A STUDY OF WHISTLING ATMOSPHERICS

V. DISPERSION

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Summary

The dispersion characteristics of whistlers recorded at Brisbane, Adelaide, and Hobart, mainly during the IGY, are examined. The dispersion recorded at each station shows a wide range of values. Diurnal (10–15 $s^{\frac{1}{2}}$) and annual variations (20–25 $s^{\frac{1}{2}}$) are observed and correlations between dispersion and F_2 critical frequency and dispersion and magnetic disturbance are discussed. No association between dispersion and sunspot number was detected. The position of the "ionospheric sources" of the whistlers is of prime importance as dispersion varies with geomagnetic latitude. Much of the variation in dispersion observed by individual stations is believed to be due to their being able to "see" ionospheric sources up to 10° away.

I. INTRODUCTION

A "whistling atmospheric" is believed to be due to energy from a lightning flash entering the ionosphere and propagating along a path, which approximately follows the direction of the Earth's magnetic field, from one hemisphere to the other hemisphere. The impulsive nature of the initiating discharge and the dispersive nature of the magneto-ionic medium through which the energy travels cause the characteristic descending tone of a "whistler".

Eckersley (1935) and Storey (1953) have investigated the phenomenon and have shown that, subject to certain approximations, the time t of travel of a frequency f is given by the equation $t = Df^{-\frac{1}{2}}$. D, which is termed the dispersion of the whistler, is usually constant (within a few percent) over a frequency range of several octaves and is given by the expression

$$D = \frac{1}{2c}\int \frac{f_0}{(f_{\mathrm{H}})^{\frac{1}{2}}}\,\mathrm{d}s,$$

where the integration is with respect to a length element ds along the whistler-path, f_0 is the local plasma frequency at each point of the path, f_{H} the local electron gyro frequency, and c the velocity of light. If the wave frequency is comparable to the gyro frequency at the top of the path a more exact analysis is necessary (Helliwell *et al.* 1956; Ellis 1956). This predicts that a wave frequency of about (depending on the electron distribution) one-third of the minimum gyro frequency will travel faster than higher and lower frequencies, thus giving rise to the "nose whistler". This is mainly a high, rather than a middle, latitude phenomenon. The above expression for D is the limiting value as f tends to zero.

In order to explain various properties of whistlers Smith, Helliwell, and Yabroff (1960) have postulated the existence of whistler ducts, i.e. field-aligned columns in which the electron density is greater than the ambient electron density. The energy

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in a whistler is believed to emerge from the ionosphere over a restricted region (Crouchley and Finn 1961; Crouchley and Duff 1962; Crouchley 1964*), with a size of the order of 200 km. This region will be referred to as the "ionospheric source" of the whistlers.

The length and maximum height of a whistler path and also the magnetic field strength along the path depend on the geomagnetic latitude of the ends of the path. Thus the dispersion of whistlers depends on geomagnetic latitude and experimental values of dispersion for several different latitudes may be used to estimate exospheric electron densities (Allcock 1959). Nose whistlers have also been used for the same purpose (Smith 1961; Carpenter 1962*a*).

II. General

The dispersion measurements reported in this paper have been made either (i) by means of a multichannel analyser (Crouchley and Finn 1961) or (ii) by measuring sonagrams by means of a graticule (Crouchley and Duff 1962). In the former case the accuracy of measurement is about $\pm 10\ s^{\frac{1}{2}}$ whereas in the latter case the accuracy, for a fine, well-defined trace may be $\pm 2\ s^{\frac{1}{2}}$, although more commonly $\pm 5\ s^{\frac{1}{2}}$ or worse (for a very diffuse specimen). The multichannel analyser has the advantage of speed but is limited to fairly well-defined whistlers, and accordingly most of the information presented herein has been obtained (except where otherwise stated) from the analysis of sonagrams. The normal operating frequency range of the Sonagraph is 80 c/s to 8 kc/s but the upper limit may be increased to 16 kc/s by replaying the magnetic tape at half-speed. Unless a whistler exhibited unusual properties below 8 kc/s it was not examined at higher frequencies. Very few nose whistlers were observed and most of the whistlers examined were too diffuse to warrant any attempt to correct for deviations from the Eckersley-Storey expression.

At Brisbane it was usually possible to identify the initiating atmospheric on the sonagram, commonly by its being the most obvious, or by comparing whistlers from the same or adjacent recording schedules when many spherics were present. The spherics associated with short (one-hop) and long (two-hop) whistlers were often equally obvious and thus it was sometimes difficult to decide what type of whistler was being examined, for the dispersion varies, from time to time, by a factor of greater than two (Figs. 1 and 3). If both short and long whistlers were observed on the same night classification was easy, but otherwise a classification had to be made on the basis of the appearance of the spheric or of the likelihood of a short whistler having an unusually high dispersion at that particular time. Even approximate information about the position of the initiating lightning stroke would have helped to remove ambiguity.

At Adelaide and Hobart a spheric which initiated a short whistler was sometimes indistinguishable from many others which were present. Spherics which initiated long whistlers were usually more obvious than those which initiated short whistlers. Accordingly, it was easier to decide if a given whistler were short or long. However, whistlers observed at these stations were commonly more diffuse and

* Preceding paper, being Part IV of the present series and referred to hereafter as Part IV.

usually of higher dispersion, and thus measurement (in the absence of the initiating spheric) was made more difficult. Not infrequently whistlers with high values of dispersion were faint, of limited frequency range, diffuse, and consequently unmeasurable. The analysis is, of necessity, somewhat biased by this fact.

The whistlers observed during any one recording period were usually similar and there were seldom marked changes in properties from one recording schedule to the next. Most estimates of dispersion are based on measurements made on short whistlers, these being much more common than long whistlers, although long whistlers, when observed, were used as a check. On some days when no short whistlers were observed the dispersion values used were obtained by dividing the long whistler values by two in order to obtain the value to be expected for a single traverse of the path.

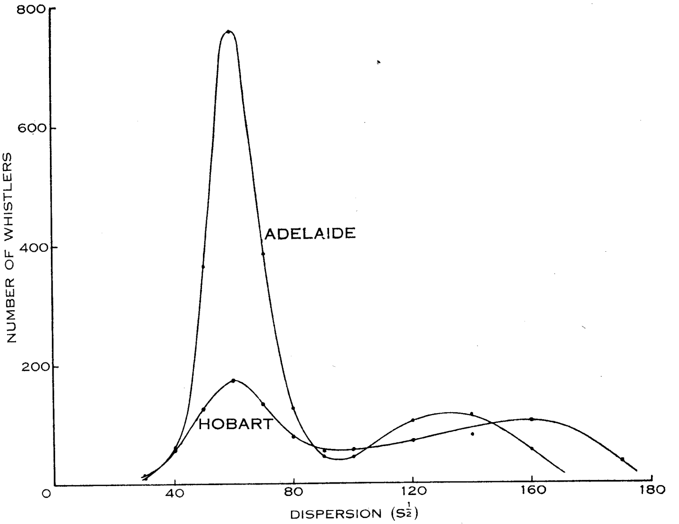

Fig. 1.—Frequency distribution of whistler occurrence versus dispersion for Adelaide and Hobart (1957, 1958) (multichannel analyser data).

III. Distribution of Dispersion Values

The values of dispersion obtained for the various stations show a considerable spread, with the maximum long-whistler dispersion being five times the minimum short-whistler dispersion. For Brisbane this range is roughly 20–100 $s^{\frac{1}{2}}$ and for the other stations from 30–40 $s^{\frac{1}{2}}$ to about 200 $s^{\frac{1}{2}}$.

A large number of dispersion values, to the nearest multiple of 10 $s^{\frac{1}{2}}$, was obtained for Adelaide and Hobart by means of the multichannel analyser. Figure 1 shows, for these stations, the (statistical) frequency distribution with respect to dispersion of all values measured for 1958. The curve drawn for Adelaide has a well-marked peak at a dispersion value of 60 $s^{\frac{1}{2}}$ (short whistlers) and a broader, less-marked peak at about 130 $s^{\frac{1}{2}}$ (long whistlers). For Hobart, the plot exhibits peaks at 60 $s^{\frac{1}{2}}$ and 160 $s^{\frac{1}{2}}$ but these are broader and less clearly defined than those shown in the Adelaide data.

Owing to the much smaller number of whistlers observed at Brisbane and Macquarie Island, there were not sufficient data available to draw similar curves.

IV. Diurnal Variation of Dispersion

The variation of D throughout the day has been examined by (i) a statistical analysis of measurements made by the multichannel analyser and (ii) preparing sonagrams for several selected days on which whistlers occurred for most of the day.

(a) *Multichannel Analyser Results*

The accuracy of measurement by this method is not adequate to show a small variation of dispersion, for, as indicated above, the dispersion of most whistlers could only be measured to the nearest multiple of 10 $s^{\frac{1}{2}}$. Accordingly, data for 1 year were subdivided into 24 groups corresponding to the 24 hourly recording schedules in the day. For each of these hourly schedules the number of whistlers for D equal to 20, 30, 40, 50, 60, 70, 80, 90, 100, 120, 140, and 160, and greater than 160 was

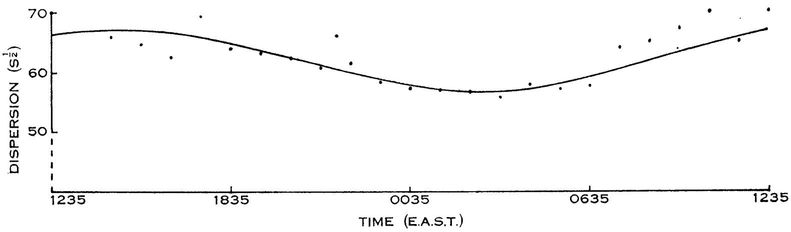

Fig. 2 (*a*).—Diurnal variation of mean whistler dispersion for Adelaide (multichannel analyser data). Standard deviation on experimental points (●) is approximately 10 $s^{\frac{1}{2}}$. Full line represents best-fitting sine curve.

tabulated. As it was often impossible to locate the causative atmospheric on the records from this analyser, there was no satisfactory method of deciding into which category whistlers should be placed when their dispersion was intermediate between those commonly observed for the short and long variety. Accordingly, it was not possible to take a mean value for each hour, using all whistlers, and the following procedure was therefore adopted. A value for the hour was assigned by taking a weighted mean of the dispersion value which occurred most commonly and the two values adjacent, on either side, to this value. The weighting factor used was the number of whistlers recorded for each of these values of D.

One thousand six hundred values of D were available for Adelaide, ranging from about 200 in an hourly group at night to about 10 during the day. As shown by Figure 2 (*a*) the average dispersion at this station shows a slow change from a maximum, probably in the early afternoon, to a minimum value, about 10–15 $s^{\frac{1}{2}}$ lower, near 0300 hours (Australian E.S.T.). While the standard deviation associated with the hourly mean values is approximately 10 $s^{\frac{1}{2}}$, the night-time points agree quite closely with the "best-fit" sine curve that is represented by the line.

The number of whistlers (470) available for Hobart is appreciably smaller than for Adelaide and also these whistlers have dispersion values which are distributed much more uniformly over the 40 $s^{\frac{1}{2}}$ to 200 $s^{\frac{1}{2}}$ dispersion range (Fig. 1). It is thus not surprising that the above method of analysis failed to show a diurnal variation in dispersion for this station.

Insufficient data were available to attempt this type of analysis for Brisbane or Macquarie Island.

(*b*) *Examination of Individual Days*

Figures 2 (*b*) (i) and 2 (*b*) (ii) show, for Adelaide, the dispersion values obtained by measuring sonagrams made for two days (June 20–21, 1958 and June 21–22, 1958) in which whistlers were recorded in most of the 24 schedules. Each value plotted is the result of the examination of from 2 to 10 whistlers, depending upon the time of day, and the vertical bars indicate the range of dispersion (diffuseness) of

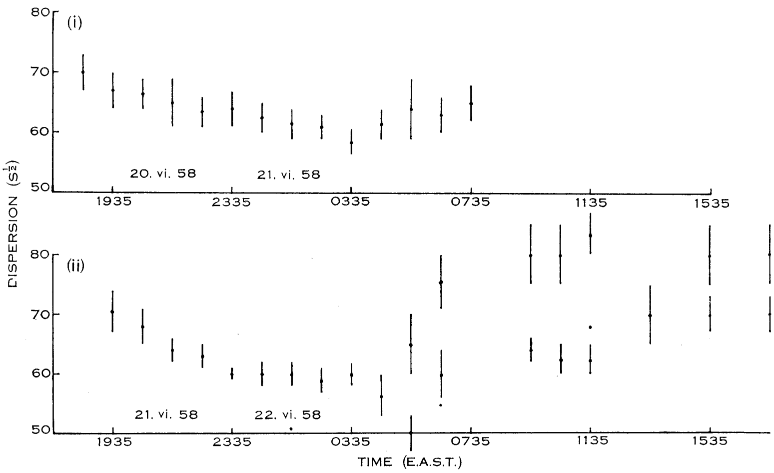

Fig. 2 (*b*).—Diurnal variation in dispersion at Adelaide for June 20–21 and 21–22, 1958. Note extra trace appearing at 0535 on June 22, 1958. (Sonagram results.)

the whistlers observed in each hour. The estimates of the accuracy of measurement were between $\pm 2\ s^{\frac{1}{2}}$ and $\pm 4\ s^{\frac{1}{2}}$, depending upon the individual whistlers, and the whistlers observed in each recording schedule were of very similar diffuseness and same mean dispersion (within the accuracy of measurement). On occasions a spheric may excite a whistler which shows two (or more) parts which have different dispersions. A whistler with two distinct traces of different dispersion is commonly called a "whistler-pair" (Storey 1953). (This phenomenon is believed to be due to more than one propagation path being available at the same time.) Figure 2 (*b*) (ii), as well as illustrating the diurnal variation, is an example of an occasion when a transition from simple whistlers to whistler pairs was observed. Sonagrams for three other occasions on which whistlers were observed for most of the day showed a similar diurnal variation of dispersion.

Whistlers were rarely observed during the day at Brisbane. However, examination of three nights upon which dispersion measurements were possible for several hours showed a similar behaviour to Adelaide. There were, for Hobart and Macquarie

Island, few days on which whistlers were observed in most recording schedules and whistlers at these stations were usually too diffuse to be measured accurately enough for this purpose. There was, however, an indication of a decrease in dispersion from late afternoon to midnight.

The examination of the data for certain individual days is thus in agreement with the statistical result of Section II (*a*) for Adelaide, and shows that similar changes occur over at least part of the day for Brisbane and possibly also for Hobart and Macquarie Island.

V. Daily Variation of Dispersion

As indicated in Section III, dispersion is a very variable quantity, which may change appreciably from one day to the next. In order to investigate those changes it was decided to assign a dispersion value to each day upon which this quantity could be measured. To eliminate the effects of the diurnal variation in D, sonagrams were prepared for whistlers which occurred in the midnight recording schedule (actually 0035 to 0037 E.A.S.T.) or as near to this time as possible. If the whistler occurred more than an hour away from this schedule a correction of 1 $s^{\frac{1}{2}}$/hr was added or subtracted in accordance with Figure 2 and nearly all of the whistlers examined occurred within 3 hours of midnight. At least five whistlers were measured when available, but occasionally only one measurable whistler was recorded. On 10–15% of the nights two or more clear traces of different dispersion were evident and on these occasions the maximum and minimum D values were tabulated. They are referred to subsequently as "upper-dispersion" and "lower-dispersion" values respectively. Diffuse whistlers were assigned the mean value of their dispersion range. As such whistlers sometimes showed different diffuseness at different frequencies some judgment had to be used, and likewise some discretion was necessary in rejecting very faint whistlers or where it was felt that the measurement was likely to be grossly inaccurate. The values obtained as described above are hereinafter referred to as "daily dispersion values" or "daily D-values".

By including 1956, 1959, and 1960 observations with IGY data, daily D-values were obtained for 105 occasions for Brisbane, similar values were obtained for 182 days at Adelaide (September 1957 to December 1958), and 80 days were measured at Hobart (September 1957 to December 1958).

(*a*) *Frequency Distribution of Daily Dispersion Values*

The frequency distribution of daily dispersion values with respect to D, in intervals of 5 $s^{\frac{1}{2}}$, is shown in Figure 3. Both upper-D and lower-D values were included in the analysis when such values had been assigned.

The modal values for Brisbane, Adelaide, and Hobart are 47 $s^{\frac{1}{2}}$, 66 $s^{\frac{1}{2}}$, and 68 $s^{\frac{1}{2}}$ respectively, and, as for the frequency distribution in which all whistlers were counted (Fig. 1), there is a spread, of the order of 20–25 $s^{\frac{1}{2}}$, in the daily dispersion values. Division of the Hobart data into two rather small groups on the basis of whether or not Adelaide received whistlers on the same day as Hobart suggested that Hobart daily D values were below 60 $s^{\frac{1}{2}}$ only when Adelaide also observed whistlers on the same day.

(*b*) *Autocorrelation and Power-spectra Analysis of Adelaide Data*

An autocorrelation analysis was performed on Adelaide upper-D and lower-D daily dispersion values, for lags of up to 60 days, using a G.E. 225 digital computer. This analysis was performed on all of the values (group (*a*), 182 days) and also, to minimize the effects of seasonal variation (Section VI), on a smaller group (group (*b*), 86 days) extending from June 1 to September 30, 1958. For group (*a*) the one-day-lag coefficients were 0·45 and 0·33 (103 pairs of values, lower-D and upper-D respectively) and for group (*b*) the corresponding values were 0·28 and 0·13 (64 pairs of values). There was an appreciable amount of "noise" present in all of the autocorrelograms. However, for group (*a*) there was an indication of a small serial correlation for about a month. For group (*b*) lower-D values there was a slight association for about a week but the higher-D coefficients varied in a rather erratic fashion.

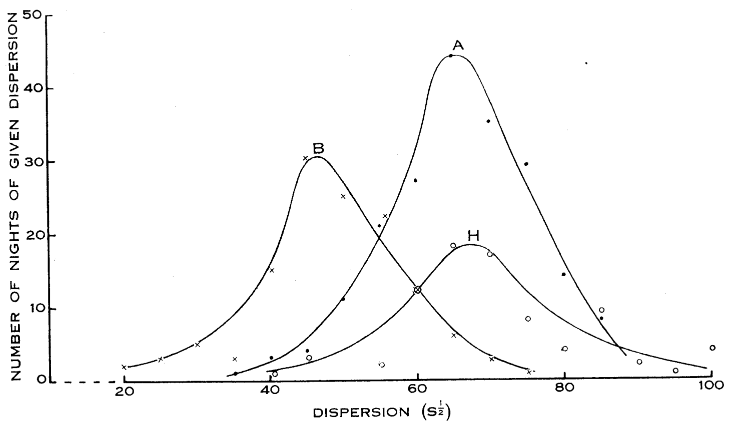

Fig. 3.—Number of occurrences of nights of given dispersion (D) versus D. Points represent centres of ranges of 5 $s^{\frac{1}{2}}$. (A, Adelaide (●); B, Brisbane (×); H, Hobart (○)).

Such serial correlation as is present is not strong and thus it is reasonable to use a weekly or monthly mean of the daily dispersion values for the investigation of long-term variations. These means will be referred to as weekly- and monthly-mean dispersions. The use of means of daily D-values, rather than the mean dispersion of all the whistlers recorded, eliminates the possibility of giving undue weight to individual days on which large numbers of whistlers were recorded.

The power spectra of the above autocorrelograms were calculated but they did not show any large components.

VI. Monthly Variation of Dispersion

Figure 4(*a*) shows a plot of the monthly-mean dispersion values for Adelaide and Hobart. In the southern-hemisphere winter it was possible to measure daily dispersion values on about 20 nights per month at Adelaide but this number fell to between 5 and 10 for other months and was only 3 for November 1957 and December 1958. The values for Hobart are based on about 6 nights per month, except for April and October 1958 when only 2 nights were used. The vertical bars indicate the standard deviation associated with each mean. For both stations the dispersion is a minimum about the middle of the year and a maximum around the

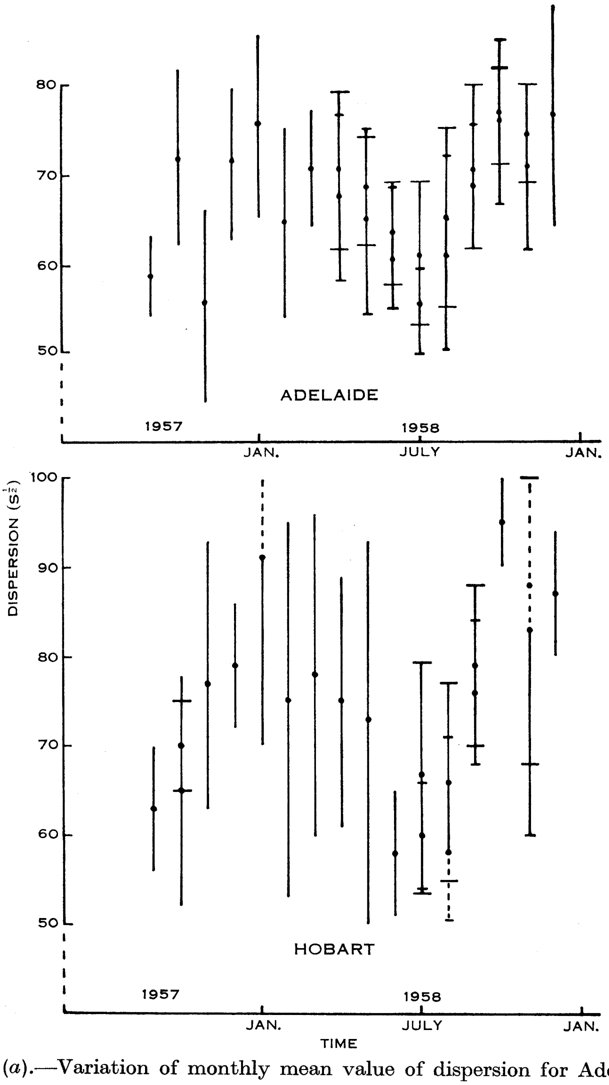

Fig. 4 (*a*).—Variation of monthly mean value of dispersion for Adelaide and Hobart (September 1957 to December 1958). Upper-*D* and lower-*D* values are shown; vertical lines represent the standard deviation (Short horizontal bars refer to lower-*D* values and longer horizontal bars to upper-*D* values.)

beginning of the year and the difference between maximum and minimum average monthly dispersion is about 20–25 $s^{\frac{1}{2}}$. These graphs are similar to ones published for Wellington (45·4°S. geomagnetic) and for northern-hemisphere stations, particularly Stanford (43·7°N. geomagnetic), (Helliwell and Carpenter 1961). The correlation coefficient between the Adelaide lower-D values and the Stanford values is 0·69 for 16 pairs of values. Since these northern- and southern-hemisphere variations show no phase difference, this variation may be annual rather than seasonal.

During the IGY period whistlers were not commonly observed at Brisbane in the summer-time, but, as shown in Figure 4(b), measurements made at a quieter site from mid 1961 onwards suggest that there is a phase difference of about 6 months between the annual variations at this station and at Adelaide.

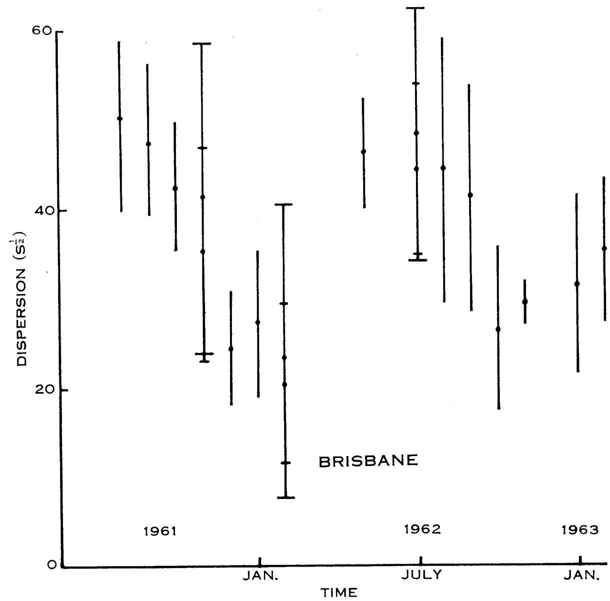

Fig. 4 (b).—Variation of monthly value of dispersion for Brisbane (August 1961 to February 1963).

VII. Daily Dispersion Values and the Occurrence of Whistlers

A comparison of Figures 1 and 3 shows that the modal dispersion value for Adelaide is 60 $s^{\frac{1}{2}}$ whereas the modal daily dispersion value is 66 $s^{\frac{1}{2}}$, suggesting that more whistlers were received on days when the daily D-value was below its modal value than when it was above this value. This point was investigated by grouping days, by means of their daily dispersion values, into 5 $s^{\frac{1}{2}}$ intervals and then calculating the average number of whistlers received per day for all of the days included in each of these dispersion intervals. A similar analysis was performed by determining the mean number of schedules per day receiving whistlers. (This quantity would be expected to be less influenced by the frequency of occurrence of lightning discharges.) Days when both upper- and lower-D values had been assigned were excluded from this analysis.

At Adelaide (Fig. 5(a)) the average daily whistler rate had its maximum value when the daily dispersion value was 55 $s^{\frac{1}{2}}$ and also whistlers were heard in more schedules on such days. For Hobart (Fig. 5(b)) the daily whistler occurrence rate was much the same over a range of 60 $s^{\frac{1}{2}}$ to 85 $s^{\frac{1}{2}}$. Some of the points are the result of averaging a very small number of values and have accordingly been given less weight in drawing the smooth curve.

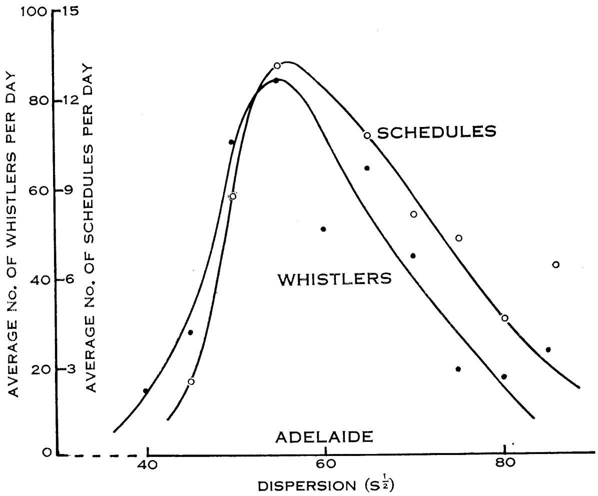

Fig. 5 (*a*).—Plot of average number of whistlers per day (●) and average number of schedules per day receiving whistlers (○) versus dispersion for Adelaide. (Points represent centres of dispersion invervals of 5 $s^{\frac{1}{2}}$.)

VIII. Comparison of Brisbane, Adelaide, and Hobart Daily *D*-Values

Daily dispersion values were measured for the same day for Brisbane and Adelaide on 23 occasions, Adelaide and Hobart on 37 occasions, and Brisbane and

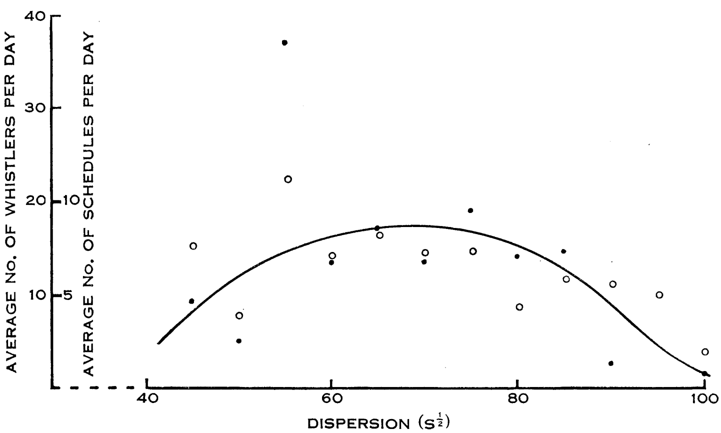

Fig. 5 (*b*).—Similar plot to Figure 5 (*a*) for Hobart. ●, whistlers; ○, schedules.

Hobart on 11 occasions. The result of comparing these values is shown in Table 1, where the "mean maximum dispersion difference" is the average value of the dispersion difference between the two stations if only a single daily-*D* value was assigned or of the maximum difference if upper- and lower-D values were assigned to either or both stations. A difference of 5 $s^{\frac{1}{2}}$ or less was not considered significant because of the experimental error involved in the measurements.

For the days on which daily D-values were assigned to both Adelaide and Hobart the means of the lower-D values were 62 $s^{\frac{1}{2}}$ and 66 $s^{\frac{1}{2}}$ respectively and of the upper D-values 65 $s^{\frac{1}{2}}$ and 70 $s^{\frac{1}{2}}$. For 37 days in which daily-D values were measured at Hobart but on which whistlers were not received at Adelaide the mean lower-D and upper-D values were 77 $s^{\frac{1}{2}}$ and 79 $s^{\frac{1}{2}}$ respectively.

IX. Dispersion and F_2 Critical Frequency

A correlation coefficient of 0·4 was reported by Storey (1953) between whistler dispersion and critical frequency (f_0F_2) of the F_2 layer of the ionosphere for 2 months' data at Cambridge in 1951, whereas Smith (1960) found no evidence of such an association for Stanford.

Table 1

comparison of "simultaneous" daily dispersion values

Station Pair	No. of Occasions	Mean Maximum Dispersion Difference ($s^{\frac{1}{2}}$)
Brisbane–	9	<5
Adelaide	14	20
Adelaide–	25	<5
Hobart	12	16
Brisbane–	1	<5
Hobart	10	25

A comparison of the graph of the monthly-mean dispersion values (Fig. 4) and of the monthly median f_0F_2 plot for Canberra and Hobart (Fig. 6) shows that the variables move in a similar fashion. Since a whistler path has ends in opposite hemispheres it would be expected that f_0F_2 values at both ends of the path would be equally important. However, the variation of f_0F_2 for Wakkanai, the ionospheric sounding station nearest to the conjugate points of Adelaide and Hobart, is roughly 6 months out of phase with that for the southern hemisphere stations. Table 2 shows the correlation coefficients for the various combinations of dispersion and f_0F_2 values. The correlation coefficients between Adelaide dispersion values and the sum of Canberra and Wakkanai f_0F_2 values and also between Hobart dispersion values and Hobart plus Wakkanai f_0F_2 values were all small (less than 0·13) and not significant.

Examination of this phenomenon on a daily basis by using midnight values of f_0F_2 and including both upper-D and lower-D daily values in the calculation gave the following correlation coefficients. Adelaide–D, Canberra–f_0F_2 0·42; Adelaide–D, Hobart–f_0F_2 0·41; Canberra–f_0F_2, Hobart–f_0F_2 0·88; (211 pairs of values in each case, 1% level is 0·18); Hobart-D, Hobart–f_0F_2 0·12 (77 pairs, 5% level 0·22).

Division of the Hobart data into two groups, using the presence or absence of whistlers at Adelaide as a criterion, still gave small non-significant values. Values for Brisbane were, Brisbane–D, Brisbane–f_0F_2 $-0 \cdot 10$ (73 pairs) (1956–1960 data) and $-0 \cdot 12$ (91 pairs) (1961, 1962, and early 1963) and Brisbane–D, Canberra–f_0F_2 $0 \cdot 13$ (78 pairs, 1956–1960). There is a significant correlation between Adelaide daily D-values and f_0F_2 at midnight at either Canberra or Hobart, but Brisbane and Hobart daily D-values do not show a significant correlation with f_0F_2 values. The similarity in correlation coefficients for Adelaide–Canberra and Adelaide–Hobart is not surprising in view of the well-known spatial correlation in f_0F_2 and of the surface range of whistlers.

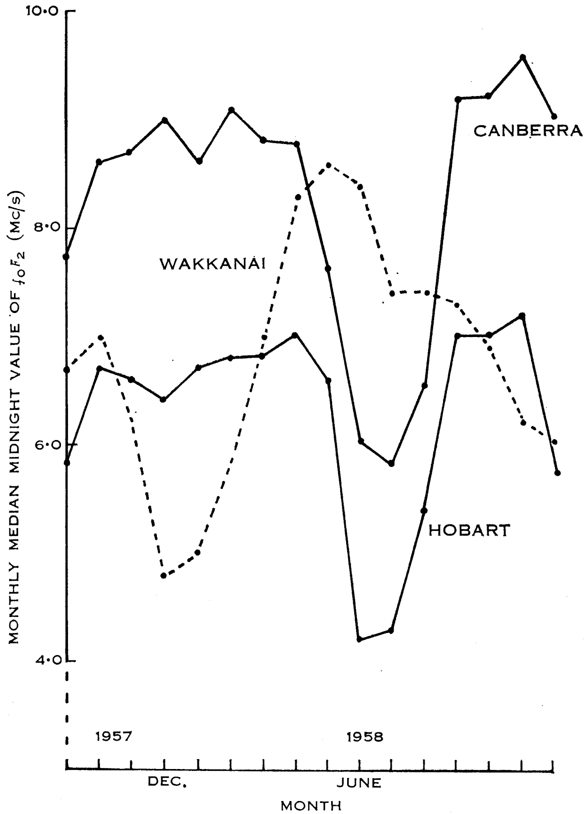

Fig. 6.—Monthly median midnight values of f_0F_2 for Canberra, Hobart, and Wakkanai.

X. Influence of Magnetic Disturbance on Dispersion

The mean values of D for different values of K_p (the planetary magnetic K-index) at the time of occurrence of the whistler were calculated but showed no significant dependence on K_p. However, various workers have suggested that the effect of magnetic disturbance on dispersion is not an immediate one but may have a variable time delay of a few days (Carpenter 1962*b*; Corcuff 1962; Outsu and Iwai 1962). These workers used nose whistler data, or plotted the daily variation of dispersion around storm days. As suitable data were not available for either of these types of analysis the following procedure was adopted. The largest value of the K_p daily-sum which occurred in the three days preceding each daily D-value was tabulated against the daily D-value. The daily D-values ranged, in steps of unity, from 40 $s^{\frac{1}{2}}$ to 82 $s^{\frac{1}{2}}$ and thus several values of K_p daily-sum were obtained for each of the 43 values of D in the above range. The mean value ($\overline{K}_p$) of the K_p daily-sums tabulated for each value of D was then calculated and the correlation coefficient between the pairs of values of D and $\overline{K}_p$ determined. This correlation coefficient was $-0\cdot34$. Using K-values from Macquarie Island instead of the planetary K-indices in a similar calculation gave a correlation coefficient of $-0\cdot49$ (5% level is $0\cdot29$). The Macquarie Island K-values were used because they had proved to be a significant parameter in the investigation of "chorus" (Crouchley and Brice 1959).

TABLE 2

CORRELATION COEFFICIENTS BETWEEN MONTHLY-MEAN DISPERSION VALUES AND MONTHLY MEDIAN F_0F_2 VALUES*

D measured at		f_0F_2 measured at		
		Canberra	Hobart	Wakkanai
Adelaide	Lower-D	$0\cdot73$	$0\cdot62$	$-0\cdot48$
	Upper-D	$0\cdot56$	$0\cdot54$	$-0\cdot35$
Hobart	Lower-D	$0\cdot63$	$0\cdot63$	$-0\cdot45$
	Upper-D	$0\cdot61$	$0\cdot61$	$-0\cdot47$

* The 5% significance level is $0\cdot50$, 16 pairs of values in each case.

XI. DISPERSION AND SUNSPOT NUMBER

Allcock and Morgan (1958) have shown a correlation between whistler dispersion and Zurich Sunspot Numbers (R_Z) about 2 months earlier. An attempt was made to detect a similar effect in the Adelaide dispersion data by calculating lag-correlograms with delays ranging from R_Z 6 months before to 5 months after dispersion. These calculations were performed using, (i) daily D-values, (ii) weekly-mean dispersions, and (iii) 4-weekly mean dispersions; lower D- and upper D-values were analysed separately in each case.

Figure 7 shows a plot of the correlation coefficients so calculated for the 4-weekly means. For the lower-D values there is a slight but non-significant positive correlation for R_Z 2–3 months before D and a negative correlation for R_Z 1 month after D (5% level is $0\cdot53$). The correlations between weekly and daily values likewise showed no definite association between the two variables except possibly a negative correlation between D and R_Z a few weeks later. It is unlikely that the negative correlations are indicative of any real association between the two variables.

An attempt was made to remove the effect of the annual variation from the dispersion data by calculating 5-weekly running means of the weekly mean dispersions, subtracting these from the weekly dispersion values at the centre of the 5-week period and calculating lag correlation coefficients between the values so obtained and weekly mean values of R_Z. Again no significant association was detected.

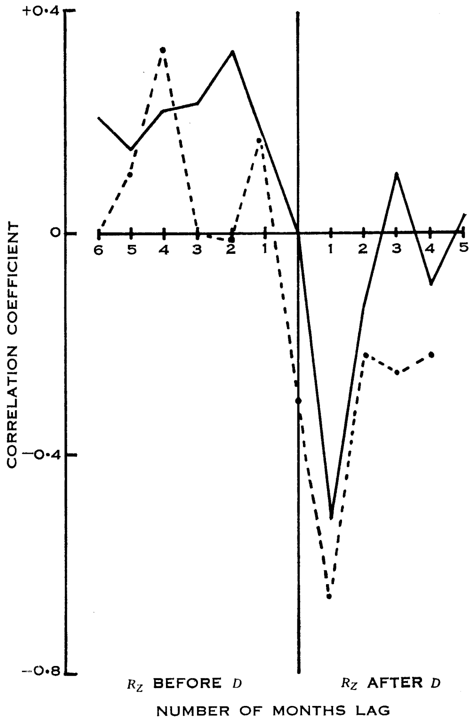

Fig. 7.—Lag cross-correlogram of 4-weekly average values Relative Sunspot Number (R_Z) and 4-weekly average values of D at Adelaide. (Full line, lower-D values; dashed line, upper-D values.)

XII. Discussion

As explained in Section I, the dispersion of a whistler depends on the latitude of its ionospheric source and also on the electron density along its exospheric path. A change in electron density along a particular path or a change of path will give rise to a change in dispersion. The diffuseness and dispersion of whistlers show that there is, on any particular evening, often only one ionospheric source within range of a particular recording station. However, for roughly one-fifth of the time whistlers may come from two or more ionospheric sources.

Any given recording station (RS) may observe whistlers which have emerged from an ionospheric source several hundred kilometres away. The effective range for "strong" whistlers is about 1000 km (see Part IV) and probably roughly half this value for the majority of whistlers. The mean dispersion observed by RS over a period of time will thus depend on the distribution of ionospheric sources with latitude. If all the whistlers RS receives come from ionospheric sources at the latitude L of RS then the mean dispersion will be representative of the latitude L. However, if all the whistlers received have come from sources at their maximum range on the high latitude side of RS then the mean dispersion at RS will refer not to L but to L plus about 9°. Likewise, if RS receives equal numbers of whistlers from sources at both higher and lower latitudes then the range of dispersions observed will correspond to the latitude range $(L-9°)$ to $(L+9°)$. Using mean dispersions from six stations at different latitudes Allcock (1959) has drawn a graph of dispersion against latitude. The variation is roughly linear and the slope about $2 \cdot 2\ s^{\frac{1}{2}}/\mathrm{deg}$. The range of daily dispersion values shown in Figure 3 (roughly $\pm 20\ s^{\frac{1}{2}}$) is thus in agreement with a latitude range of $\pm 9°$ and a change of dispersion of $2 \cdot 2\ s^{\frac{1}{2}}/\mathrm{deg}$.

In summer ionospheric sources do not commonly occur at geomagnetic latitude 45° (Adelaide) and whistlers occur most frequently about latitude 51° (Hobart) (Part IV). Thus the mean dispersion for Adelaide in summer would be expected to be characteristic, not of latitude 45°, but of some higher latitude, possibly about 50°. In winter more whistlers are received at Adelaide than at higher or lower latitudes, and hence the mean dispersion at Adelaide at this time of the year probably refers to latitude 45°. This seasonal shift of ionospheric sources would thus be expected to cause a decrease, of about 10–12 $s^{\frac{1}{2}}$ in mean dispersion at Adelaide from summer to winter. Likewise, a similar change would be expected for Hobart, which, in summer, is at the latitude of maximum occurrence of whistlers and, in winter, is at a higher latitude than the region of maximum whistler occurrence. (Graphs of whistler-occurrence versus latitude are shown in Part IV.) However, the mean dispersion in summer is about 20–25 $s^{\frac{1}{2}}$ higher than in winter. Thus, it seems unlikely that the change in ionospheric source position is enough to explain the observed change of mean dispersion.

The seasonal variation of dispersion at Brisbane (35°S.) for 1962 is similar to that observed at Toyakawa (25°N., geomagnetic) rather than to that at Wakkanai (35°N.) and is approximately 6 months out of phase with that observed at Adelaide in 1958. The mean dispersion at Brisbane in winter would, because of the distribution of ionospheric sources with latitude, be expected to be equivalent to that of sources a few degrees higher in latitude. However, there is little evidence to show how ionospheric sources are distributed around Brisbane in summer. If this distribution were uniform, then the mean dispersion observed would refer to latitude 35° and thus be smaller than the mean dispersion in winter. The changes observed are, however, several times larger than would be expected for this mechanism.

While some of the annual variation of dispersion may be explained in terms of the occurrence of ionospheric sources, there are annual changes of dispersion that are not explicable in this fashion. Dispersion seems to be lower at low latitude stations in January than in June and conversely for middle and higher latitude stations. Furthermore, the nature of the annual variation appears to depend on geographical position as well as geomagnetic latitude and in some places a semi-annual variation is observed (e.g. Poitiers, Corcuff 1962). The annual variation in

Earth–Sun distance produces a change of 7% in E-region electron densities (Appleton 1963) but the same proportional change in electron density over a whistler path, ending at middle latitudes, would only cause a change of 2–3 $s^{\frac{1}{2}}$ in dispersion. Annual changes in air density in the ionosphere are known to exist (Cook 1962). The origin of these is also obscure but it has been suggested (Paetzold and Zschörner 1961) that they are due to an interaction between the ionosphere and the interplanetary plasma.

A positive correlation between dispersion and f_0F_2 would be expected if the F_2 region contributed a substantial amount to the dispersion or if the electron density at points along a geomagnetic field line were related to that in the F_2 region. In both of these cases it would be expected that f_0F_2 variations in the two hemispheres would be equally important in determining dispersion changes. The correlation coefficients of Section IX indicate that such is not the case. However, part of the seasonal change in dispersion at Adelaide and Hobart is believed to be due to changes in the position of the ionospheric sources and these changes may be related, as suggested in Part IV, to changes in f_0F_2. Thus it seems likely that the correlation reported between monthly D-values and monthly-median f_0F_2 for Adelaide and Hobart is due to changes in ionospheric source position. Adelaide is at a latitude where changes in f_0F_2 would be expected to have a relatively large influence on the occurrence and position of ionospheric sources and correlation is apparent between the daily as well as the monthly values of dispersion and f_0F_2. However, Hobart, at a higher latitude, is in a region where, on the average, the influence of f_0F_2 on the occurrence of ionospheric sources would be less marked and accordingly daily values would be expected to show less correlation. The seasonal changes in dispersion at Brisbane are apparently not related to ionospheric source position and there is no significant correlation between daily value of dispersion and f_0F_2.

The average diurnal variation in dispersion at Adelaide, which is between 10 $s^{\frac{1}{2}}$ and 15 $s^{\frac{1}{2}}$, i.e. 15–20%, is smaller and rather more gradual than that reported by Rivault and Corcuff (1960) for geomagnetic latitude 49°N. and also less than that reported by Iwai and Outsu (1958) for Toyokawa. Since there is a diurnal change in F-region electron content in a similar fashion to dispersion, this must contribute to the dispersion changes. The importance of F-region changes will depend on what fraction of the whistler path occurs in this region and will thus depend on latitude. Storey (1953) has estimated that the ionosphere contributes 6 $s^{\frac{1}{2}}$ at latitude 55° and Rivault and Corcuff (1960), for latitude 49°, estimate a change in the ionospheric contribution from 13 $s^{\frac{1}{2}}$ to 5 $s^{\frac{1}{2}}$ from late afternoon to the time of minimum f_0F_2. while at latitude 24° this change has been estimated to be from 25 $s^{\frac{1}{2}}$ to 10 $s^{\frac{1}{2}}$ (Iwai and Outsu 1958). While it is possible that the diurnal variation of dispersion is due to ionospheric changes, particularly if a corresponding change occurs over the whole whistler path, there may be other factors involved also. An average movement of ionospheric sources towards the equator from afternoon to about 0200 or 0300 (local) and then a return polewards would give a similar effect. Such a movement would be in accord with Brisbane seeing a maximum in whistler occurrence about 0200 local. Also, examination of the diurnal variation of the number of schedules per month containing whistlers (as distinct from the average number of whistlers per schedule) shows two distinct maxima about 0500 and 2000 for Adelaide in September 1957 and June 1958, the two months with the maximum number of whistlers, and suggestions of this phenomenon in some other months. There is also some evidence (Matthew 1961) of field-aligned columns of ionization moving predominantly towards the equator before midnight and predominantly towards the poles in the early hours of the morning.

The connection between magnetic disturbance and dispersion 1–3 days later, as mentioned earlier, has been explained as a decrease in latitude of the whistler path or a change in electron density in the magnetosphere. It is known that the occurrence of whistlers increases at latitude 24° (Outsu and Iwai 1962) and decreases at high latitudes at magnetically-disturbed times (Allcock and Rodgers 1961; Laaspere, Morgan, and Johnson 1963), and a similar shift of the occurrence of chorus was noted by Crouchley and Brice (1959) but without any time delay being detected and with the association with K-Macquarie Island being stronger than with K_p as reported for D. In this, as in all other aspects of the study of dispersion, an accurate knowledge of the position of the ionospheric source, preferably by some experimental method, is greatly needed. This lack of knowledge may also explain the lack of evidence of association between D and R_Z, as Allcock and Morgan's (1958) measurements were made upon long whistlers, which predominantly occur at higher latitudes than Adelaide, while the Adelaide measurements were made mainly on short whistlers.

XIII. Conclusions

The dispersion of whistlers recorded at a particular station varies, from time to time, by about ± 20 $s^{\frac{1}{2}}$ from the modal value of dispersion. Some of the variation is due to diurnal and seasonal changes in dispersion and some to a receiver being able to observe whistlers which have emerged from the ionosphere over a latitude range of 10° to 20°. The correlation observed between dispersion and f_0F_2 at middle latitude stations is probably due to ionospheric sources being, on the average, some degrees nearer to the equator when f_0F_2 is low, and the annual variation in dispersion is, in part, due to the same cause. However, there are annual changes in dispersion, with Adelaide and Hobart having a higher dispersion at the beginning than at the middle of the year and conversely for Brisbane, which are not explicable in this manner. No significant correlation was detected between dispersion and Relative Sunspot Number.

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