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Electron-Density Variations in the Magnetosphere Deduced from Whistler Data

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Abstract. Electron-density variations in the magnetosphere at a geocentric distance of 2 to 4 earth radii are deduced from whistler observations made, primarily, at Stanford, California, and Seattle, Washington. The whistler quantities scaled are frequency and group delay at the whistler nose and group delay at 5 kc. Depressions in electron density are found to be associated with severe magnetic storms ($K_p \geq 6$) in both 1958 and 1961. Typical depressions exhibit density levels about 15 to 20 per cent below average levels. The annual variation, with a minimum near the June solstice, is observed in every year from 1958 to 1961. The ratio of June to January density levels is about 0.66 in 1958 and 0.81 in 1961. This variation is discussed as a possible indicator of a systematic variation in the physical environment of the earth along its orbit. The secular variation shows a 20 to 25 per cent reduction in electron density from early 1958 to early 1961. There is some evidence that the larger part of the observed reduction occurs near the December solstice, when the annual variation shows a maximum. Secular and annual variations are found in the latitude of the field-line-path endpoint of typical Stanford whistlers. From 1958 to 1961 the average latitude moves slowly equatorward through about 1° while remaining several degrees on the poleward side of Stanford. The annual variation shows an equatorward movement from January to June through 4° or 5°. As a matter of methodology, it is found that a limited quantity of data on frequency and group delay at the whistler nose can be used to remove path ambiguities from more easily obtained single-frequency group-delay data (which include whistler-mode echoes from pulse transmissions). When this is done, important information can be obtained on whistler propagation, and the group-delay data can then be used directly in the study of magnetospheric density variations.

INTRODUCTION

This is a report on variations in electron density in the magnetosphere, particular attention being devoted to the secular and annual variations. The region of the magnetosphere described by the measurements extends in the geomagnetic equatorial plane to a geocentric distance ranging from 2 to 4 earth radii. The results on electron density are deduced from whistler-dispersion data over the period from July 1957 to November 1961. An important feature of the analysis is a comparison of the January–June period of 1958 with the same period in 1961.

The data confirm and extend the picture of the annual density variation reported by *Helliwell* [1961] and *Smith* [1961*a*]. Considerations of path ambiguity in single-frequency group-delay data lead to a surprising annual variation in the path latitude of Stanford whistlers.

NATURE OF THE DATA AND METHODS OF ANALYSIS

Whistlers as a means of studying density variations. A whistler is produced by VLF energy that originates in a lightning flash and propagates between the hemispheres along a dispersive path following approximately the lines of force of the earth's magnetic field. Spectrographic records of several well-defined examples of this phenomenon are illustrated in Figure 1. The record of September 26, 1960, shows a whistler with a single component. An arrow marks the causative atmospheric, the essentially undispersed energy that propagates at approximately the speed of light in the earth-ionosphere wave guide from the lightning flash to the receiver. The record of June 7, 1959, illustrates two closely spaced, multicomponent whistlers. Several of the traces exhibit an observable 'nose,' a frequency of minimum group delay.

The whistler group-delay integral is usually written

$$t = \frac{1}{2c} \int_{\text{path}} \frac{f_0 f_H \, ds}{f^{1/2}(f_H - f)^{3/2}} \qquad (1)$$

where

t = group delay from originating discharge at frequency f.

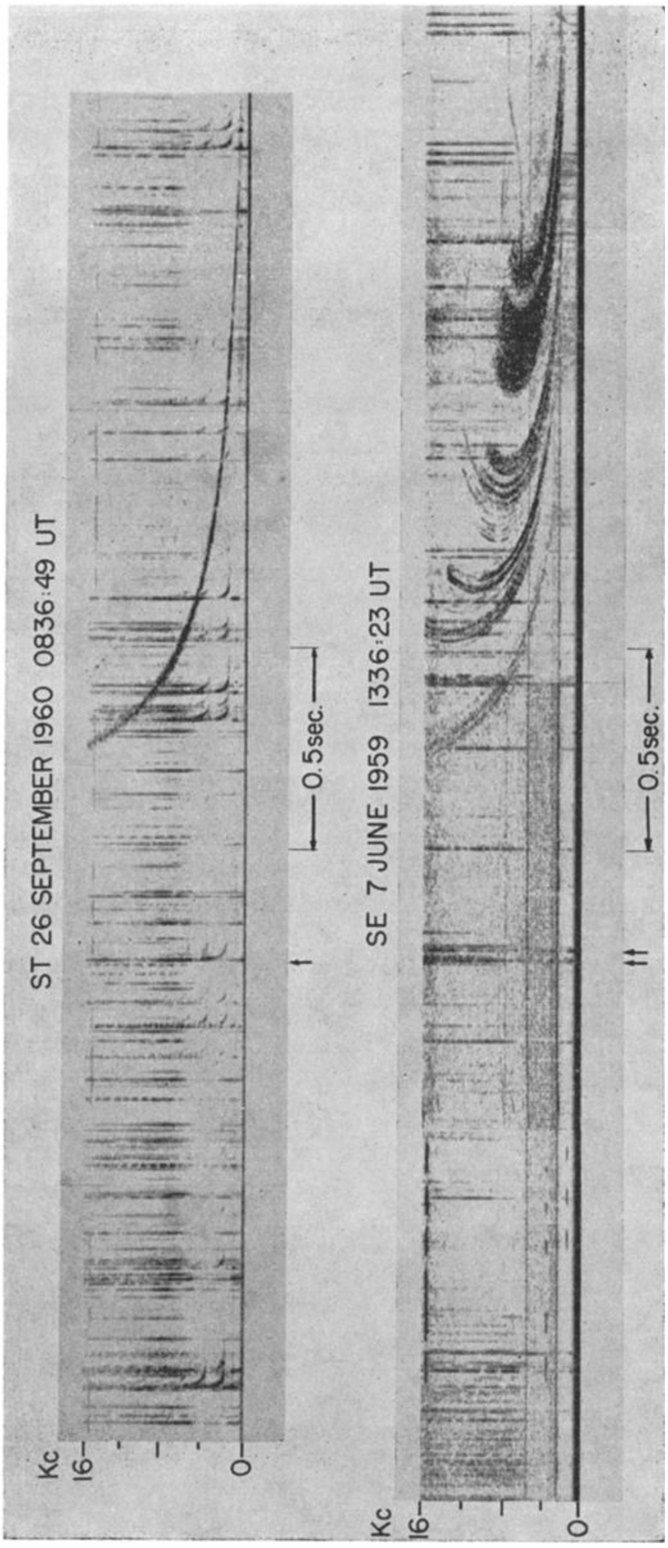

Fig. 1. Spectrographic records of single-component whistler (*top*) and two closely spaced, multicomponent nose whistlers (*bottom*).

ds = element of path length.

f_0 = local electron plasma frequency (proportional to $N^{1/2}$, where N is the number density of electrons).

f_H = local electron gyrofrequency (proportional to geomagnetic field strength H).

c = velocity of light.

Theoretical study of this equation, under the assumptions of a centered dipole approximation to the earth's field and longitudinal field-line propagation [*Smith,* 1961*b*], shows that the nose frequency of a whistler trace identifies approximately the location of the associated field-line path [*Smith,* 1960]. Nose frequency f_n increases with decreasing values of θ_0, the geomagnetic latitude of the field-line-path endpoints, rising from approximately 6 kc at θ_0 = 60° to 43 kc at θ_0 = 45°. The relation between f_n and θ_0 is found to be relatively insensitive to the choice of a model of electron-density distribution [*Smith,* 1960], and, to a first approximation, we consider it to be model-independent.

Equation 1 shows that, with f_n determined, the group delay at the whistler nose t_n is proportional to the square root of the scale factor of the electron-distribution function used to specify f_0 along the path. Thus, an observed

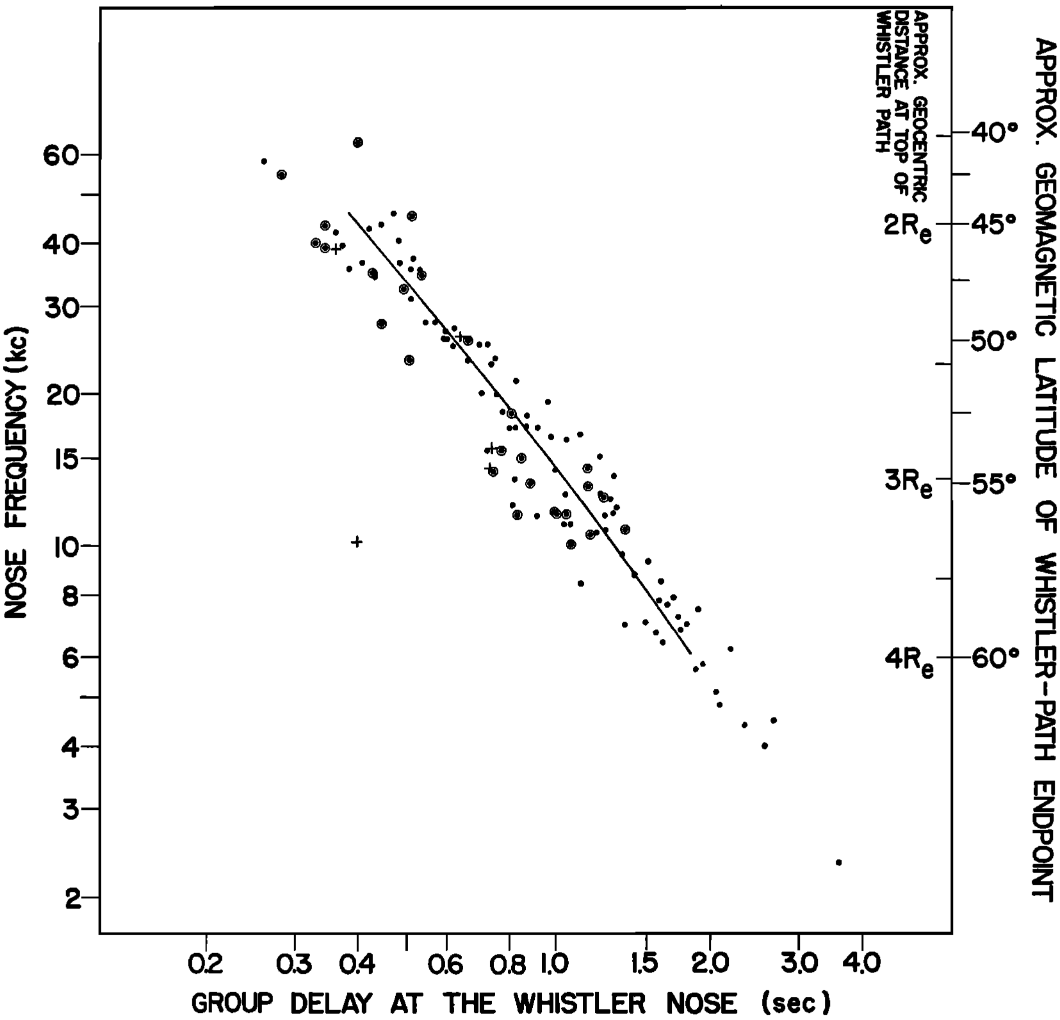

Fig. 2. Whistler data from January to June 1958. Points marked by circles or crosses represent magnetically disturbed periods. The solid line indicates the approximate center of the band of 'quiet' points.

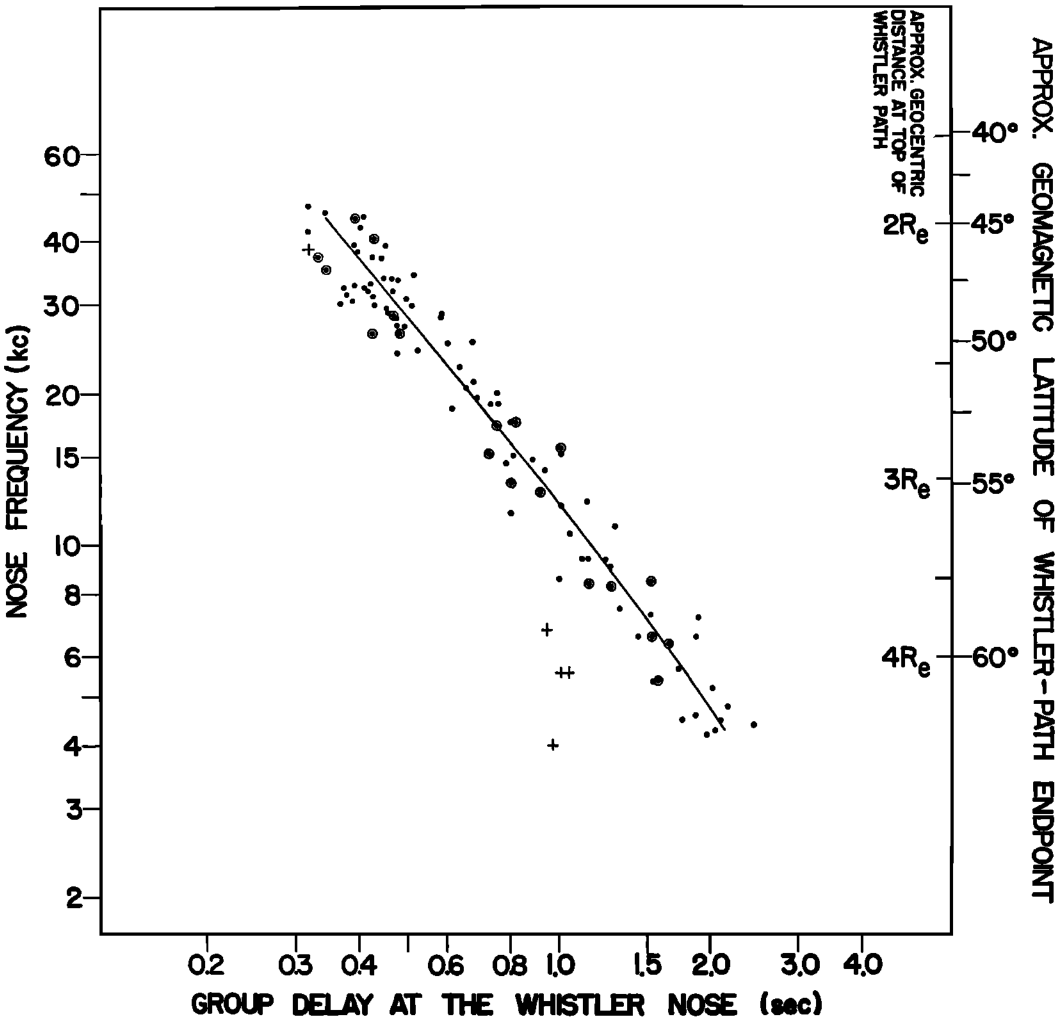

Fig. 3. Whistler data from January to June 1961. Points marked by circles or crosses represent magnetically disturbed periods. The solid line indicates the approximate center of the band of 'quiet' points.

2:1 variation in t_n at fixed f_n implies a 4:1 change in the electron-density level along the associated path, provided that the form of the electron-distribution function has not changed significantly between observations. In this report we shall assume that such a change does not occur; and, as a further simplification, we shall study relative density variations only, thus avoiding the necessity of choosing a particular model of the magnetospheric distribution. If it is believed that certain significant changes in the distribution function do occur, then to that extent our numbers for electron-density change may be considered measures of 'apparent' change.

It should be recalled that whistlers are an especially valuable means of studying the magnetosphere because (1) they probe the region along the field lines and are thus particularly sensitive to quantities under geomagnetic control, such as electron density; and (2) the principal contribution to the group delay is made in the region of tenuous ionization along the top of the path.

Method of scaling and presenting (f_n, t_n) *data.* To obtain information on electron-den-

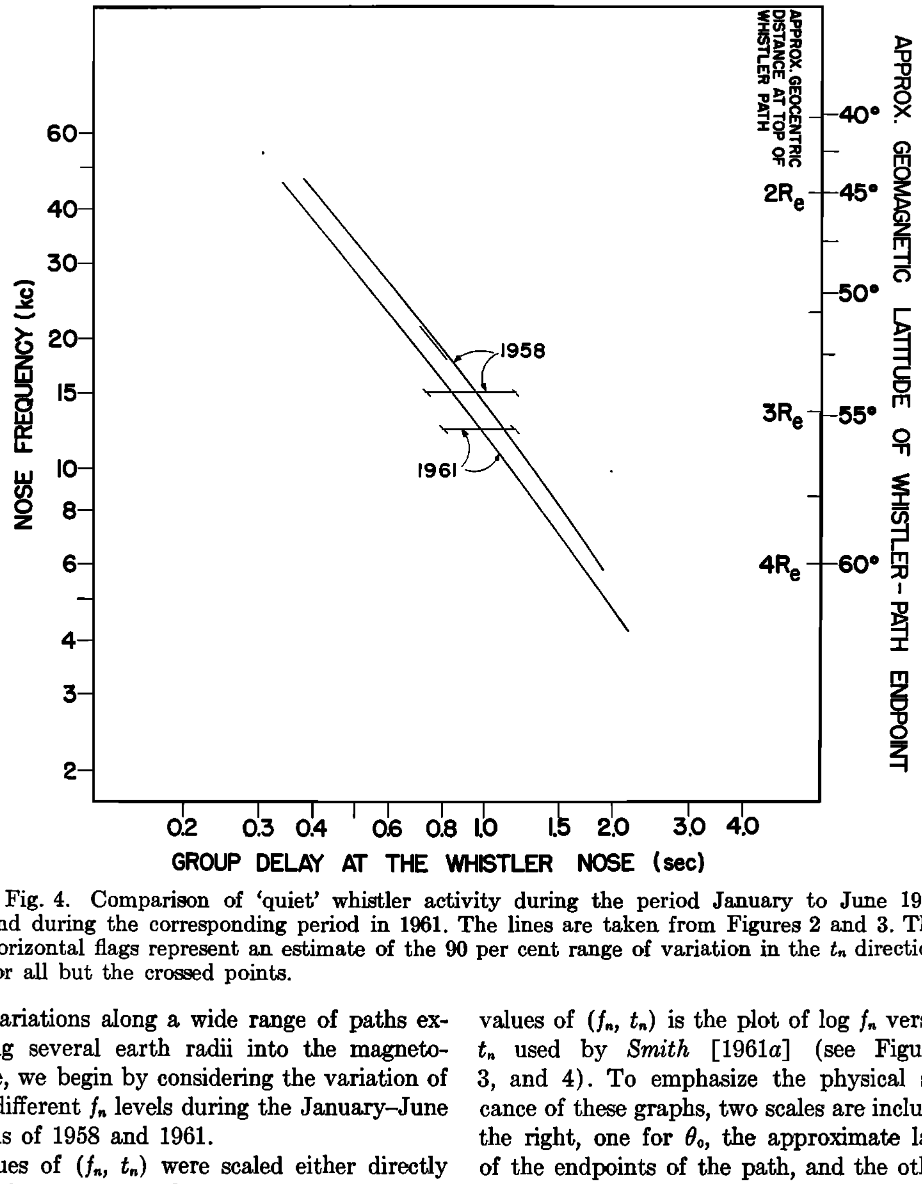

Fig. 4. Comparison of 'quiet' whistler activity during the period January to June 1958 and during the corresponding period in 1961. The lines are taken from Figures 2 and 3. The horizontal flags represent an estimate of the 90 per cent range of variation in the t_n direction for all but the crossed points.

sity variations along a wide range of paths extending several earth radii into the magnetosphere, we begin by considering the variation of t_n at different f_n levels during the January–June periods of 1958 and 1961.

Values of (f_n, t_n) were scaled either directly from the records or by the extension method recently described by *Smith and Carpenter* [1961]. A majority of the observed values of f_n below 15 kc/s were scaled directly.

Most of the 1958 data represent IGY recordings at Stanford, California, and Seattle, Washington. Other important sources of 1958 data were Wellington, New Zealand; Boulder, Colorado; and Kotzebue, Alaska. The 1961 data are drawn from recordings at Stanford and Seattle.

A convenient graphical means of studying values of (f_n, t_n) is the plot of log f_n versus log t_n used by *Smith* [1961*a*] (see Figures 2, 3, and 4). To emphasize the physical significance of these graphs, two scales are included on the right, one for θ_0, the approximate latitude of the endpoints of the path, and the other for geocentric distance at the top of the associated whistler path as it crosses the geomagnetic equatorial plane.

The relation between f_n and θ_0 shown in the figures was obtained by *Smith* [1960], using a centered dipole approximation to the earth's magnetic field and an electron-density model wherein number density of electrons is proportional to magnetic field strength, that is,

$$N = Kf_H \qquad (2)$$

where K is constant along a particular field line and f_H is the electron gyrofrequency. As noted previously, other models of density distribution lead to an f_n-θ_0 relation not substantially different from the one illustrated.

Consider Figure 2 as an example of the kind of graph used to study whistler activity. The data points are grouped in a band that has a negative slope and a slight downward curvature. Note that the bulk of the measurements are associated with paths extending to distances ranging from 2 to 4 earth radii in the geomagnetic equatorial plane. The width of the band may be considered a measure of electron-density variations along the associated magnetospheric paths during the course of the observations, the highest density levels being indicated by points near the right-hand (high-t_n) side of the band.

Scaling uncertainty is such that, whereas the 90 per cent range of uncertainty in path location increases in typical cases from ±0.5° near $\theta_0 =$ 60° to ±3° near $\theta_0 =$ 45°, the corresponding 90 per cent range of uncertainty in t_n level remains roughly ±8 per cent [*Carpenter*, 1962*a*].

Figures 2 and 3 represent the January–June periods of 1958 and 1961, respectively. The observing stations and UT recording days associated with the two figures are listed in Table 1. At most, one whistler per recording day from each of two stations is included, with the exception of January 5, January 13, and February 5, 1958. For multicomponent whistlers, the two values of (f_n, t_n) at the highest and lowest observed values of f_n, plus a single intermediate value, are used. For the 1958 data, 113 points represent 62 recording days; for the 1961 data, 100 points represent 48 recording days.

As a means of indicating the effect of magnetic storms on the data, observations preceded within 72 hours by one or more 3-hour K_p levels of 6 or 7 are circled, and those preceded by levels of 8 or 9 are marked by crosses.

The 'lines' drawn in Figures 2 and 3 represent the approximate center of the band of 'quiet' points (those not circled or crossed). The position of this reference line was determined by drawing a line along the edge of the band, finding the first moment of the quiet points about this line in several equal intervals along its length, and smoothing the results by use of running means that extend over several of the intervals.

TABLE 1. Observing Stations* and UT Recording Days for Whistler Data Illustrated in Figures 2 and 3

Month	1958	1961
Jan.	(KO) 5, 11, 30,31	
	(WE) 4, 5, 13, 14	(ST) 4, 5, 24, 26, 29
	(ST) 5, 8, 13, 14, 27	(SE) 5, 17, 18, 24, 25, 28, 29
	(SE) 13	
Feb.	(BO) 2, 5, 10, 13, 24, 27	(ST) 5, 9, 12, 16, 18, 22
	(KO) 5	(SE) 22
	(WE) 8, 12, 14, 18, 20, 22, 24, 25 and 26	
	(ST) 5	
	(SE) 1, 5, 11	
March	(WE) 11, 13, 16	(ST) 4, 9, 10, 12, 24, 25, 30
	(ST) 4, 7, 8, 9, 15, 18, 20	(SE) 5, 19
	(SE) 21, 23	
	(DU) 13	
Apr.	(ST) 14, 15, 23	(ST) 4, 9, 10, 17, 24, 25
	(SE) 15, 17, 19, 23, 25	(SE) 7, 10, 16, 17, 20, 21, 29
	(DU) 2	
May	(ST) 1, 2, 17, 21	(ST) 13, 18, 25, 28
	(SE) 1, 7, 16, 20, 21, 31	(SE) 25, 26
June	(EL) 20	(ST) 7, 8, 13, 26
	(ST) 2, 5, 10, 11, 12, 14, 24	(SE) 7, 9, 14, 16, 26, 27
	(SE) 1, 5, 12, 20, 25	
	(UN) 19	

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* Station codes: Boulder (BO); Dunedin (DU); Ellsworth (EL); Kotzebue (KO); Seattle (SE); Stanford (ST); Wellington (WE); Unalaska (UN).

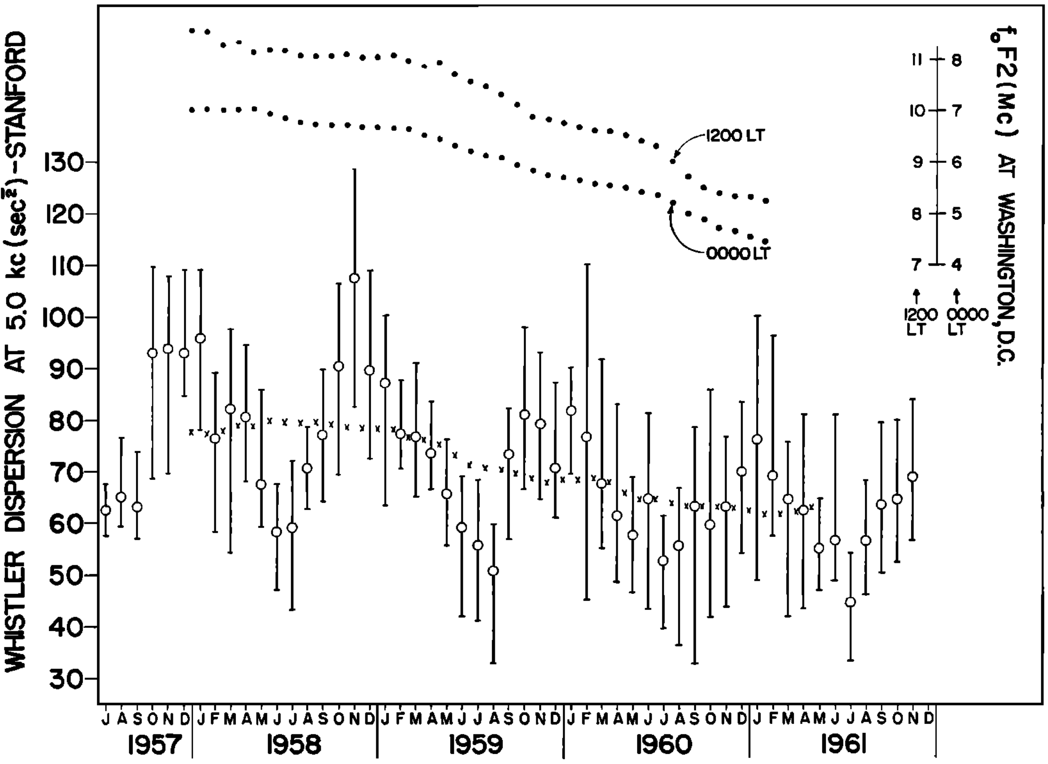

Fig. 5. Whistler-dispersion data showing an annual and a secular variation, and 12-month running means of f_0F_2. Circles indicate monthly values of D_5 (whistler dispersion at 5 kc/s), and flags show the 90 per cent range of daily values during the month. The 12-month running mean of D_5 is indicated by x's.

The positions with respect to the reference line of monthly values of (f_n, t_n) are found by calculating for each whistler the average logarithmic deviation from the reference line in the t_n direction, and then averaging over all values for a month. Here we assume that the available daily values of (f_n, t_n) representing a month are distributed roughly parallel to the reference line. This assumption is based in part on the fact that typical values of monthly average deviation from the reference line represent a significant fraction of the width of the data band.

Single-frequency group-delay measurements. Group-delay measurements at a single whistler frequency, and measurements of whistler-mode echoes from pulse transmissions, are far more easily obtained than values of (f_n, t_n). Unfortunately, group-delay data contain no direct information on whistler-path-endpoint latitude and therefore can be used as a measure of electron-density variation only to the extent that such information is obtained from other sources.

Whistler dispersion at 5 kc/s has been scaled on a routine basis at Stanford for several years. It is defined as

$$D_5 = t_5\sqrt{5000}\ \mathrm{sec}^{1/2} \qquad (3)$$

where t_5 is a measure, weighted by trace amplitude, of the delay from the originating discharge to the appearance of the whistler energy at 5 kc/s. For a long (two-hop) whistler the observed value of D_5 is divided by 2.

Figure 5 illustrates the behavior of 5-kc/s whistler dispersion at Stanford for the period beginning July 1957 and extending to November 1961. Monthly average dispersion is marked by a small circle and a flag indicating the 90 per cent range of daily dispersion values. The 12-month running mean values are indicated by x's. The running mean is calculated on the basis of the monthly numbers, which are averages over the available daily values of D_5. The daily value is obtained from a single whistler, usually recorded near local midnight. During the period July 1957 to November 1961, the number of daily values obtained per month was typically 17.

Having described our two basic types of data, (f_n, t_n) and D_5, we now consider the variations they exhibit.

RESULTS OF DATA ANALYSIS

Effect of magnetic storms. Experimental evidence has recently been presented showing the occurrence of reductions in time delay at the whistler nose during the 72-hour period following 3-hour K_p values of 6 or more [*Carpenter*, 1962*a*]. Let us examine this important effect before looking at the annual and secular variations.

For the 1958 data shown in Figure 2, 4 of the 5 points marked by crosses ($K_p = 8$ or 9 at least once in the preceding 72 hours), and 19 of 27 circled points ($K_p = 6$ or 7 at least once in the preceding 72 hours), lie to the left of the line fitted to the 'quiet' data. For the 1961 data (Figure 3), all 5 of the crossed points and 12 of 19 circled points lie to the left of the line. The storm effect is somewhat obscured in Figure 3 by the fact that 3 of the 4 circled points lying relatively far to the right of the line are associated with a single storm, during which a 3-hour K_p level of 6 was reached only once.

A somewhat clearer picture of the storm effect is conveyed by Figure 6. To obtain this graph, storm periods were identified and arbitrarily defined as beginning with the appearance of the first K_p level of 6 or more following a quiet period of at least 36 hours. The average horizontal displacement from the quiet line was obtained for each whistler represented by circles or crosses, and the results were then averaged over the relevant storm period. The final values for individual storms are indicated by vertical lines on a scale of N_{ST}/N_Q, the ratio of average 'storm' electron-density level to the typical or quiet level for the calendar month in which the storm occurred (the latter level is based on observations preceded, over a 72-hour period, by 3-hour K_p levels of 5 or less). As a crude means of indicating the severity of storms, the vertical lines are divided into three groups. The lines 3 units high are associated with K_p levels of 8 or 9. Those 1 unit high indicate observations preceded within 72 hours by a single 3-hour K_p value of 6 only, and all others are in the 2-unit category. The very severe storms represented by the 3-unit lines occurred on February 11, 1958, May 31, 1958, and April 14, 1961.

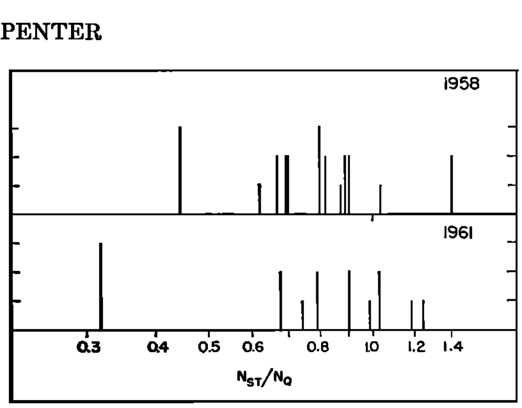

Fig. 6. Graph of N_{ST}/N_Q, the ratio of average magnetospheric electron-density level during a magnetically disturbed period to average electron-density level for 'quiet' days in the calendar month during which the storm began. The height of the vertical line is a crude measure of the severity of the storm. Periods involved are January to June in 1958 and 1961.

The figure illustrates in dramatic fashion the deep depressions associated with some severe storms. It documents the picture conveyed by Figures 2 and 3, where we observe that storm activity tends to increase the width of the bands of data, particularly by addition of circled and crossed points on the low-t_n side. From Figure 6 we see that storm effects are in a general sense the same during both the 1958 and 1961 periods of observation, although the relative reduction in typical cases appears to be slightly less in 1961. A typical value of density reduction is about 20 per cent in 1958, and about 15 per cent in 1961.

Since observations associated with severe storms constitute the minority of cases in both periods under study, the position of the line in Figures 2 and 3 is changed only slightly when the circled points are included in the calculations. Figure 4 shows the two lines calculated on the basis of the quiet data. When the circled points are included, the slope of the lines is virtually unchanged. The 1958 line is displaced slightly to the left to a position indicated by the short, thin line in Figure 4; the 1961 line is not displaced significantly. Thus, the relative decrease in magnetic-storm activity from 1958 to

1961 tends to reduce the separation of the lines and therefore reduces the apparent magnitude of the secular variation in electron density.

It should be pointed out that storm variations in the magnetosphere show wide differences with latitude and longitude [*Carpenter*, 1962*b*]. These differences, as well as important temporal changes, are obscured by the averaging processes used to obtain Figure 6. Such matters, which will be discussed in future reports, do not have a significant effect on the material presented in this paper.

Annual variation of electron density in the magnetosphere. Reports on the annual variation have been made by *Smith* [1961*a*] and *Helliwell* [1961]. Our purpose here is simply to present additional and more-detailed information.

The month-by-month variations in the data of Figures 2 and 3 are plotted in Figure 7 as a ratio of monthly average t_n level to average t_n level for the January–June period (t_n/t_{n_0}). To minimize the effect of severe magnetic disturbance, only quiet whistler observations, associated with K_p levels of 5 or less, were used.

The resulting graph shows a great deal of similarity between the annual variation in 1961 and that in 1958. There appears to be (despite the limitation to a 6-month period) a narrow minimum near the June solstice and a broad maximum near December, with some tendency over the 1958–1961 period toward a lessening of the disparity in width. Relatively high density values for April suggest the possibility of a semiannual component, but further analysis is clearly required before it can be properly identified.

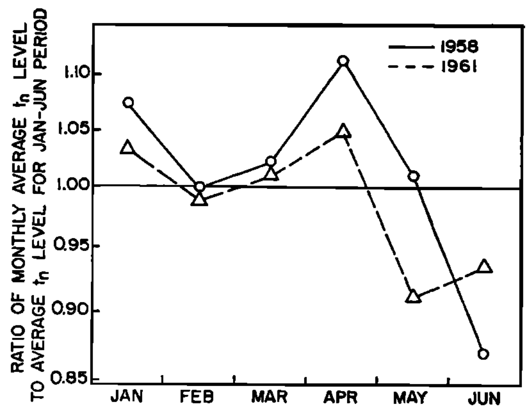

Fig. 7. The ratio of monthly average t_n level for whistlers to the average t_n level for the January to June period, showing the annual variation. All quantities are based on observations preceded within 72 hours by 3-hour K_p indices of 5 or less.

The over-all range of variation in 1958 appears somewhat larger than in 1961, an observation that is borne out by a comparison of the widths of the data bands in Figures 2 and 3. Horizontal flags representing an estimate of the 90 per cent width of the bands (including circled points) are drawn in Figure 4 and show a decrease in length from 1958 to 1961.

On the basis of Figure 7, the June–January ratio of t_n level is about 0.81 in 1958 and 0.90 in 1961, and the corresponding ratios for electron density are 0.66 and 0.81. It is clearly of interest to extend the graph to apply to the remaining months of the year as well as to other years.

As a means of verifying and elaborating the picture presented by the (f_n, t_n) data, consider the 5-kc/s dispersion data of Figure 5. The annual variation is a dramatic feature of D_5, appearing in every year, but with a decreased magnitude in 1960 and 1961. Relatively broad maximums and narrow minimums are in evidence, particularly in 1958 and 1959. Note, as an interesting detail, that an unusually large value of monthly average dispersion, 107.5, was obtained for November 1958, magnetically the quietest month during the IGY-IGC.

The magnitude of the annual variation in D_5 is larger than that indicated by the (f_n, t_n) data. From 1958 to 1961, the ratio of June–July–August values of D_5 to November–December–January values falls in the range 0.65–0.75, compared with 0.80–0.90 for the (f_n, t_n) June–January ratios. This relatively large difference suggests that significant variations in path-endpoint latitude influence the D_5 results.

Let us examine path variations, which are interesting both as a feature of whistler propagation and as a problem in the interpretation of whistler delay data. We shall return to consideration of the annual variation in the discussion.

Annual variation in path latitude of Stanford whistlers. By combining D_5 and (f_n, t_n) data, a graph can be prepared (see Figure 8) that will relate monthly average D_5 to a monthly average value of θ_0 (whistler-path-endpoint latitude). Given a particular functional form of electron

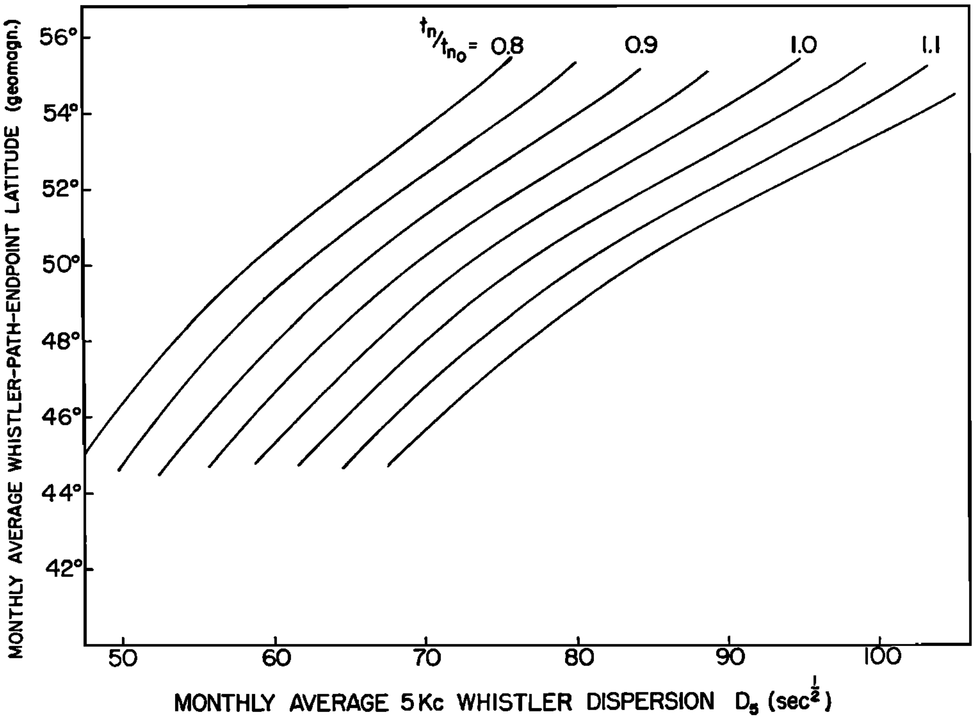

Fig. 8. Relation between dispersion at 5 kc/s and whistler-path-endpoint latitude, based on the electron-density model $N = Kf_H$ and the reference line for 'quiet' whistler activity during the period January to June 1958.

distribution in the magnetosphere, and given a reasonably well-behaved observational curve relating f_n and t_n such as one of those illustrated in Figure 4, a unique relation between group delay (or dispersion) at 5 kc/s and f_n (or θ_0) can be obtained.

Figure 8 applies to the January–June data of 1958, and expresses a relation between D_5 and θ_0 that is parametric in t_n/t_{n0}, the ratio of average t_n level for a month to the reference level. Since t_n/t_{n0} and D_5 have already been obtained (see Figures 5 and 7), the value of θ_0 for each month can be read immediately. (Actually, since the effects of magnetic activity have not been removed from D_5, it is necessary to obtain monthly values of t_n/t_{n0} that include the observations preceded by K_p levels of 6 and 7. The resulting graph of t_n/t_{n0} is generally similar to that of Figure 7 but shows slightly smaller values for most months.)

Figure 9 shows a plot of monthly average whistler-path latitude for Stanford whistlers in the January–June period of 1958 and 1961 and for Seattle whistlers from January to June in 1958. The Stanford data show that typical whistler-path endpoints lie some 4° or 5° closer to Stanford in the northern-hemisphere summer than in winter. The pattern of change is essentially the same in 1961 as in 1958, although the 1961 values lie, on the average, somewhat closer to Stanford (43.7°N). The average of the six monthly values for 1961 is 50.2°, and that for 1958 is 51.0°.

Note that the phase of the annual path variation is essentially the same as that of the annual density variation, reinforcing the effect of the density variation on D_5 and producing the surprisingly large fluctuations seen in Figure 5.

One of the more striking aspects of the data is the tendency for Stanford to observe whistlers that terminate, as far as the field-line path is concerned, some hundreds of kilometers from the receiver. A previous report on Whistlers-west data [*Helliwell and Carpenter*, 1961] suggested the existence of a region of high whistler activity extending poleward from about 47° and exhibiting a peak around 51°. The data shown here provide independent evidence of the

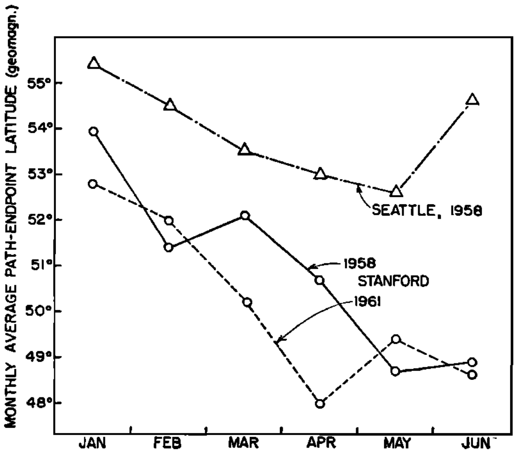

Fig. 9. Monthly average path-endpoint latitudes for Stanford and Seattle, derived from measurements at the whistler nose and from 5-kc/s dispersion data. The centered dipole approximation to the earth's field is used.

existence of preferred regions of whistler propagation lying to the north of Stanford.

The 1958 Seattle data show a range of path variation considerably smaller than the 1958 Stanford data. As a qualitative check on the reasonableness of the f_n–θ_0 relation implicit in Figure 9, we note that Seattle observes a set of average endpoint latitudes that range over a degree or two on either side of the Seattle receiver (53.6°N). We would expect this on another ground, namely, that Seattle is relatively near the previously mentioned peak of whistler activity.

As a check on our analysis of path variations, all values of f_n scaled for the months of January and June at Stanford were tabulated. Most of the numbers are from the years 1958 and 1961. The median of 18 values for January is 24.7 kc/s, corresponding to the path latitude 50.2°; for June the median of 19 values is 35.2 kc/s, corresponding to the latitude 47.1°. This path information is independent of the previous calculations, since it does not contain any information on t_n levels. It is essentially a measure of the behavior of the relatively stronger, better-defined whistler traces, whose path endpoints may be expected, particularly near the December solstice, to lie somewhat closer to the Stanford receiver than the endpoints calculated for D_5.

It should be noted that we are not attempting to develop a precise physical picture of the concept of monthly average whistler-path latitude. It should also be noted that although a particular model of electron density, $N = Kf_H$, was used to obtain Figures 8 and 9, the use of any of a relatively wide range of other models would produce only minor modifications, such as a translation up or down through one or two degrees of the entire curve of Figure 9 and some still smaller scale changes in the shape of the curve.

Secular variation of electron density in the magnetosphere. The slow variation may be considered in several ways. One measure of the reduction in density from early 1958 to early 1961 is the separation of the quiet lines of Figure 4. The ratio of t_n in 1961 to t_n in 1958, for fixed f_n, varies from about 0.88 at the magnetospheric level $2R_E$ to 0.90 near the level $4R_E$, and the corresponding ratios for electron density are 0.77 and 0.81.

Another measure of the 1958–1961 density reduction is the ratio of monthly average t_n level in 1961 to the same quantity for 1958. The ratio is obtained by assuming that the two lines in Figure 4 are identical, with the exception of a horizontal translation, and that they are separated by the observed separation near the level $3R_E$. (The departures from this condition are not great enough to upset the first-order picture.) Combining the average logarithmic distance between the lines with the information on monthly t_n levels in Figure 7, we obtain the results illustrated in Figure 10. The average value of the t_n ratio for 6 months is 0.87, corresponding to a density ratio of 0.76.

The secular variation should also be reflected in single-frequency group-delay measurements. *Allcock and Morgan* [1958] and *Kimpara* [1960] have reported a positive correlation between whistler group delay and sunspot activity, the whistler result lagging about 2 months behind sunspot number.

Figure 5 shows a running mean of D_5 for Stanford (marked by x's). The values exhibit a relatively smooth decrease, beginning with mid-1958. The picture conveyed by the (f_n, t_n) data is thus given independent support, although the ratio of the values representing early 1961 to similar values for 1958 is about 0.80, somewhat below the ratio of about 0.88 found from the (f_n, t_n)

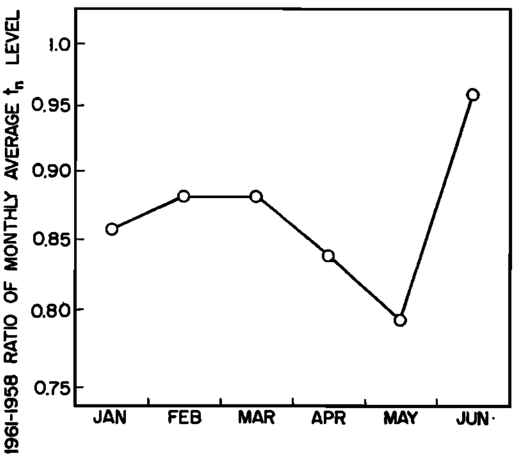

Fig. 10. Ratio of monthly average t_n level in 1961 to the corresponding quantity for 1958. The square of the ratio is a measure of the secular change in electron density.

data. (When the monthly dispersion value is represented by the median instead of the mean of the daily numbers, the 1961–1958 ratio is 0.81.)

Another quantity that may be compared with the (f_n, t_n) results is the 6-month (January–June) average of D_5. When this number is expressed as a fraction of the 1958 value, we obtain 0.96, 0.90, and 0.84 for 1959, 1960, and 1961, respectively.

The difference between 0.80–0.84 for D_5 and 0.88 for the (f_n, t_n) results is not large, but it does suggest the presence of a small secular change in whistler-path latitude. An equatorward movement through about 1° near $\theta_0 = 50°$ would change the average path length (and thus the group delay) by about 5 per cent, which is approximately the amount of the discrepancy between the D_5 and the (f_n, t_n) results. The existence of this type of slow path movement has been noted previously.

One of the most intriguing aspects of the secular variation is the apparent tendency to exhibit large variations from year to year between periods near the December solstice, and relatively smaller changes between the successive June–July periods. The best documentation of this point should be the monthly ratios plotted in Figure 10, but they need to be extended to other months and years before an adequate picture can be presented. The value indicated for May is questionable, since relatively few observations were made for May 1961. Figure 10 does demonstrate in a qualitative way the point being made, but the best picture is probably that of Figure 5. There we see that the average of the two or three smallest values in each year decreases by roughly 10 to 12 per cent over the 1958–1961 period. From 1959 through 1961 there appears to be very little change in the minimum D_5 level. In contrast, the average of the three largest values of D_5 decreases by about 25 per cent over the 1958–1961 period. Although a part of this decrease is probably accounted for by a slow path movement in the equatorward direction, the relative density reduction still appears to be significantly greater for the maximums than for the minimums. Note that the decrease of the maximums continues through the 1959–61 period.

Secular variation in f_oF_2, 1958–1961. It is of interest to plot the behavior of the F_2-layer critical frequency during the period spanned by the whistler data. Twelve-month running means of monthly f_oF_2 values observed at Washington, D. C., and reported in the CRPL-F series, are illustrated in Figure 5 by the dotted curves. (Values for August 1957 and October 1958 were not available.)

Although Washington, D. C., is roughly 4500 km to the east of Stanford and Seattle, its geomagnetic latitude, 50.4°N, represents a position intermediate with respect to Stanford, 43.7°N, and Seattle, 53.6°N.

The ratio of values of the running mean representing early 1961 to similar values for 1958 is about 0.64 for observations at local midnight and 0.71 for observations at noon. The corresponding ratios in electron density are 0.41 and 0.50. When 6-month averages are calculated for the January–June period, the numbers for 1961, expressed as a fraction of the 1958 values, are 0.57 for midnight and 0.66 for noon, with corresponding density ratios of 0.33 and 0.44.

The reduction from 1958 levels by 20 to 25 per cent in the magnetosphere is to be contrasted with a reduction by roughly 60 per cent at the F_2-layer maximum. These markedly different numbers should spur interest in the question of physical processes in the magnetosphere and in the transition region between the F region and the magnetosphere. Further experimental work on satellite measurements of integrated electron content, topside sounding, satellite experiments at VLF, and whistler studies (diurnal variation, latitude effects, etc.) should prove helpful in the study of these processes.

Hanson and Ortenburger [1961] have recently provided some theoretical support for the whistler observations through their investigation of the theory of coupling between the normal F region and the protonosphere (the part of the outer ionosphere composed predominantly of protons and electrons). On the basis of the model used, they indicate that, even over a solar cycle, large changes in proton concentration would not be expected near the base of the protonosphere.

Diurnal variation of electron density in the magnetosphere. Diurnal studies of whistler dispersion have been conducted by a number of workers, including *Iwai and Outsu* [1958], *Rivault and Corcuff* [1960], and *Allcock* [1960]. These authors observed an afternoon maximum and a post-midnight minimum in dispersion. The observed variation includes two effects, a component attributed to the diurnal behavior of the F region, and a comparable component attributed by the authors to the magnetosphere itself. Typically, the magnetospheric density variation shows a reduction of about 30 per cent from maximum to minimum.

A diurnal study using (f_n, t_n) data has been undertaken by the author, but the work is still in a preliminary stage. The evidence gathered thus far suggests that there may be significant seasonal, annual, and solar-cycle changes in the diurnal variation of magnetospheric density as well as important changes with location and magnetic activity. In particular, a number of cases have been observed in which no significant magnetospheric variation occurred during local night.

It seems clear that the possibility of path ambiguities must be carefully eliminated in an extensive treatment of diurnal effects. Because the sources of whistlers may be widely separated from the whistler paths, (f_n, t_n) methods would seem preferable, in such a program, to techniques that involve direction finding of whistler sources.

Most of the (f_n, t_n) results quoted in this report are from nighttime observations in the local time period 0000 to 0600. Thus far no evidence has been found in daytime results that would significantly alter the conclusions reached in this paper.

Discussion

The annual variation has not been explained, but, on the other hand, it has not yet been fully described. How do the phase and amplitude of the variation behave as a function of geomagnetic longitude?

The author has studied the annual variation over the 110° range of geomagnetic longitudes from 250°E to 0°, and has found relatively little change in amplitude or phase over this range. A limited quantity of dispersion data obtained by Rivault and Corcuff at Poitiers, France (geomagnetic longitude 81.8°E), has also been studied by the author. These data show evidence of an annual variation, with amplitude and phase similar to those observed in the 110° range mentioned above.

Although the whistler evidence needs to be extended by measurements in the eastern hemisphere of the earth, the available results suggest strongly that the amplitude and phase of the variation do not vary substantially with longitude. If this is in fact so, the variation probably cannot be explained on the basis of localized quantities, such as the annual variation in geomagnetic latitude of the subsolar point at a particular geomagnetic longitude. *Helliwell* [1961] has pointed out that, if this geomagnetic asymmetry is the controlling factor, the annual variation in electron density should reverse its phase in the eastern hemisphere of the earth.

Investigations of the F_2 region by *Yonezawa and Arima* [1959], and of the E region by *Shimazaki* [1960], provide evidence of an annual density variation, with a December maximum and June minimum. *Paetzold and Zschörner* [1961], who have studied the variations in the acceleration of several satellites, have deduced an annual variation in upper air density that is similar in phase to the magnetospheric variations discussed above. The authors find a broad maximum near the December solstice, and an increase in magnitude of the variation with altitude over the range of observations from about 200 to 700 km.

Although the annual variation as observed in the different ionospheric and magnetospheric regions may not be explained by a single mechanism, the evidence on satellite drag from a number of satellites lends strong support to our suggestion that the annual magnetospheric variation is essentially independent of geomagnetic longitude.

All the investigators mentioned above have remarked that the eccentricity of the earth's orbit is in itself insufficient to explain the magnitude of the observed variations. Paetzold and Zschörner suggest the possibility that an interstellar wind due to the solar motion in the local stellar system produces a shift in the interplanetary plasma cloud to a position somewhat eccentric to the sun. This is an interesting suggestion in the light of our observation that slow changes in solar activity seem to have a relatively small effect on the low magnetospheric density levels observed near the June solstice. In a communication to the author, J. C. Brandt suggests that the containment of the interplanetary plasma is done by the interstellar magnetic field, and that in considering the distortion of the interplanetary plasma cloud, it is probably important to emphasize the magnetic nature of the interaction causing the distortion. Whatever the physical mechanism involved, evidence is accumulating for a systematic annual variation in the physical environment of the earth along its orbit.

The study of whistler-path-endpoint latitudes suggests a number of attractive possibilities for research. Important information may be gained about the physical basis of field-line propagation and the propagation characteristics of whistler-mode signals from VLF transmitters. The effect on whistler ray paths of horizontal gradients in the F region may be explored. The effect on whistler observations of the departures of the earth's field from the dipole model may be studied, and important information may eventually be gained about the nature of the geomagnetic field at distances of several earth radii.

CONCLUSIONS

It should be remembered that most of the detailed whistler observations underlying this report were made at Stanford, California, and Seattle, Washington, whose geomagnetic coordinates are 43.7°N, 298.4°E, and 53.6°N, 294.4°E, respectively. The whistler paths associated with the observations extend to distances ranging from 2 to 4 earth radii in the geomagnetic equatorial plane, and it is this region to which we refer when discussing magnetospheric density levels.

The effect of magnetic storms on electron-density levels is generally the same in both 1961 and 1958, although the relative reduction in typical storms appears to be slightly less in 1961. A whistler observation preceded within 72 hours by a 3-hour K_p value of 6 or greater typically shows an electron-density level substantially below the quiet level for the calendar month in which the storm occurred. A typical value of density reduction is about 20 per cent in early 1958 and about 15 per cent in early 1961.

Magnetic storms do not seriously affect the attempt to measure secular variations in electron density. When observations preceded within 72 hours by K_p levels of 6 or 7 are included in the (f_n, t_n) analysis, there is only a small reduction in the apparent size of the 1958–1961 density variation.

The annual variation in magnetospheric density levels is characterized by a maximum near the December solstice. A detailed analysis of (f_n, t_n) data for the January–June periods of 1958 and of 1961 shows that the June–January ratio of electron density is about 0.66 in 1958 and 0.81 in 1961. There appears to be a narrow minimum near the June solstice and a broad maximum near the December solstice, with some tendency over the 1958–1961 period toward a lessening of this disparity in width. Relatively high density values for April suggest the possibility of a semiannual component.

The D_5 data, based on group-delay measurements at 5 kc/s for Stanford whistlers during the period July 1957 to November 1961, show the annual variation in each year. The magnitude of the fluctuation is surprisingly large, owing to the presence of an in-phase variation in the average path latitude of Stanford whistlers. A straight density interpretation of the D_5 variations, with the path changes not considered, would lead to summer-winter density ratios that are too small—in the range 0.42–0.56 instead of 0.66–0.81.

The annual variation in magnetospheric density levels has not been explained; it certainly deserves fuller investigation. As yet we have not established conclusive evidence for the continuing appearance of the annual variation at longitudes far from that of Stanford, and it is hoped that workers in several regions will investigate the situation, making possible a worldwide picture.

When the secular variation in the (f_n, t_n) data is studied, the average electron-density level in the magnetosphere for the January–June period in 1961 is found to be 75 to 80 per cent of the value for the same period in 1958. There is some evidence that the larger part of the observed reduction occurs near the December solstice.

Single-frequency group-delay measurements at 5 kc/s on Stanford whistlers (D_5) over the period July 1957 to November 1961 reveal a similar decrease from 1958 to 1961 and thus corroborate in a general way the results derived from (f_n, t_n) data. The decrease in D_5 from early 1958 to early 1961 is augmented by a slow, equatorward movement through about 1° of the average whistler-path-endpoint latitude for Stanford whistlers.

The 1958–1961 variation in f_oF_2 at Washington, D. C., shows a reduction in electron density to roughly 40 per cent of the 1958 levels as compared with 75 to 80 per cent for the magnetosphere. Extrapolating to the approaching sunspot minimum, we estimate that the magnetospheric electron-density level will be reduced to 60–70 per cent of the 1958 value, and the corresponding number for the F_2 maximum will be in the range 15–30 per cent (at Washington, D. C.).

The discovery of an unexpected and as yet unexplained annual variation in the path latitude of Stanford whistlers dramatizes the importance of the somewhat laboriously obtained (f_n, t_n) measurements. The path phenomenon is generally the same in both 1958 and 1961, and is characterized by an equatorward movement of typical whistler-path endpoints through some 4° or 5° from January to June, with the monthly average endpoint latitude always on the poleward side of Stanford. The field-line portion of typical Stanford whistler paths can terminate hundreds of kilometers north of the receiver, while Seattle, to the north, is observing path-endpoint latitudes that are relatively near by. Previous evidence of the existence of preferred regions of whistler propagation on the poleward side of Stanford is thus reinforced; it can doubtless be elaborated upon in future studies.

As a matter of methodology, we have found that the results of a limited number of (f_n, t_n) measurements may be used to reduce path ambiguities in more extensive but less sophisticated data. After this is accomplished, such data may be used as an important source of information on electron-density variation. The combination of (f_n, t_n) results and single-frequency group-delay data also leads to important information on whistler propagation, such as the evidence of path variations shown above.

Stanford has recently issued the first of a planned series of reports providing routine data on: (1) whistler group delay at 5 kc/s, (2) frequency and group delay at the whistler nose, and (3) whistler-mode group delays from pulse transmissions at 18.6 kc/s [*Carpenter and Carpenter*, 1962]. This series will make possible a continued and more detailed study of the subjects discussed in the present report.

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