A STUDY OF WHISTLING ATMOSPHERICS

IV. COMPARISON OF OBSERVATIONS AT WIDELY SPACED STATIONS

By J. CROUCHLEY*

[*Manuscript received August* 5, 1963]

Summary

Whistlers observed at stations separated from one another by up to 3000 km are examined statistically and by comparing simultaneous whistlers. It is shown that whistlers are not commonly observed further than 1000 km away from their "ionospheric source", i.e. the limited region through which they emerge from the ionosphere, and that a lightning stroke may produce whistlers with different dispersions at stations with a separation of this order of magnitude. Ionospheric sources are most common around (geomagnetic) latitude 44–46° in winter and around latitude 50–52° in summer (southern hemisphere). It is suggested that this change is related to changes in the electron density of the ionosphere.

I. INTRODUCTION

A comparison of whistlers recorded at four stations, each separated from its nearest neighbour by about 100 km (Crouchley and Duff 1962), showed that the four stations observe the same dispersion for a whistler excited by a particular lightning flash and that there may be an appreciable change in the subjective strength, i.e. as judged by ear, of a whistler over a distance of 300 km. These results and the diffuseness of the whistlers (Crouchley and Finn 1961) suggested that the energy was spreading out from a nearby region, the size of which varied, from night to night, from a few tens of kilometres to about 200 kilometres. This region was termed the "ionospheric source". This paper extends the previous work to station spacings of up to 3000 km.

II. COMPARATIVE OCCURRENCE STATISTICS

(a) Correlation and Station Spacing

It is well known that the number of whistlers observed at a station varies very considerably from day to day (e.g. Crouchley 1961) and that there is some correlation between the numbers of whistlers received each day at separated stations. Figure 1 shows a plot of the correlation coefficient r between daily total numbers of whistlers observed at pairs of stations with spacing up to 3000 km. The data for the three most closely spaced stations were taken from the records obtained during 1960 (southern-hemisphere) winter by Crouchley and Duff (1962), whereas the rest of the data were obtained from IGY records for southern-hemisphere winter 1958 except that for Toyokawa–Wakkanai, which was obtained from the summer of 1957–1958.† Between 50 and 120 pairs of values were used for the calculations and the standard errors of the correlation coefficients are shown by means of the vertical

* Physics Department, University of Queensland, Brisbane.

† New Zealand data kindly supplied by G. McK. Allcock and Japanese data kindly supplied by Professor A. Kimpara.

bars. It is clear that the correlation between stations decreases as the separation increases and has reached a small value for separation of 2000 km. The circles shown in Figure 1 refer to the data of Section III (*a*) and the curve, as explained in Section IV, is derived on the basis of a whistler having a maximum range of 1000 km.

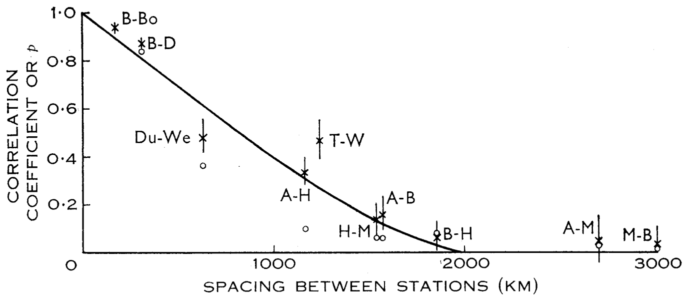


Fig. 1.—Showing the decrease in correlation between daily total whistler occurrence figures as station separation increases. Circles (○) refer to normalized coincidence probabilities (Section III(*a*)) and the full line is the fractional area common to two stations assuming 1000 km effective radius (Section IV). (A, Adelaide; B, Brisbane; Bo, Bonalbo; D, Dorrigo; Du, Dunedin; H, Hobart; M, Macquarie Island; T, Toyokawa; W, Wakkanai; We, Wellington.)

(*b*) *Whistler Occurrence and Latitude*

The graph showing the occurrence of whistlers as a function of geomagnetic latitude (Crouchley 1961) shows a very considerable change in the yearly average

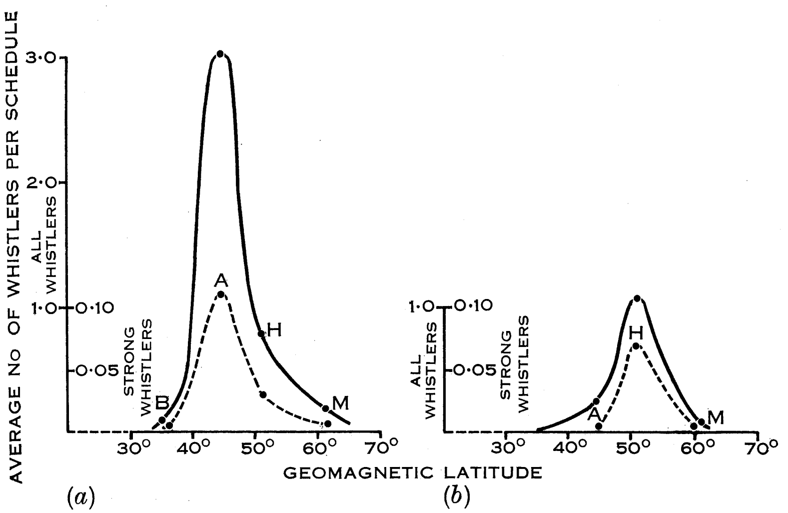


Fig. 2.—Average rate of whistler occurrence versus geomagnetic latitude (—— all whistlers, – – – – "strong" whistlers). (*a*) for winter months; (*b*) for summer months.

occurrence of whistlers for a 9° (i.e. 1000 km) change of latitude. If similar plots are made for winter and summer months separately, a similar result is obtained but the region of maximum occurrence of whistlers is seen to shift by some degrees. Figure 2(*a*) shows a plot of the average number of whistlers received per schedule

(2-min recording period) at Brisbane, Adelaide, Hobart, and Macquarie Island for June, July, August 1958 (winter months) and Figure 2(*b*) shows a similar plot for summer months (November, December 1957, January 1958). In each case the full line represents an estimate of the latitude variation of the occurrence of whistlers of all strengths while the dotted line is the corresponding curve for whistlers of subjective strength greater than two. Experience with closely spaced stations shows that most whistlers travel at least 300 km, i.e. 3° of latitude. Accordingly, the smooth curves, though drawn through only a few points, should be a correct indication of the shift, with season, of the region of maximum whistler occurrence. It is assumed in drawing these curves that there is not a sudden large change with longitude near any of the stations. Figure 3 shows a plot of the percentage of schedules in which

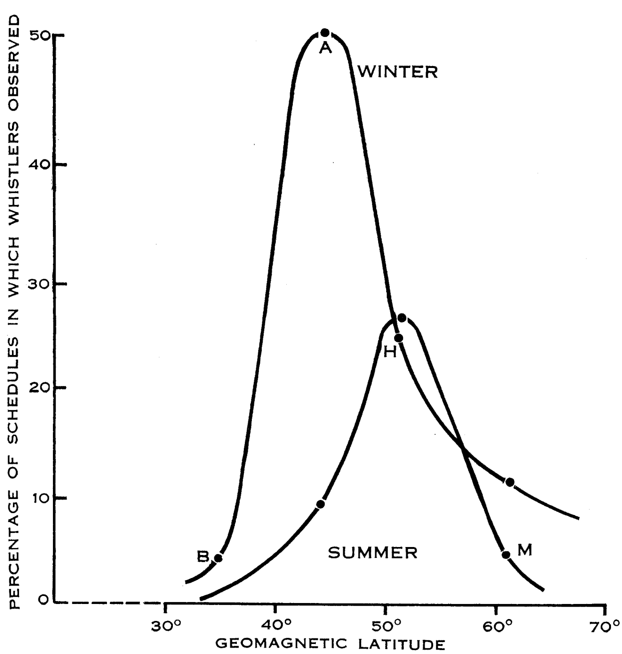


Fig. 3.—Average percentage of schedules in which whistlers were received (for summer and winter months) versus geomagnetic latitude.

whistlers were observed. For this plot the observation of only one whistler in a schedule allowed it to be counted and thus the totals would be expected to be much less influenced by the number of lightning strokes occurring. A similar shift of the peak of the curve with season is apparent.

III. Simultaneous Observations

The correlation in whistler occurrence between spaced stations may be due to (i) individual whistlers being heard simultaneously at different stations or (ii) to some external factor common to two or more stations, e.g. a complete absence of lightning strokes over a large region, or to a combination of both effects. The first possibility is examined in this section.

(a) *Statistical*

Comparison of the original record sheets for pairs of stations shows that many whistlers were sometimes reported as occurring nearly simultaneously at both stations. As many whistlers lasted about a second the time of occurrence was only reported to the nearest second. Accordingly, whistlers which were reported as occurring within 2 s were counted as simultaneous for the purposes of this comparison. Some of these coincidences might be expected to occur by chance, particularly if both stations are observing whistlers at intervals of a few seconds. An estimate of the number of chance coincidences may be made in the following way. The recording schedule of 120 s may be considered to be composed of 30 periods of 4 s each, and thus

Table 1

OCCURRENCE FIGURES FOR SIMULTANEOUS WHISTLERS

Abbreviations of place names as for Figure 1

<table>
<tr><td>Period</td><td colspan="6">Winter 1958</td><td colspan="2">Winter 1960</td></tr>
<tr><td>Number of whistlers</td><td colspan="2">B</td><td colspan="1">A</td><td colspan="2">H</td><td colspan="1">M</td><td>B</td><td>D</td></tr>
<tr><td>observed (x_i)</td><td colspan="2">226</td><td colspan="1">5096</td><td colspan="2">1481</td><td colspan="1">513</td><td>418</td><td>467</td></tr>
<tr><td>Station pairs</td><td>A–B</td><td>A–H</td><td>A–M</td><td>B–H</td><td>B–M</td><td>H–M</td><td colspan="2">B–D</td></tr>
<tr><td>Apparent No. of coincidences (s)</td><td>84</td><td>528</td><td>78</td><td>59</td><td>6</td><td>75</td><td colspan="2">391</td></tr>
<tr><td>Number of chance coincidences (c)</td><td>25</td><td>250</td><td>30</td><td>8</td><td>1</td><td>20</td><td colspan="2">23</td></tr>
<tr><td>s/c</td><td>3·4</td><td>2·1</td><td>2·6</td><td>7·4</td><td>6·0</td><td>3·8</td><td colspan="2">16·0</td></tr>
<tr><td>$p = (s-c)/(x_i x_j)^{\frac{1}{2}}$</td><td>0·06</td><td>0·10</td><td>0·03</td><td>0·08</td><td>0·01</td><td>0·06</td><td colspan="2">0·84</td></tr>
</table>

the arrival of x whistlers at station A in a schedule gives a probability of $x/30$ of a particular period being occupied. An independent whistler arriving at station B in the same period has thus a chance of $x/30$ of appearing simultaneously and y such whistlers have $xy/30$ chances of being counted as simultaneous. Table 1 shows the results obtained.

Since the number of whistlers recorded varied markedly from station to station, the estimated number of true coincidences for a given pair of stations has been normalized by dividing by the geometric mean of the numbers of whistlers observed at these stations. This quantity, which has been denoted by the symbol p in Table 1, is plotted in Figure 1 (small circles) against station separation. Its variation with distance is similar to that of the correlation coefficients.

(b) *Detailed Comparison of Simultaneous Whistlers*

Although it commonly happens that apparently simultaneous whistlers are very weak at one or more of the stations, it has been possible to prepare satisfactory sonagrams for several occasions on which whistlers appeared simultaneously, as judged by the criterion of Section III(a). For this purpose initial timing was made by means of the timing seconds pips from the tapes and accurate timing was achieved by the comparison of spherics on the sonagrams. This was usually fairly easy to do between Adelaide and Brisbane but more difficult with either of these stations and Hobart. Table 2 shows the values of dispersion at the different stations as measured by means of a graticule. In most cases it was possible to locate the initiating spheric on all traces but, even when this was not possible, the differences of dispersion should be reasonably accurate, for a spheric which was observed at all stations was then used as a reference point. Some whistlers showed only a single trace while others showed several traces or covered a range of dispersion. The various dispersion values shown in the table for a particular whistler thus refer to individual traces or to the dispersion range.

A study of these figures reveals some similarities and differences. On some occasions it was possible for a whistler to be received simultaneously at two or more stations with the same mean dispersion but different strengths and somewhat different diffuseness, e.g. September 4, 1957 and September 17, 1957 (Plate 1). However, on other occasions, the same initiating discharge caused whistlers with slightly, but definitely, different times of occurrence and dispersion at two different stations, or sonagrams from one station showed traces which were not present at the other station, e.g. June 24, 1958, 0135 and July 1, 1958, 0135.

The results for June 23–24, 1958, are particularly interesting. On some sonagrams Brisbane showed a whistler which had one or two fine traces with a lower dispersion than that for Adelaide. On other occasions the Brisbane whistlers were less diffuse but of a similar dispersion to those at Adelaide or showed a fine trace of lower dispersion and also a more diffuse part which coincided with part of the Adelaide whistler. These two parts were sometimes energized simultaneously by the same spheric (e.g. 0235 : 71, Plate 2, Brisbane and Adelaide) or sometimes independently by different spherics (0235 : 73, Brisbane only; 0235 : 75, Adelaide only). The whistlers observed at Adelaide and Brisbane were below the threshold of audibility at Hobart, but this station, quite independently, also received some whistlers (0135 : 13 and 0135 : 31) of similar dispersion and also a whistler of about twice the short whistler dispersion (0235 : 77). This latter whistler was not preceded by a clear-cut initiating spheric.

Usually, but not invariably, a higher latitude station did not show traces of lower dispersion than those shown by the lower latitude station but it commonly showed higher dispersion traces not shown by the lower latitude station. The data of September 16, 1958, (Table 2) show a clear example of this point. Furthermore a $3\times$ and $5\times$ echo was received at Adelaide on only the part of the trace showing a dispersion of 70–90 $s^{\frac{1}{2}}$ and a faint unmeasurable $3\times$ echo was observed at Hobart.

There is evidence of a diurnal variation of dispersion in the results for June 23, 1958, and June 24, 1958. This point will be discussed in further detail in Part V of this series of papers (Crouchley 1964).

TABLE 2

COMPARISON OF SIMULTANEOUS WHISTLERS

The numbers in the boxes are the measured dispersion D in $s^{\frac{1}{2}}$. Bold type indicates a strong component

Date	Time (E.S.T.)	Brisbane	Adelaide	Hobart	Comments
4.ix.57	0235 : 27	Five traces 45	No record	Two traces 45	Same dispersion
14.ix.57	2235 : 11	45, (8–6 kc/s) Fine trace	40–45, 55–65, 80–90, 255 (i.e. 3×85)	None from this spheric	Different D and $3\times$ echo at Adelaide
17.ix.57	1735 : 114	Probably same dispersion at all stations but diffuse; Brisbane has smaller diffuseness, D about 100			
	1935 : 70	Not available	63, 68, 70–80	60–80	Common components
23.vi.58	2235 : 48	52 and 54	Faint 52, 60–70	No whistler	
	2235 : 29	Faint 50, 57–60	57–66 (no 50)	No whistler	
24.vi.58	0135 : 13	No whistler	No whistler	55	
	0135 : 25	49, 51, 60 (very faint)	54–68	No whistler	
	0135 : 31	No whistler	No whistler	55	
	0135 : 59	49, 52	53–68	very faint	
	0135 : 90	49, 51	52–68	No whistler	
	0135 : 115	48, 51 (?)	57–63	No whistler	
	0235 : 06	50, 56–58	50–60	No whistler	
	0235 : 20	50–58	53–70 (?80)	No whistler	
	0235 : 71	50–52, 54–57 (below 4 kc/s)	52–62	No whistler	
	0235 : 73	50	No whistler	No whistler	
	0235 : 75	No whistler	55–60	Extremely faint	
	0235 : 77	No whistler	No whistler	about 110	
	0235 : 91	48–51 and 55 (below 5 kc/s)	50–60	No whistler	
	0235 : 92	50, 55 (below 5 kc/s)	52–**55**–58	No whistler	
	0235 : 94	No whistler	No whistler	about 60	
	0335 : 66	51–59	49–60	No whistler	
	0335 : 102	50–58	54–64	No whistler	
	0535 : 11	53–60	55–**60**–70		
	0535 : 54	53, 59	57–**59**–63, 70	No whistler	

TABLE 2 (*Continued*)

Date	Time (E.S.T.)	Brisbane	Adelaide	Hobart	Comments
1.vii.58	0035 : 15	43	Does not sonograph	No whistler	
	0135 : 56	43–46 (faint), 70 (faint)	50–60 (faint) 65–**70**–75, 80 (faint)	No whistler	
	0135 : 113	42–44	50–**58**–60, 80 (faint)	No whistler	
18.vii.58	0035 : 90	45–**50**–55	**50**, 56, **80**, 150–160	50, 80	Echo at A
27.vii.58	0035 : 18	54–58	35 (very faint), 58–65	No whistler	
16.ix.58	2135 : 99	58–68	60–90, 210–280 i.e. $3\times(70–93)$, 360–470, i.e. $5\times(72–94)$	70–105 and faint unmeasurable $3\times$echo	

IV. DISCUSSION

Since there is usually no detailed knowledge of the values of many of the quantities that might be expected to influence the area on the surface of the ground over which a whistler may be heard, it is only possible to discuss the experimental results in broad terms. Thus the position and intensity of the initiating lightning stroke, the exospheric path, ionospheric parameters at appropriate places, and ionospheric source positions would be expected to be of considerable importance but are usually unknown. While the range is probably a very variable quantity it is necessary to make some working estimate if dispersion and other data are to be interpreted or if a suitable station spacing for future investigations is to be decided upon.

The decrease in correlation between the daily occurrence totals as the separation between two stations increases shows that the observations are almost independent when this spacing is 2000 km, and likewise the ratio of the number of simultaneous whistlers to the geometric mean of the numbers of whistlers observed at the two stations is very small for 2000 km spacing. (Since this ratio is a rough measure of how occurrence at station A affects occurrence at station B, it is probably better to compare it with the square of the correlation coefficient which measures how the variations at A influence the variations at B. This does not materially effect the overall picture.) The reporting of very weak whistlers is, of necessity, not very accurate as they are usually almost inaudible in the background noise, and thus the numbers of concident whistlers listed in Section III (*a*) may be an underestimate. However, it is shown in Section III (*b*) that there is sometimes a difference of dispersion between whistlers produced at different stations by the same lightning flash, and accordingly these should not be counted as simultaneous whistlers when attempting to estimate the average range. Thus a more exact analysis would require a detailed examination of every whistler, but this would be an almost impossible task and probably pointless unless the other variables were also known.

If, as discussed below, it is assumed that energy is radiated uniformly over a hemisphere from an ionospheric source and propagation conditions are uniform in all directions, then coincident whistlers are most likely to be heard at two widely-spaced stations if the ionospheric source is midway between the two stations. If, under these conditions, the station spacing is greater than the diameter of the area illuminated by the ionospheric source it will not be heard at either. Thus 1000 km is an approximate estimate of the radius of the area illuminated by an ionospheric source and of the maximum distance at which most whistlers may be observed from their ionospheric source. Likewise, a station is unlikely to observe most of the whistlers emerging from an ionospheric source if that source is at a ground range of more than 1000 km. Since there is certainly a range of intensities of lightning flashes which will give rise to whistlers, the discussion above does not preclude the possibility of the occasional very intense flash giving rise to a whistler which is heard over much greater distances nor does it preclude the possibility of particularly favourable propagation conditions either in a particular direction or in general giving rise to larger ground ranges. Since ionospheric sources are believed to have dimensions of up to at least 200 km this estimate is uncertain by at least this amount.

TABLE 3

COMPARISON OF OBSERVED AND ESTIMATED NUMBERS OF COINCIDENT WHISTLERS

	A–B	A–H	A–M	B–H	B–M	H–M
Observed minus chance coincidences	59	278	48	47	5	55
1000 km range and total No. of whistlers	275	1110	0	165	0	91
1000 km range and No. of strong whistlers	85	460	0	69	0	28

Assuming, as above, that a whistler station can observe whistlers if the ionospheric source is at a maximum range of 1000 km, then one may calculate how much of the area which a given station observes is also within range of another station a known distance away. The ratio of this common area to the area observed by either station is shown by the curve of Figure 1. It is now possible to test approximately the consistency of this estimate of 1000 km with the data of Sections II (*b*) and III (*a*) by using the curve of Figure 1, the latitude variation of Figure 2, and the known position of the stations to estimate how many coincident whistlers would be expected to occur between the station pairs. This may be done by assuming that all whistlers have a range of 1000 km and thus obtaining from the latitude variation graph the number of whistlers occurring per unit area at the mean latitude of the area common to the two stations and thus the number occurring in this common area. The numbers so obtained are shown in the second row of Table 3. Another approach is to use the latitude variation in the occurrence of strong whistlers, for these are most likely to travel greater distances. To calculate the number of strong whistlers per unit area it is then necessary to decide how far away an ionospheric source may be from a station and still produce whistlers which are classed as strong. A distance of 300 km seems reasonable, as judged from the closely-spaced station observations (Crouchley and Duff 1962), for this purpose. The numbers so obtained are shown in the third row of Table 3.

Assuming that all whistlers have a range of 1000 km leads to numbers which are several times too large (except for Macquarie Island) whereas the assumption that only strong whistlers travel this far gives numbers which are more nearly in agreement with those observed. Helliwell and Carpenter (1961) consider that a whistler of average strength has a range of 500 km. Since the quantities involved in the calculations are only approximately known the agreement may be considered satisfactory except for Macquarie Island. However, lightning is very rarely observed at high latitudes and thus the interference to observation from this source is considerably reduced. It is likely that the effective radius depends on the latitude of the ionospheric source and that whistlers spread further at higher than at middle or low latitudes. Various workers (e.g. Allcock 1960) have suggested that whistlers received at high latitudes have propagated to these regions from middle latitudes. The effective radius may also depend for large distances on the direction of propagation (e.g. Martin 1961).

While the calculation of the field strength as a function of distance from a small source located in the ionosphere above a reflecting ground is essentially a full-wave problem at the frequencies involved, it nevertheless seems worth while making a simple estimate based on a uniform hemispherical radiator and the inverse-square law. The assumption of a uniform radiator seems a reasonable one, for at 5 kc/s the free-space wavelength is 60 km and energy is believed to emerge from ionospheric sources that commonly have a size of 100–200 km. Furthermore, the discrete traces observed in many whistlers suggest that such a source is made up of a collection of much smaller regions. The attenuations, so calculated, at surface distances of 100, 500, and 1000 km, as compared to that on the ground immediately below the source for each height are shown in Table 4.

To adjust these values to a common reference level, namely, on the ground immediately below a source 50 km above, amounts of 6, 12, and 24 dB must be added to the 100, 200, and 800 km height values respectively. The value for a height of 50 km and range of 1000 km has been omitted because a station observing under such conditions would be beyond the region directly illuminated by the source, i.e. beyond "line-of-sight" propagation. Estimates made by means of stepped-gain sonagrams show that the difference in strength between "weak" and "strong" whistlers is about 15–20 dB, although this range is doubtless exceeded if very weak and the occasional very strong whistlers are compared. Iwai and Outsu (1958) suggest a maximum spread in strength of about 22 dB. The figures of Table 4 suggest that the height of the source above the ground will have a very considerable influence not only on the strength immediately below but also on the range. A very high source would, on this model, produce relatively weak whistlers of roughly constant strength over a wide range while a very low source would produce whistlers which exhibited large changes in strength in a few hundred kilometres. Since some of the 20 dB variation observed in practice must be due to variations in the intensity of the lightning discharge, a source height of between 100 and 300 km would seem most likely and such a height would still give rise to a significant change in strength over 300 km as reported by Crouchley and Duff (1962). Also it is known that field-aligned columns of ionization commonly exist in the *F* region (Thomas *et al.* 1962) at latitudes where whistlers occur and that the height of the bottom of the *F* region at night is commonly 200–300 km. Similar calculations indicate that a suitably positioned lightning stroke may illuminate a region of the ionosphere large enough to excite whistlers that emerge simultaneously from ionospheric sources separated by a distance of the order of 1000 km. Furthermore, Swift (1963) has shown, by a full-wave treatment and a "step" model of the lower ionosphere, that the attenuation in passing through the ionosphere is not markedly dependent on the angle of incidence. However, Maeda and Oya (1962) show that the penetration is greatest at large angles of incidence if a sharp-boundary model is used. Table 2 shows examples of whistlers which have been observed at widely separated stations by spreading from one ionospheric source (Plate 1) and also of occasions when the same lightning flash has generated whistlers with different dispersion components at such stations. This latter phenomenon is probably due to the existence of two or more widely spaced ionospheric sources.

TABLE 4

ESTIMATES OF ATTENUATION WITH DISTANCE FOR VARIOUS "IONOSPHERIC-SOURCE" HEIGHTS

Height (km)	Distance (km)			
	0	100	500	1000
50	0 dB	7 dB	20 dB	—
100	0 dB	4 dB	15 dB	21 dB
200	0 dB	2 dB	9 dB	14 dB
800	0 dB	0 dB	2 dB	5 dB

The information presented above makes it possible to decide on a suitable value for the spacing between whistler recording stations. Since on the average about 80% of the whistlers which are observed at two stations 300 km apart are common to both stations, then whistlers emerging from an ionospheric source located between stations with double this spacing have a probability of about 0·8 of being observed at one or other station. Increasing this spacing to 1000 km roughly halves this probability of observation. A station spacing of 600–800 km is a reasonable compromise, with the smaller value being desirable around middle latitudes where there are marked changes in the occurrence of whistlers with both latitude and season.

Since the occurrence of whistlers depends on the presence of both suitable lightning strokes and suitable propagation conditions, then both of these factors may contribute to the shift, with season, of the latitude of maximum whistler occurrence. However, such meteorological data as are available (Haurwitz and Austin 1944; Kimpara 1955; WMO/OMM 1956) makes it appear unlikely that the ratio of the frequency of occurrence of lightning at the latitude of Adelaide to that at the latitude of Hobart (or their conjugate points) would have been about three to one in winter and one to four in summer. It thus appears likely that ionospheric sources are, on the average, some 5° or 6° further from the equator in summer than in winter.

There are certain similarities in the occurrence and properties of whistlers and spread-F which suggest that the two phenomena may be related. Their seasonal and diurnal variations are similar at Brisbane and Adelaide, the diffuseness of whistlers observed at Hobart is greater when spread-F is also observed (Crouchley and Finn 1961), and the duct and column sizes suggested by these authors are similar to the patch and column size of field-aligned columns observed in the ionosphere in association with spread-F (Singleton and Lynch 1962). Singleton (1961) has also compared the enhancement of electron density ($\Delta N/N$) observed in spread-F with that required to sustain guiding in field-aligned ducts (Smith, Helliwell, and Yabroff 1960). His work suggests that, in winter-time, any enhancements observed above latitude 50° are adequate to support propagation and that only the maximum enhancement is adequate at latitude 30°. Between these two limits a fraction, decreasing with decrease in latitude, of the enhancements occurring may serve as a guide for whistlers and below 30° no observed enhancement is sufficient for this purpose. Further if, as suggested by the same author (Singleton 1962), ΔN, though rather variable, does not change markedly with season, then the above latitude limits of 30° and 50° would be expected to be increased by about 8–10° in local summer due to the larger values of f_0F_2 and corresponding larger values of N at this time of the year. Also the occurrence of spread-F is greater at latitude 50° than at latitude 30°. Thus a station such as Adelaide (latitude 45°), which is near to one limit (higher probability of occurrence) in winter, is near to the other in summer and might be expected to show correspondingly large changes in whistler occurrence. These changes would be expected to be smaller at Hobart and be to some extent cancelled by a marked increase in the occurrence of long whistlers (local lightning sources) in summer. If the occurrence of ionospheric sources is related, on the average, to the value of f_0F_2, then a station such as Adelaide might be expected to show a negative correlation between whistler occurrence and f_0F_2. For monthly median midnight f_0F_2 at Canberra (the nearest ionosonde) and monthly average whistler rate at Adelaide the correlation coefficient is $-0\cdot75$ (1% level is $0\cdot62$) and for f_0F_2 and the percentage of schedules containing whistlers it is also $-0\cdot75$. However, it should be pointed out that the general seasonal variation of spherics in the northern hemisphere (i.e. sources of short whistlers) might, though unrelated, be expected to vary in roughly the opposite way to f_0F_2 at Canberra.

Carpenter (1962) has shown, from nose whistler data, that whistlers received at Stanford (43·7°N. geomagnetic) had paths with end-points at, on the average, 54°N. in January 1958 and 49°N. in June 1958. A similar but smaller variation was also reported for Seattle (54°N.). This shift of path end-point is thus of similar magnitude and in the same direction at the same time of the year (i.e. polewards in January) in both hemispheres. Likewise, monthly median values of f_0F_2 at local midnight for San Francisco (near to Stanford) and Victoria (near to Seattle) vary in a similar fashion through the year as those for Canberra and Hobart.

A general shift of ionospheric sources as discussed above might be expected to change the average dispersion of whistlers received. This matter will be discussed in the following paper (Part V, Crouchley 1964).

There is no direct experimental evidence about the nature of ionospheric sources. They may be the ends of magneto-ionic ducts stretching from the lower parts of the ionosphere in one hemisphere along a magnetic field line to a corresponding position in the other hemisphere. Alternatively, they may be groups of field-aligned columns of ionization stretching only a few hundred kilometres through the F region. Smith (1961) advances evidence for the existence of magneto-ionic ducts, but experiments at Brisbane (Thomas, McInnes, and Crouchley 1963) have failed to obtain evidence of duct guiding at 16 and 55 Mc/s. Observations of whistlers at two closely conjugate stations might help to elucidate this question.

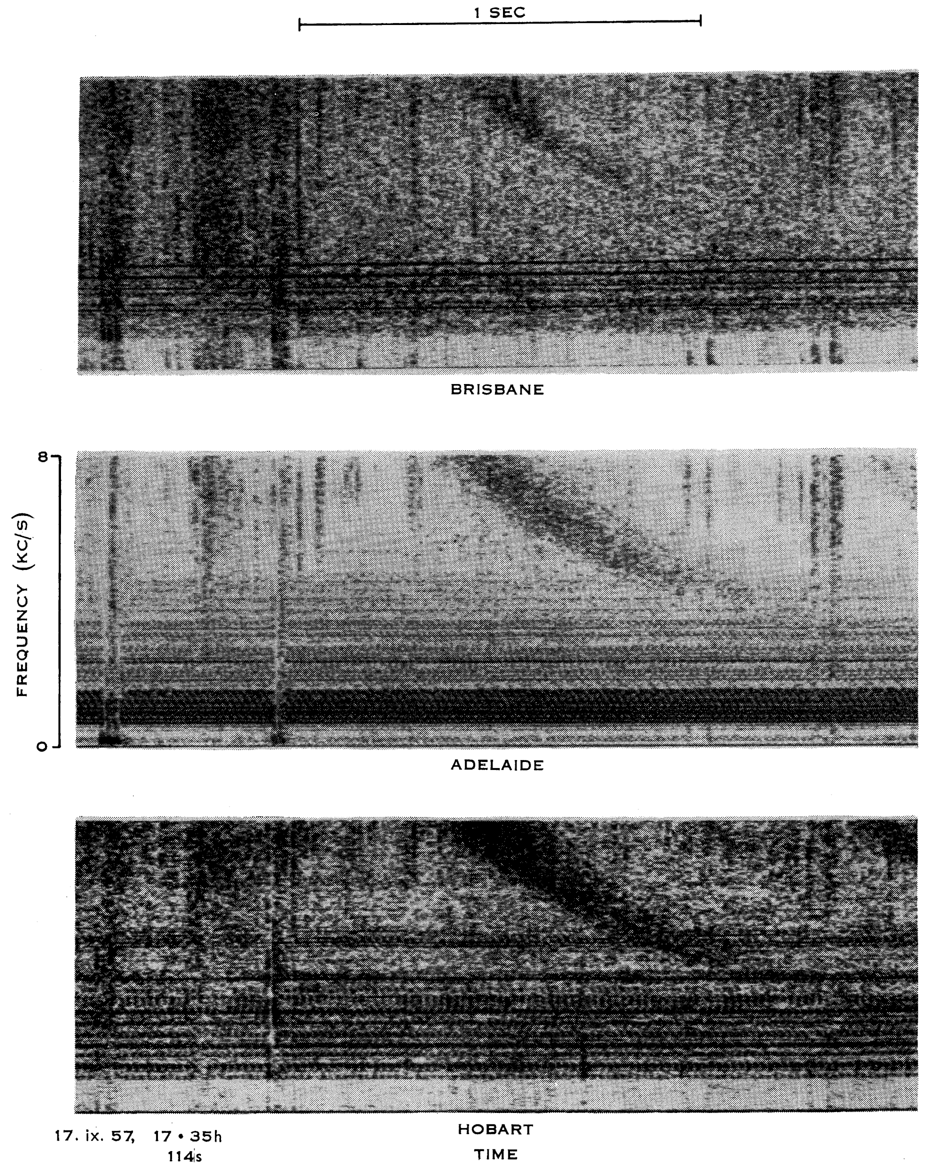
V. Conclusions

While the surface range of a whistler is a very variable quantity a whistler recording station does not commonly receive whistlers that have emerged from an ionospheric source more than 1000 km away. Accordingly, a station spacing of less than this amount is necessary to investigate adequately the behaviour of whistlers over a region. A spacing of 600–800 km is desirable. Ionospheric sources are most probably located below 300 km height and this height influences the way in which the strength of the whistler changes with distance. A single lightning flash may illuminate exospheric paths terminating in widely spaced ionospheric sources and thus give rise to whistlers of different dispersions at different stations. Ionospheric sources occur most commonly at geomagnetic latitudes 44–46° in winter and at 50–52° in summer (southern hemisphere). This change may be associated with changes in electron density in the ionosphere.

VI. Acknowledgments

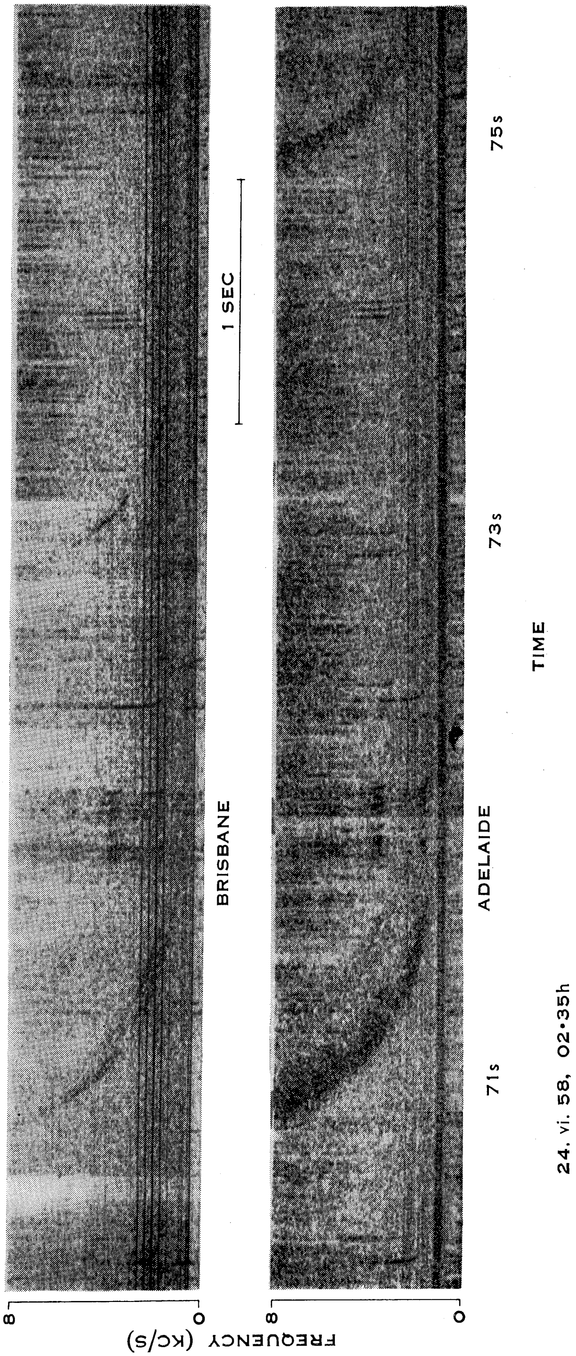
Whistler recording at distant stations was only possible by virtue of the various organizations named in Part I of this series of papers (Crouchley 1961). The assistance of these organizations is gratefully acknowledged. Miss B. Ross ably prepared many of the sonagrams used and assisted with the numerical computations. Recording and analysis of the records would not have been possible but for the financial assistance of the Australian National Committee for the IGY, of the Radio Research Board of CSIRO, and of the University of Queensland. Ionospheric data were kindly supplied by the Ionospheric Prediction Service of the Department of the Interior. It is a pleasure to acknowledge the interest and assistance of Professor H. C. Webster.

STUDY OF WHISTLING ATMOSPHERICS. IV



An example of a whistler which emerged from one ionospheric source and spread to widely spaced stations.

STUDY OF WHISTLING ATMOSPHERICS. IV



An example of the occurrence of two independent ionospheric sources which were sometimes energized simultaneously (e.g. 71s) and sometimes independently (e.g. 73s and 75s).

VII. References

Allcock, G. McK. (1960).—*Nature* **188**: 732.

Carpenter, D. L. (1962).—Technical Report No. 11, P. 16, Radioscience Laboratory, Stanford University.

Crouchley, J. (1961).—*Aust. J. Phys.* **14**: 22.

Crouchley, J. (1964).—*Aust. J. Phys.* **17**: 88.

Crouchley, J., and Duff, K. J. (1962).—*Aust. J. Phys.* **15**: 470.

Crouchley, J., and Finn, R. J. (1961).—*Aust. J. Phys.* **14**: 40.

Haurwitz, B., and Austin, J. M. (1944).—"Climatology." Plates 14 and 15. (McGraw-Hill: New York.)

Helliwell, R. A., and Carpenter, D. L. (1961).—Whistlers–West IGY-IGC, Final Report, p. 28, Radioscience Laboratory, Stanford University.

Iwai, A., and Outsu, J. (1958).—*Proc. Res. Inst. Atmos., Nagoya Univ.* **5**: 50.

Kimpara, A. (1955).—*Proc. Res. Inst. Atmos., Nagoya Univ.* **3**: 1.

Maeda, K., and Oya, H. (1962).—Proc. Int. Conf. on Ionosphere. p. 461 (Inst. Phys. and Phys. Soc.: London.)

Martin, A. G. (1961).—*J. Atmos. Terr. Phys.* **20**: 207.

Singleton, D. G. (1961).—*Nature* **189**: 215.

Singleton, D. G. (1962).—*Aust. J. Phys.* **15**: 242.

Singleton, D. G., and Lynch, G. J. E. (1962).—*J. Atmos. Terr. Phys.* **24**: 363.

Smith, R. L. (1961).—*J. Geophys. Res.* **66**: 3699.

Smith, R. L., Helliwell, R. A., and Yabroff, I. W. (1960).—*J. Geophys. Res.* **65**: 815.

Swift, D. W. (1963).—*J. Res. Nat. Bur. Stand.* **66D**: 663.

Thomas, J. A., et al. (1962).—Scientific Report No. 16, Radio Research Section, Physics Dept., University of Queensland.

Thomas, J. A., McInnes, B. A. and Crouchley, J. (1963).—*J. Atmos. Terr. Phys.* (in press.)

WMO/OMM (1956).—World distribution of thunderstorm days, No. 21. T.P. 21, World Meteorological Organization, Geneva.