrate that, neglecting surface winds which are largely controlled by surface topography, the prevailing tropospheric and stratospheric winds blow from the southwest to northwest quadrant, and are thus generally orthogonal to the knife-edge (see figure 1). The latter disrupts the flow, producing turbulence over the eastern coast and giving rise to such phenomena as leewaves, the presence of which is indicated by frequent displays of lenticular cloud formations. We suggest that the tropospheric turbulence so caused may generate acoustic waves which propagate upward into the ionosphere, and that this mechanism may account for the observed high incidence of events. A simple comparison of days with high wind speeds at 2 km altitude (as measured at about 12 U.T. each day) and days of high acoustic activity for the small sample of data as yet available does not produce significant correlations. However, this is quite understandable since the production mechanism is likely to depend in a complicated way on the manner in which wind velocity and atmospheric temperature vary with height. Also, the resultant waves may sometimes be strongly attenuated and/or refracted in the mesosphere, depending on the winds and temperatures prevailing there, and thus not reach ionospheric heights.

5. Summary

The first results from the Antarctic Doppler experiment confirm our expectations that the zone would provide very exciting data. In the main experiment we will concentrate on studying the morphology and causative mechanisms of both the t.i.ds and the acoustic waves which frequently occur in this region.

The authors gratefully acknowledge the unstinting support of the Office of Polar Programs (National Science Foundation–U.S.A.) and staff of Palmer Station; the Instituto Antarctico Argentino and staff of Almirante Brown; and members of B.A.S. staff at Argentine Island, Adelaide Island and aboard R.R.S. *Bransfield*. Without the continuing help of these groups the experiment would not be possible. We would particularly like to thank Mr P. Fitzgerald of B.A.S. who managed the installation of both the trial and main experiments.

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