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GEOPHYSICAL INSTITUTE

UNIVERSITY
OF ALASKA

COLLEGE
ALASKA

Scientific Report No. 4

AF 19(604)-1859

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AN INVESTIGATION OF WHISTLERS AND CHORUS AT HIGH LATITUDES

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The research reported in this document has been sponsored by the Electronic Research Directorate of the Air Force Cambridge Research Center, Air Research and Development Command.

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Date Submitted:

April, 1959

Approved by:

C. T. Elvey, Director
Geophysical Institute

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ABSTRACT

The whistlers and chorus received at College, Alaska during the period from December 1955 through March 1958 are studied particularly with respect to temporal variations.

The diurnal curves for whistler activity show maxima after midnight local time while the seasonal variation peaks during the winter. It appears that these variations in whistler activity are in part explainable in terms of very low frequency propagation conditions.

The diurnal variation of chorus shows a maximum at about 1400 hours local time. By the use of data from lower latitude stations a dependence of this time of diurnal maximum on the geomagnetic latitude of the station is shown.

The coefficients of correlation for chorus activity versus magnetic activity were determined on a monthly basis. A seasonal variation in these correlations is indicated which appears to be unique for the geomagnetic latitude of College.

A preliminary statistical study of one of the more easily measured characteristics of chorus is discussed. The characteristic chosen is the mid-frequency in an element of chorus. A diurnal variation in this parameter is indicated.

INTRODUCTION

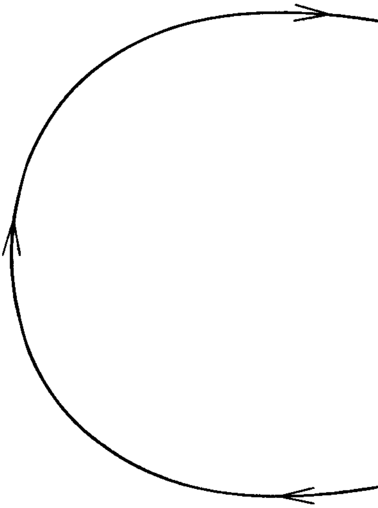
It is known that a variety of natural phenomena occur in the audio frequency portion of the electromagnetic spectrum which may be observed by means of a high gain audio amplifier and an antenna. They have been called "audio atmospherics." One type of audio atmospheric may appear as a descending tone starting perhaps above 10 kc and ending at about 1 kc one or two seconds later. These descending tones, known as "whistlers" or "whistling atmospherics" have been the subject of much investiation during recent years. Whistlers were first reported by Barkhausen(1) in 1919 and a plausible theory of their nature was presented by Storey in 1952(2).

According to Storey's theory, whistlers are originated by lightning discharges. Part of the radiation of the discharge may propagate in a longitudinal mode along the geomagnetic lines of force to the magnetic conjugate point of the opposite hemisphere (Fig. 1). Some of the energy is reflected to travel back along the same path. This process may be repeated several times resulting in "echoes". There can be no propagation unless an electron density of several hundred electrons per cubic centimeter exists everywhere along the path. Thus the wave pocket originating from the discharge propagates a long distance through a dispersive medium, where the group velocity and hence the time of propagation depends on the frequency.

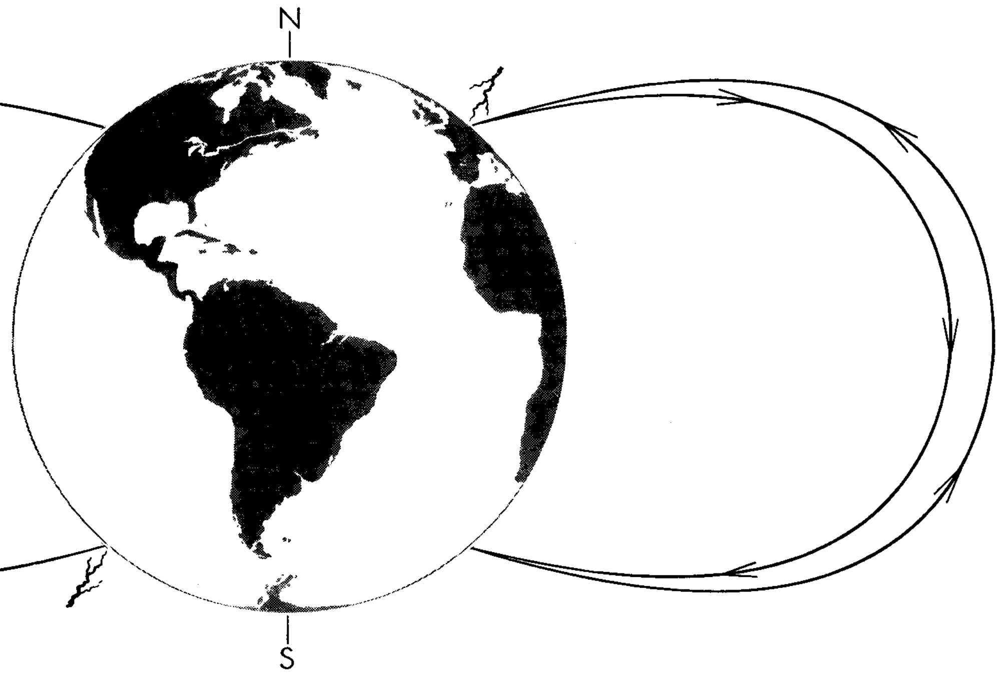
Since the length of the geomagnetic lines of force is a function of the observer's latitude, it might be supposed that the characteristics of whistlers change with latitude. Until 1955 whistlers had been observed only in intermediate latitudes, with a highest latitude of observation of 58°, and it was clearly important to ascertain (a) whether whistlers occurred in high latitudes and in the affirmative case (b) how their characteristics differed from those observed in intermediate latitudes. Consequently, a whistler recording station was established at College (geomagnetic latitude 64.5°) in 1955 to seek the answers to these questions. The first question about the occurrence could soon be given an affirmative answer. Spectral analysis at Stanford University of some examples of whistlers which were recorded at College on July 10, 1955 revealed a new and unusual property of the high latitude whistlers. As noted above, the usual whistler begins at some frequency and descends in tone. The high latitude whistlers begin at some intermediate frequency (3-4 kc) and both rise and descend in tone. As plotted by an audio spectrograph, the shape is approximately a parabola with its axis aligned along the time coordinate; hence the name "nose" whistler (Fig. 2). On the basis of these results a theory was developed by a research group at Stanford University[3] and independently by Ellis[4] which indicates that an approximation made by Eckersley in the development of his dispersion theory is not sufficient for high latitude whistlers.

The corrected dispersion theory permits one to infer that the frequency of maximum group velocity is of the order of one quarter of the gyromagnetic frequency along the path. The magnetic field lines at the latitude of College, Alaska causes the disturbance to propagate to a point about 30,000 km from the earth. At this distance the magnetic field strength is such that the gyromagnetic frequency is of the order 12 kc. Thus the frequency of maximum group velocity is about 3 kc. This theory predicts that the frequency of maximum velocity will be at about 30 kc for some of the low latitude whistler stations.

Other atmospherics such as the "chorus", which are received on the same equipment can also be studied. Chorus can be described as a multitude of quickly rising tones. This phenomenon has been referred to as "dawn chorus" for historical reasons but the word "dawn" conveys no information and is in fact misleading since whether it occurs at dawn or not has been shown to depend on the geomagnetic latitude of the station. Thus it is probably desirable to use only the word "chorus", although objections have been made.[(5)] The origin of this phenomenon is unknown but there is evidence which indicates a connection with solar particle activity. A systematic study of chorus in high latitudes should contribute to a theory of origin.



Fig



. 1. The Paths of Whistler Propagation.

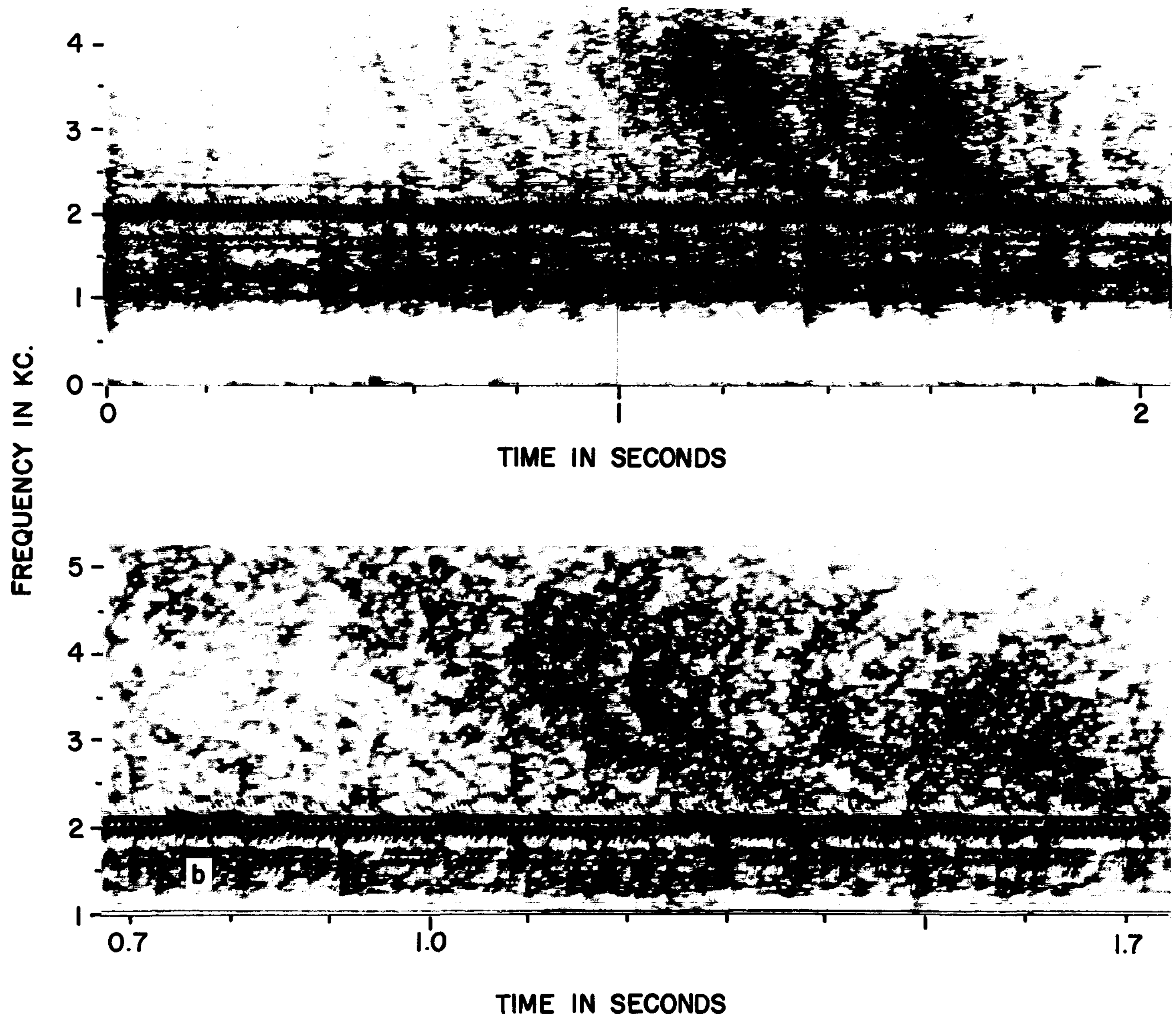


Fig. 2. A Typical Nose Whistler Recorded at College, Alaska.

INSTRUMENTATION

Fig. 3 is a block diagram showing the whistler receiver. The signal is received on a loop antenna in the form of a triangle having a height of 30 feet and a base of 60 feet. Since the loop has only one turn, it is necessary to use a specially built transformer to couple the very low impedance of the loop to the preamplifier. The preamplifier, which has a voltage gain of 120 db, is connected through a 1,000 ft. cable to a tape recorder. A programming unit is provided to turn the detector on at prearranged intervals. This unit is capable of turning the device on each hour for an integral number of minutes, and has generally been set for one minute to give an hourly sample but after June 1957 the interval has been changed to two minutes to conform to IGY standards. This sampling technique permits an estimate of the diurnal variation and makes it possible to undertake correlation studies with other phenomena such as magnetic activity.

The bandwidth of the system is essentially determined by the frequency response of the preamplifier which is shown in Fig. 5. At times high pass filters have been used to eliminate a.c. harmonics as high as 2 kc.

To obtain the data from the tapes a monitor station has been set up. This monitor station is provided with a tape recorder and an adjustable filter to reduce interfering power line harmonics. A second tape recorder is used to copy interesting events. For frequency versus time analysis of an event a sound spectrograph is provided. This machine plots frequency as a function of time by an electric spark on prepared paper. The frequency range is 200 cycles to 8 kc and the time scale is 2.4 seconds. This instrument is manufactured by Kay Electric Co. and is known as a "sonagraph" while the frequency time plots are known as "sonagrams". These graphs show the power line harmonics as horizontal lines, static and tweeks as vertical lines. Fig. 2 is an example of a "sonagram".

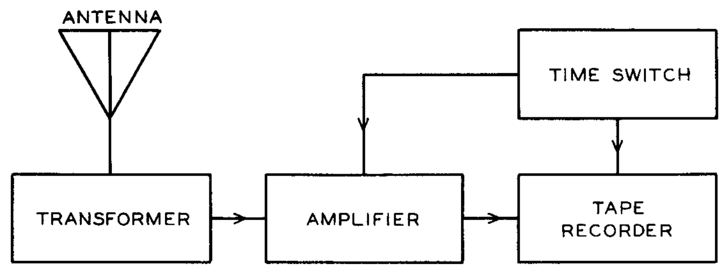


Fig. 3. Block Diagram of the Whistler Receiver.

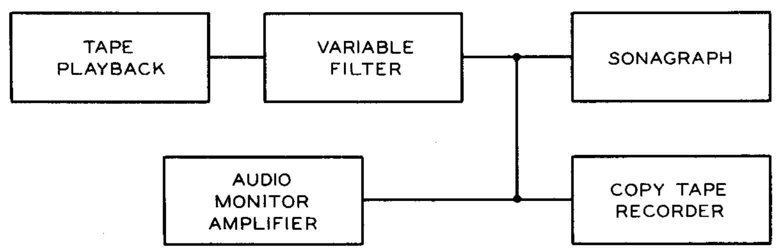


Fig. 4. Block Diagram of the Monitor Station.

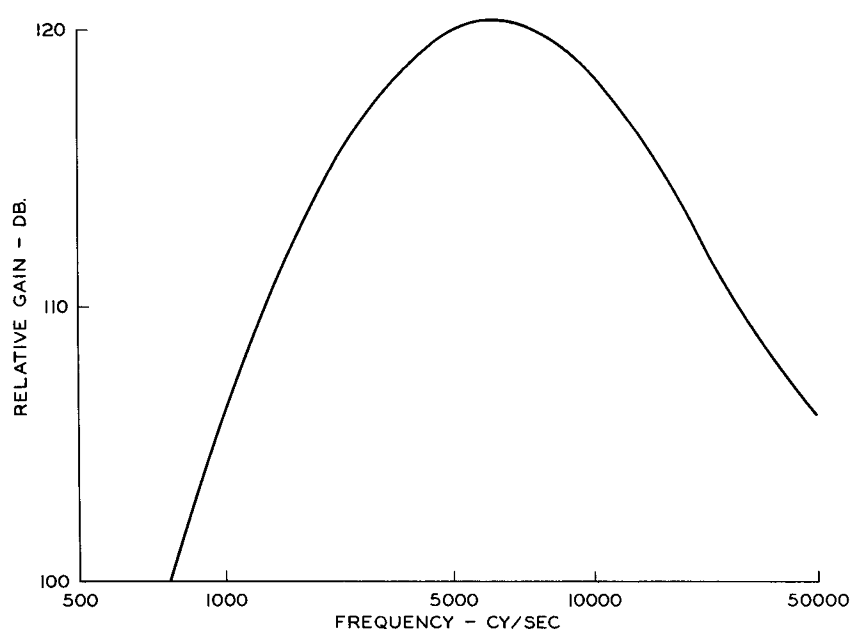


Fig. 5. Sensitivity Curve of the Preamplifier.

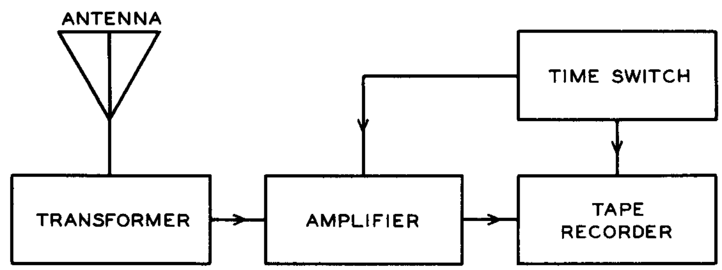


Fig. 3. Block Diagram of the Whistler Receiver.

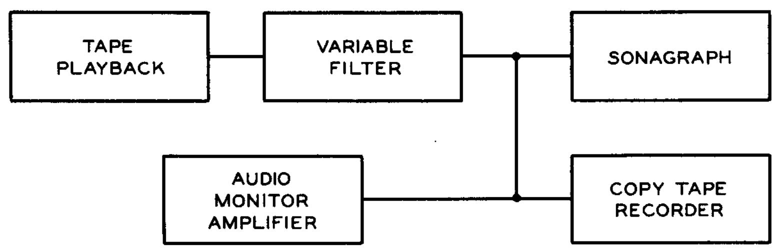


Fig. 4. Block Diagram of the Monitor Station.

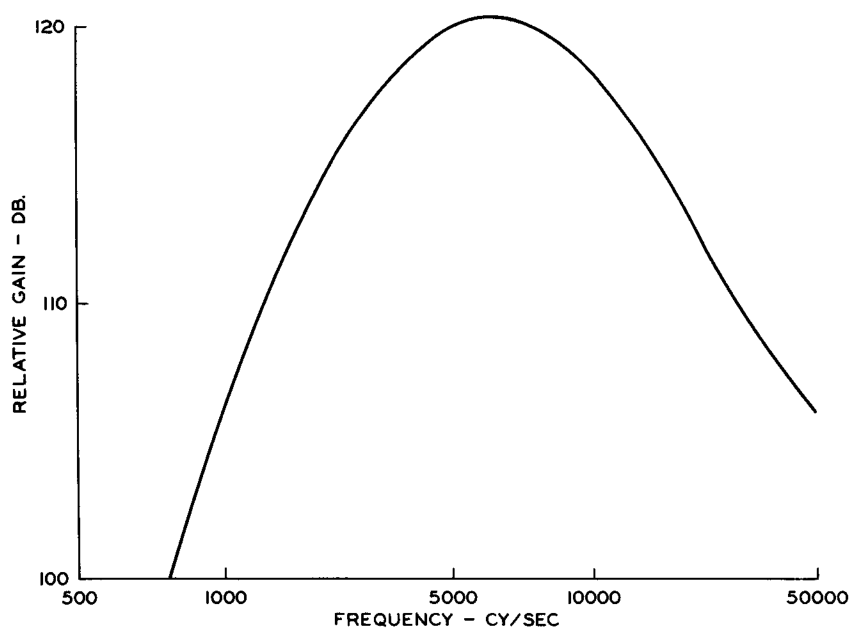


Fig. 5. Sensitivity Curve of the Preamplifier.

OBSERVATIONS

The analysis reported here covers the period from December 1955 through March 1958. The period 1-5 December 1955 was sampled on a four minute per hour basis, the period 23 December 1955 - 12 July 1957 for one minute per hour, and the period 12 July 1957 - 31 March 1958 for two minute per hour. The whistler data are normalized with respect to these operating times.

The equipment was first installed at the homestead of an employee of the Geophysical Institute between June 1955 and May 1956. Initially the a.c. noise level at this site was quite satisfactory but in February 1956 a change in the power line configuration caused a large increase in the received noise. For this reason the receiver was moved to a field station of the Geophysical Institute. Although the noise level at the new station was known to be fairly high, it represented the best available location. High pass filters were inserted in the recording system to minimize the noise interference. Tests with a small portable receiver indicated that the noise was primarily due to a pattern of currents flowing in the ground between points of large power consumption. Several attempts were made to reduce the noise by relocation of the loop within a 1,000 ft. radius of the station. Finally in May 1957, a suitable location was found. The reduction in noise was sufficient to discard the use of filters during recording.

The data obtained during the period of February 1956 to May 1957 are satisfactory for a study of diurnal and day to day variations during that time but for compatibility with data obtained before and since that time, it is desirable to use a weighting factor on the indices. This factor was determined independently for both the whistlers and chorus by the following empirical technique. All the data were first roughly normalized with respect to seasonal variations. Averages were then determined for the period of the high noise level and for that of the low noise level. The weighting factor then is the ratio of the high to low noise level averages. This ratio was found to be 3 for both the whistlers and chorus. The agreement between the two independent determinations may be noted. This factor is applied to the high noise period in the analysis below.

The data extracted from the tapes by aural monitoring are entered in daily logs. Before the start of IGY the tapes were returned to service after copying interesting and unusual events onto another tape in order to conserve tape. After the start of the IGY the original tapes have been preserved.

During the monitoring process, an integer index (0-5) is assigned to the chorus for each hour depending on a subjective determination of strength Daily indices are formed by summing the hourly integers over a Greenwich day. These indices are, of course, quite rough because of their subjective nature.

As part of the IGY program an IGY whistler receiver obtained for Stanford University was installed during January 1958. Routine observations were continued on the old equipment until the 31 March 1958 giving a three month overlap between the two receivers.

ANALYSIS - WHISTLERS

Diurnal Variations

Fig. 6 shows the diurnal variation in the rate of occurrence of whistlers during the period of this investigation which is obtained by averaging the observations for each month. It is clear that the maximum rate occurs during the early morning hours. The short vertical lines indicate the average times of sunrise and sunset at the bottom of the ionosphere above College. During the months of May, June, and July the effect while still present, is much less pronounced. The sharp decrease in activity usually occurs very close to the time of sunrise. The recovery, however, requires several hours after sunset. These results are consistent with the hypothesis that propagation conditions determine to a large extent the number of whistlers received.

Seasonal Variations

Fig. 7 is a histogram of the normalized average daily rate of occurrence of whistlers over each month during the period of the present study. It is apparent that most whistlers occur during the winter months, particularly December and January. This pattern of variation differs from that reported by Storey[2]. He found that the "long" whistlers were more prevalent during the summer and the "short" more prevalent during the winter. Lumping the short and long together he found little seasonal variation. Storey's results are consistent with the hypothesis that the short whistlers are due to lightning discharges occurring in the southern hemisphere while the long are due to discharges in the northern hemisphere.

The fact that the maximum number of whistlers occur during the winter months might mean that the short whistlers are much more prevalent than the long at this latitude. At lower latitudes the long whistlers are distinguished from the short by the occurrence or absence of a prominent tweek one or two seconds before the whistler. During the observations of several thousands of whistlers at College, Alaska, only a few have had an easily detectable associated tweek. However, the absence of an associated preceeding tweek does not necessarily imply a short whistler. A large number of random tweeks occur most of the time. If the associated tweek occurs too far in advance of the whistler even a tantative provisional association becomes difficult since it may be mixed up with a number of random tweeks. At high latitudes it may be that the interval between tweek and whistler is too great for subjective association.

To illustrate the seasonal trends it is desirable to average the data for each month of the study over corresponding months of each year. Observations are available during the months of January, February, March, for the three years 1956-58, and December for the three years 1955-57. Also, during all other months for the two years 1956-57, excepting the months of April and May for which observations were obtained essentially only during the year 1957 (a few days of observation are available for 1956). The result of averaging the observations by month of the year is shown in Fig. 8. The similarity between this curve and the curve of sunlit hours (Fig. 9) suggests the possibility that the seasonal variation in the rate of occurrence may be due to some phenomenon under solar control. One possibility is that the propagation of very low frequencies between the earth and the ionosphere is so controlled. It seems reasonable that the number of whistlers observed depends on propagation conditions because the propagation conditions determine the distance over which a whistler of a given strength can be detected. The number of whistlers received is related linearly to the square of this distance since the probability of receiving a whistler is proportional to the area. It is difficult to correct for this factor without more direct measurements of the propagation parameters.

Correlation with Magnetic Activity

Storey found a small positive correlation between the occurrence of whistlers and magnetic activity[8]. He suggested that this correlation is due to the possibility that the ionization of the outer ionosphere becomes too small to support whistler propagation during magnetically quiet periods and replenished during storms. If true, it would seem that the effect might be enhanced at high latitudes, since the whistlers propagate much farther out from the earth.

Using daily indices of whistler activity determined from the number of whistlers received at College and the daily K-index sums for College, the coefficient of correlation has been determined for the period December 1955 to February 1958. This value is .004 for 648 days. This low value, however, does not exclude the possibility of a cyclic variation in the coefficient of correlation. Fig. 10 shows the correlation coefficient determined on a monthly basis for each month in this study. The whistler index used is simply the daily sums of whistlers received during the Greenwich day and the index of magnetic activity is the daily K figure sums for College, Alaska. A cursory examination of this graph indicates a random variation of the coefficient about zero, which is to be expected from an overall zero correlation. However, a closer inspection reveals several apparently significant departures notably during the months of September 1956 and June 1957. The probability of obtaining either of these two coefficients by change alone is less than 1 in 100. We note also that the correlation tends to be positive during equinoxes and negative during soltices. Another test is to assume that the overall coefficient is zero and determine the confidence belts considering the number of days used in each month. The average number of days used is 26. For 25 days and a zero coefficient of correlation the probability is 5 per 100 that the coefficient will exceed $\pm$ 0.4 by chance alone. In 25 months this belt is exceeded 4 times, which is 16% compared with an expected 5%. While this value is probably not high enough to be considered significant, it indicates that further study must be made before a conclusion can be reached concerning the covariance of whistlers and magnetic activity at high latitudes.

Summary

Analysis shows that a number of differences exist between the occurrence of whistlers at high and low latitudes. In high latitudes the seasonal variation peaks during the winter months. The diurnal variation is similar for high and low latitudes except that it has a maximum during the early morning hours in high latitudes instead of the early evening hours as shown by Storey. Also the diurnal variation is much less pronounced in summer than winter. These differences can be explained at least in part, by propagation conditions at high latitudes.

The covariance between magnetic activity and the occurrence of whistlers in high latitudes also shows a definite departure from that of lower latitudes. The data presented are not sufficient to determine whether any connection exists or whether a seasonal variation exists. However, they do show a result quite different from the correlation coefficient of 0.4 reported by Storey. It might be tentatively assumed that there is no correlation between magnetic activity and occurrence of whistlers in high latitudes

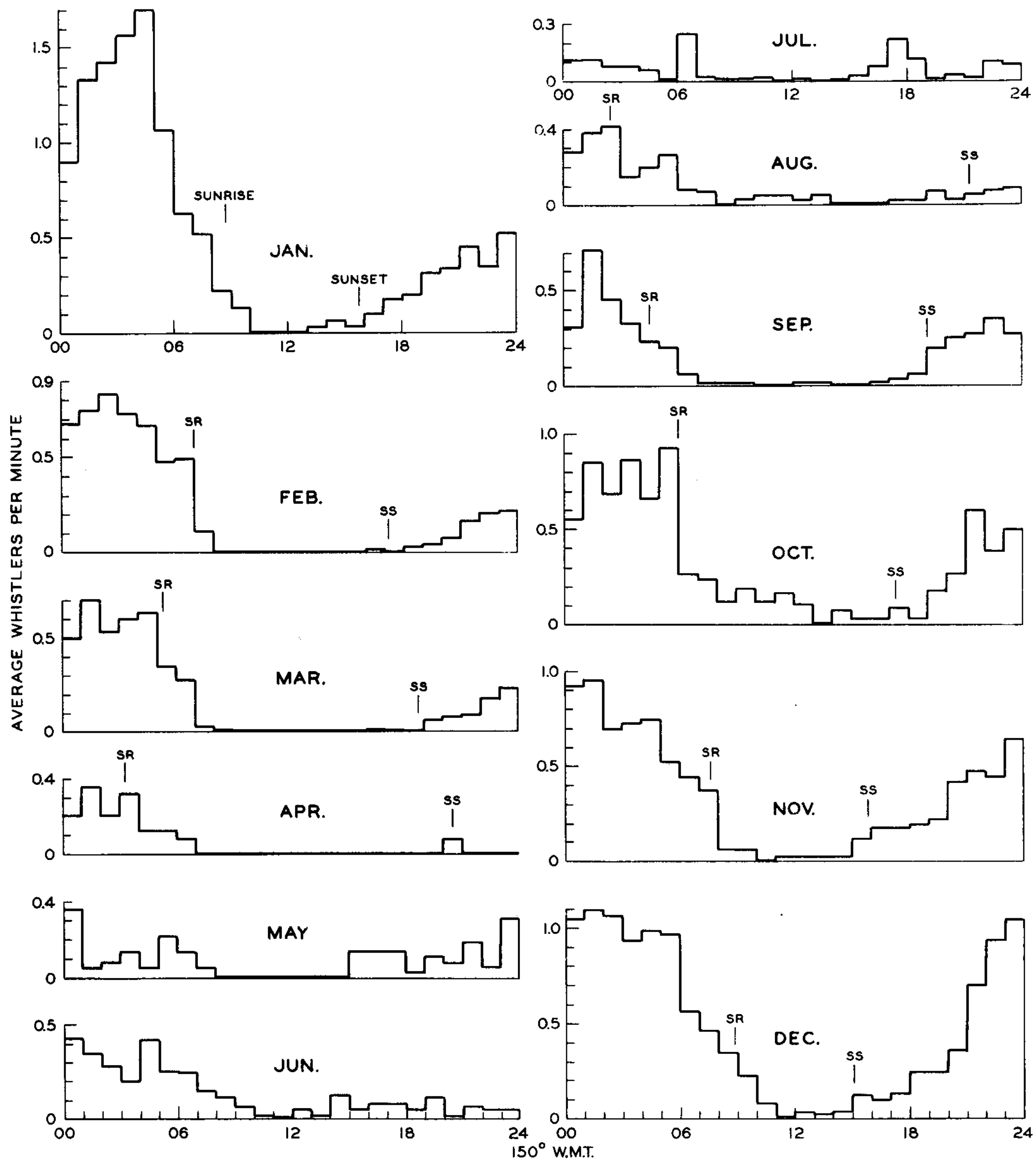


Fig. 6. Diurnal Variation of Whistler Occurrence at College.

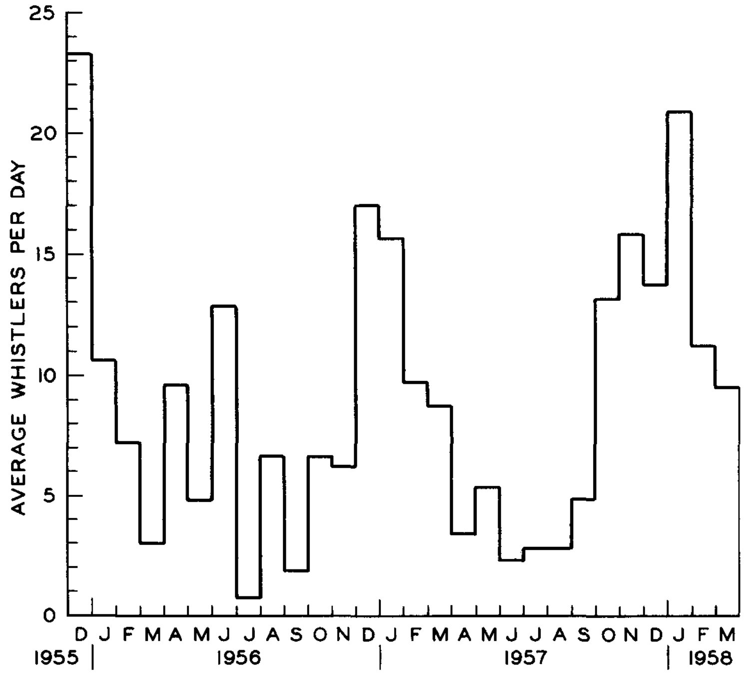


Fig. 7. Average Daily Occurrence of Whistlers at College.

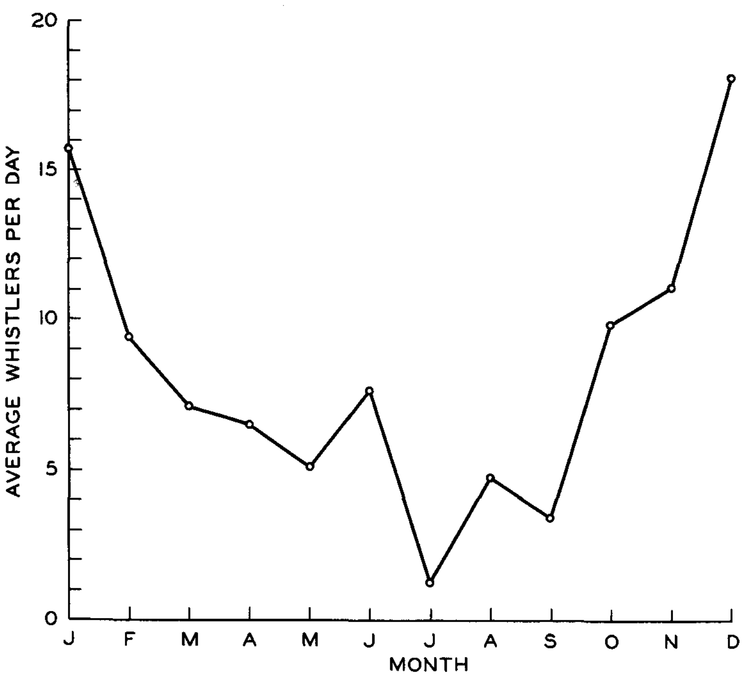


Fig. 8. Seasonal Variation in Occurrence of Whistlers at College.

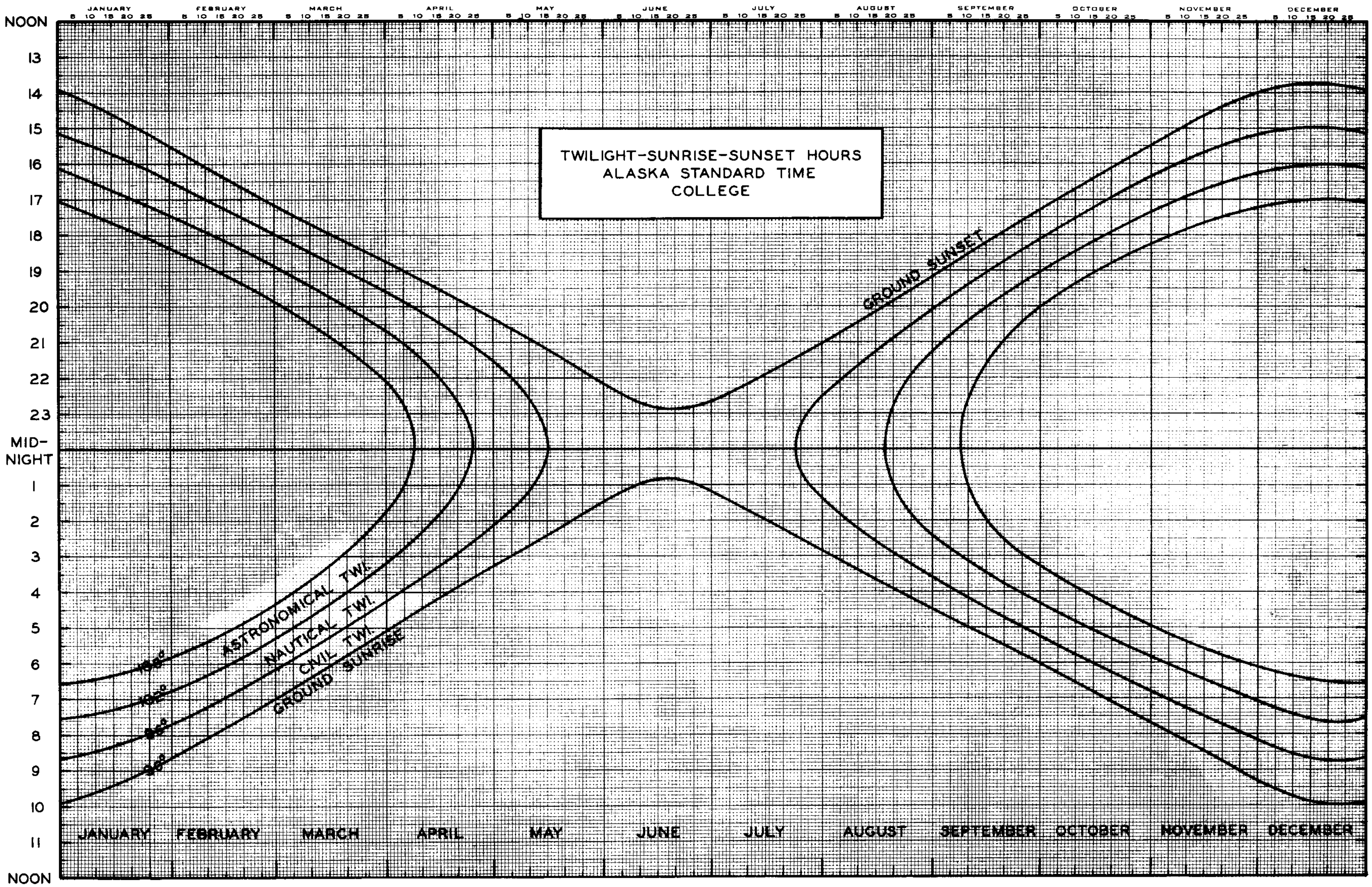


Fig. 9. Sunlight Curve.

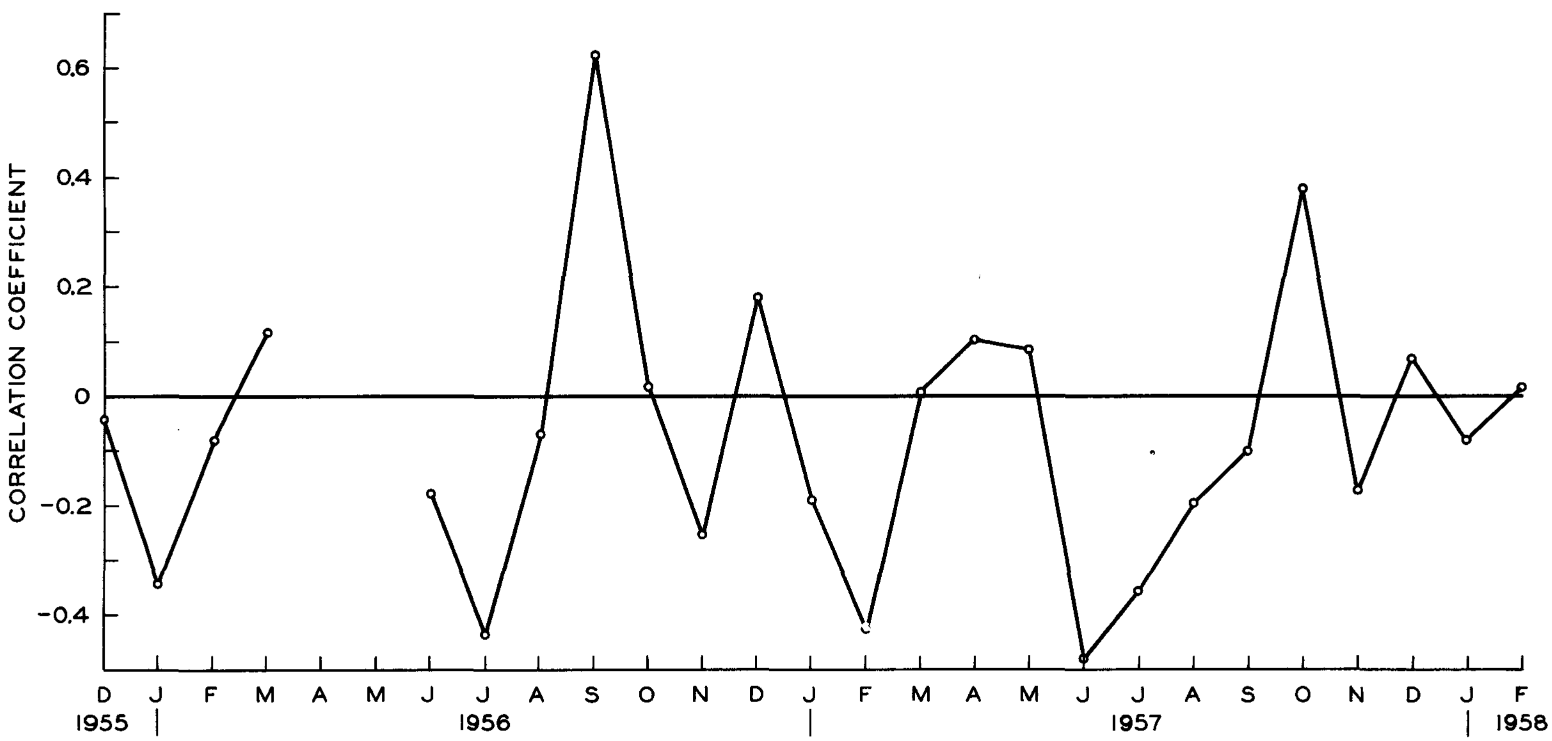


Fig. 10. Correlation of Daily Whistler Occurrence vs. Daily K-index Sums for College by Month.

ANALYSIS - CHORUS

Diurnal Variation

Fig. 11 shows the average occurrence of chorus for each month. These histograms were obtained in the following manner. An integer index (0-5) was assigned to each hour based on the strength of chorus received. The hourly indices for a particular hour, were summed over the month. Repeating this sum for each hour in the day results in an average diurnal curve for the month. Finally the results for each month were averaged with those for the corresponding months of each year in the study. The main feature shown is a maximum near 1400 hours local time which shows a small systematic variation with season. Fig. 13 shows this small seasonal variation in the time of diurnal maximum.

The fact that this peak occurs at 1400 hours is a departure from the results at lower latitudes*. The local times of maxima for various stations have been obtained, partly from data received on a data interchange program. Fig. 12 is a plot of the times of maxima as a function of the geomagnetic latitudes of the station. One might also consider local geomagnetic time instead of geographic time as the variable with which the function should be plotted. A similar plot in which geomagnetic time has been used shows about the same amount of scatter as the plot using geographic time, hence, it is possible to determine which is the "proper" variable to use from the data presently available. One reason for this lack of discrimination is the fact that most of the stations involved in the study made recordings every three hours instead of each hour. The time resolution of three hours is

*These results were presented in a paper to the AAAS during September 1956 and published in NATURE[6] (August 1957). McK Allock[7] has also noted this effect in an independent investigation using the same data.

larger than the corrections for magnetic time, the largest of which is 1.7 hours. During the IGY all of the stations will record hourly thus it may be possible to determine whether geomagnetic time is the "proper" variable to use. In the meantime it is probably better not to prejudice the situation by using a special time other than the usual local time.

The diurnal curves show secondary peaks during the winter months which appear to be significant. The time of this peak is one hour later in January and November than that of December. Most of the other curves show peaks displaced about one hour per month from the December peak. The month of July apparently shows the two peaks merged by a broad maximum. Fig. 13 shows a plot of these times of maximum as a function of time of year. These results indicate the possibility that a secondary maximum exists which exhibit a seasonal variation in time of diurnal occurrence. The present data are not sufficient to definitely establish the indicated seasonal variation although the occurrence of a secondary maximum during the winter appears to be significant.

Seasonal Variations

Fig. 14 shows the average daily chorus indices for each month. The results for the months between February 1957 to May 1957 have been modified to take into account a higher noise level during that time as explained above. A winter time maximum is shown and possibly a secondary maximum during the summer months.

Correlation with Magnetic Activity

Storey[8] has found a correlation coefficient between the occurrence of chorus and the Arbinger K-figure of 0.64 over a period of 90 days, comprising the months of February, March, and July of 1951.

Fig. 15 is a plot of the monthly correlation coefficients between daily chorus indices for College and daily K-index sums for College. From this graph, it is seen that the covariance between chorus and magnetic activity varies in such a way that it is positive during solstices and negative during equinoxes.

This seasonal variation appears to be quite systematic. To test the significance of the excursion assume that the actual correlation coefficient is zero. The 95% confidence belt for 25 pairs of data for a zero coefficient is $\pm$ 0.4. Thus it can be expected that if the population coefficient is indeed zero then this belt will be exceeded in about 5% of the cases studied. In this study the belt is exceeded 8 times in 28 months or about 28%. Since the number of days available in each month varies from month to month, some of them having less than 25 days, it might be desirable to study each month individually with respect to the confidence belt. Table I contains a tabulation of the 95% confidence belts for each of the months studied. These belts are exceeded in 6 of the 28 months or 21%. It therefore appears that the seasonal variation noted is statistically significant.

Fig. 16 shows the diurnal variations of the coefficient of correlation on a three hourly basis for the months of December 1957, January, February, and March of 1958. They are derived by correlating the three-hourly sums of chorus with the three-hourly K-indices for College. A coefficient is thus determined for each three-hour period in a day over the month. These curves show that even during a month when the correlation is significantly positive on a daily sum basis that a negative correlation on a three-hourly basis, exists during the night. It is apparent that the correlation between daily sums is determined to a large extent by the daytime part of these curves, which is a reasonable supposition considering the diurnal variation of occurrence of chorus.

TABLE I

Date	Correlation Coefficient Daily Chorus Sums vs. Daily K Sums for College	Number days data	95% Confidence belt for Population Coefficient = zero	Correlation Coefficient Daily Chorus sums vs. daily Auroral Indexes for College	Correlation Coefficient Daily Chorus sums for Washington D.C. vs. Daily K Sums for Fredericksburg
Dec '55	.539	12	± 57		
Jan '56	.276	20	± 44	.64	
Feb	.192	19	.43	.413	.570
Mar	-.119	27	.38	.140	.661
Apr	.202	5	.88		.655
May	-.139	8	.70		.553
June	.526	30	.37		.628
July	.196	20	.44		.667
Aug	.260	30	.37		.728
Sept	.107	21	.43		.291
Oct	-.441	24	.41	-.374	.499
Nov	-.101	21	.43	.131	.637
Dec '56	.453	26	.39	.703	.543
Jan '57	-.012	22	.42		.731
Feb	-.370	24	.41		.656
Mar	-.416	27	.38		.735
Apr	-.793	26	.39		.462
May	.059	28	.38		.496
June	-.010	30	.37		.314
July	.442	16	.50		
Aug	.110	27	.38		
Sept	-.278	23	.41		
Oct	.068	28	.38		
Nov	.065	28	.38		
Dec '57	.566	26	.39		
Jan '58	.146	31	.36		
Feb	.181	28	.38		
Mar	-.236	25	.40		

The state of knowledge of the origin of chorus at present affords no simple explanation of the peculiar behavior reported here. One might consider the geometric configuration of field lines with respect to the direction of arrival of solar particles at different times of the year. A more profitable approach might be to consider the presence of an obscuring phenomenon which is also dependent on solar particles such as ionospheric absorption. It is known that absorption correlates well with magnetic activity[9] and that the amount increases considerably during equinoxes. One might expect a negative correlation between absorption and chorus and a positive correlation between chorus and solar particle activity. Thus, either a positive or a negative correlation with the K-figure might result depending on the amount of absorption present. In either case, the magnitude of the correlation coefficient is likely to be low since some absorption is present most of the time and since solar particle activity must be present to generate the chorus.

It is known that the amount of absorption is larger at high latitudes than at low. If the explanation of this seasonal variation in terms of ionospheric absorption is correct, it is apparent that the effect might be less pronounced at lower latitudes. It is likely that the correlation would always be positive with the K-figure but a careful analysis of the low latitude data might reveal a small variation with respect to season.

To compare the high and low latitude correlations, the chorus data for Washington, D.C. was correlated with K-indices for Fredericksburg on a monthly basis. Fig. 15 shows these monthly correlations. There appears to be little systematic variation but a random variation about 0.6. Assuming a population correlation coefficient of 0.6, the probability is 95% that the sample correlation coefficient is between 0.3 and 0.8 for 30 pairs of data.

This belt is exceeded only once in the 17 months sutdied. These results, therefore, do not show a seasonal variation of the correlation coefficient, although they do not exclude its possibility.

Correlation with Aurorae

There has been some speculation that the origin of chorus might somehow be connected with auroras. This conjecture seems unlikely, however, because of the different diurnal variations. Observations of aurorae were made several times while listening to the whistler receiver to determine whether any of the audio frequency radio noise can be attributed to the aurorae. Chorus or other noises which could be attributed to auroras, were not present during any of these tests although considerable aurorae were present. Correlations between daily indices of the two phenomena were made on a monthly basis for six months of 1956. Even though no direct connection with aurorae can be supposed, five of the months showed a positive correlation higher than that obtained between K-indices and chorus. Table I summarizes these various correlations. This fact can be taken to mean that the aurora is a better measure of magnetic activity to use with chorus than are K-indices. The K-indices are a measure of the extent of the variations in the magnetic field rather than over-all magnetic activity. Because of the obvious limitations in the use of auroral indices, however, it is usually necessary to use K-indices. As might be expected, these results tend to show the same systematic seasonal variation as that of the correlation between K-indices and chorus.

Characteristics of Chorus

Chorus has a high degree of variability in its many characteristics. It is usually a multitude of short ascending tones but can also decrease in frequency with time or stay almost constant. An individual element might start with a decrease followed by an upward sweep in frequency. It usually goes through a range of 2 or 3 kc. This range may be shifted up or down limited only by the bandpass of the instrumentation.

A statistical analysis of the characteristics should contribute significantly to the knowledge of chorus. For a preliminary study the average frequency (i.e., the mid-frequency of its range) has been used. Fig. 17 is a histogram of the frequency of occurrence of the mid-frequency as measured on the chorus obtained between December 1955 to March 1958 for which sound spectrograms have been made. The curve is a normal distribution fitted to the data. The mid-frequency of most frequent occurrence is 3.5 kc according to this plot. How much the frequency response of the instrumentation affects these results is determined to a large extent by the response of the preamplifier which peaks at about 5 kc. The low frequency end of the spectrum is limited by harmonics of 60 cycle noise up to about 1.5 kc. Thus, it seems that the actual peak can be no higher than 3.5 kc but it might be somewhat lower.

Fig. 18 shows the diurnal variation of the mid-frequency. A least squares sine curve has been fitted to the data. The minimum is at about noon local time while the maximum is near midnight.

Although these results are preliminary they show that more work should be done on analysis of the characteristics. They should be compared with those at lower latitudes to determine any latitude dependence. A short term experiment could be performed using equipment designed for frequencies less than 2 kc at a remote low noise site to determine whether the value 3.5 kc is in fact, the most usual mid-frequency. It would also be helpful to have a generally accepted scheme for classifying chorus. Other measurements of characteristics such as the rate of change of frequency might also be made and analyzed statistically.

Summary

Chorus, as received at College between December 1955 and March 1958, shows seasonal and diurnal variations of occurrence. The diurnal variation is significantly different from those obtained in lower latitudes at its time of maximum. The seasonal variation shows a maximum in the winter and a possible maximum during the summer. These results also appear to differ from those obtained at low latitudes in that the maxima at Washington, D.C. seem to occur at the equinoxes.

The different diurnal curves makes it unlikely that propagation conditions of low frequency radio waves between the earth and ionosphere can be the cause of the diurnal variation. The time of maximum is seen to be a function of latitude. Thus, it appears that the observed diurnal variation is essentially a characteristic of the phenomenon of chorus itself, rather than one of some other phenomenon. The seasonal variation observed might be attributable to other phenomena such as ionospheric absorption.

The correlation between chorus and magnetic activity has a seasonal variation. This variation might be due to a complex interaction between three or more phenomena. It appears that the generation of chorus is related in a positive manner to magnetic activity and hence, possibly solar corpuscular radiation.

Neither theory nor analysis of chorus has progressed to a point where one theory or another can be considered more likely. For the time being the various theories proposed must be considered essentially conjectures. There is some evidence, however, indicating that chorus might be generated by solar particles. Further investigation in this direction may lead to conclusive results.

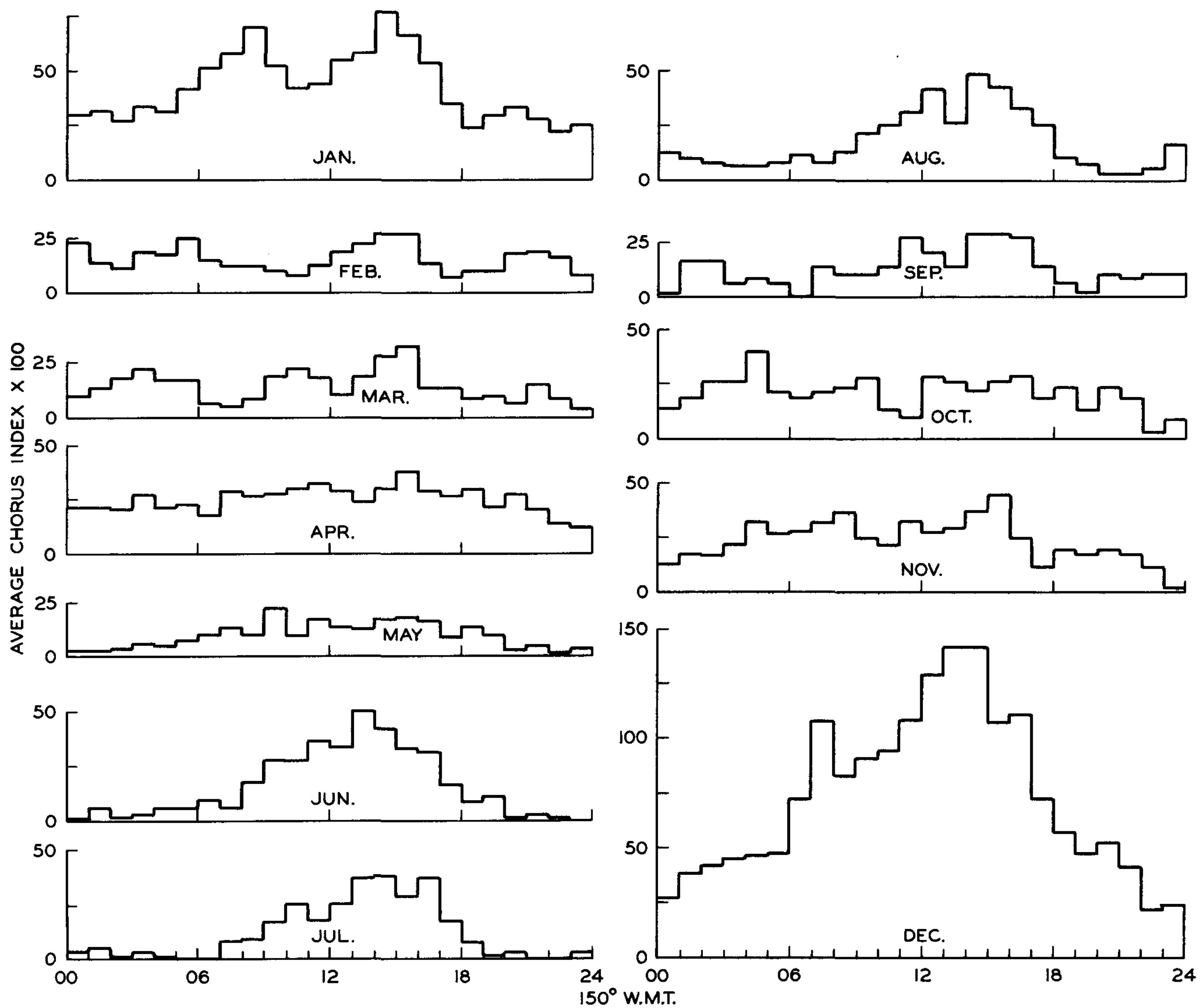


Fig. 11. Diurnal Variation of Chorus Indexes.

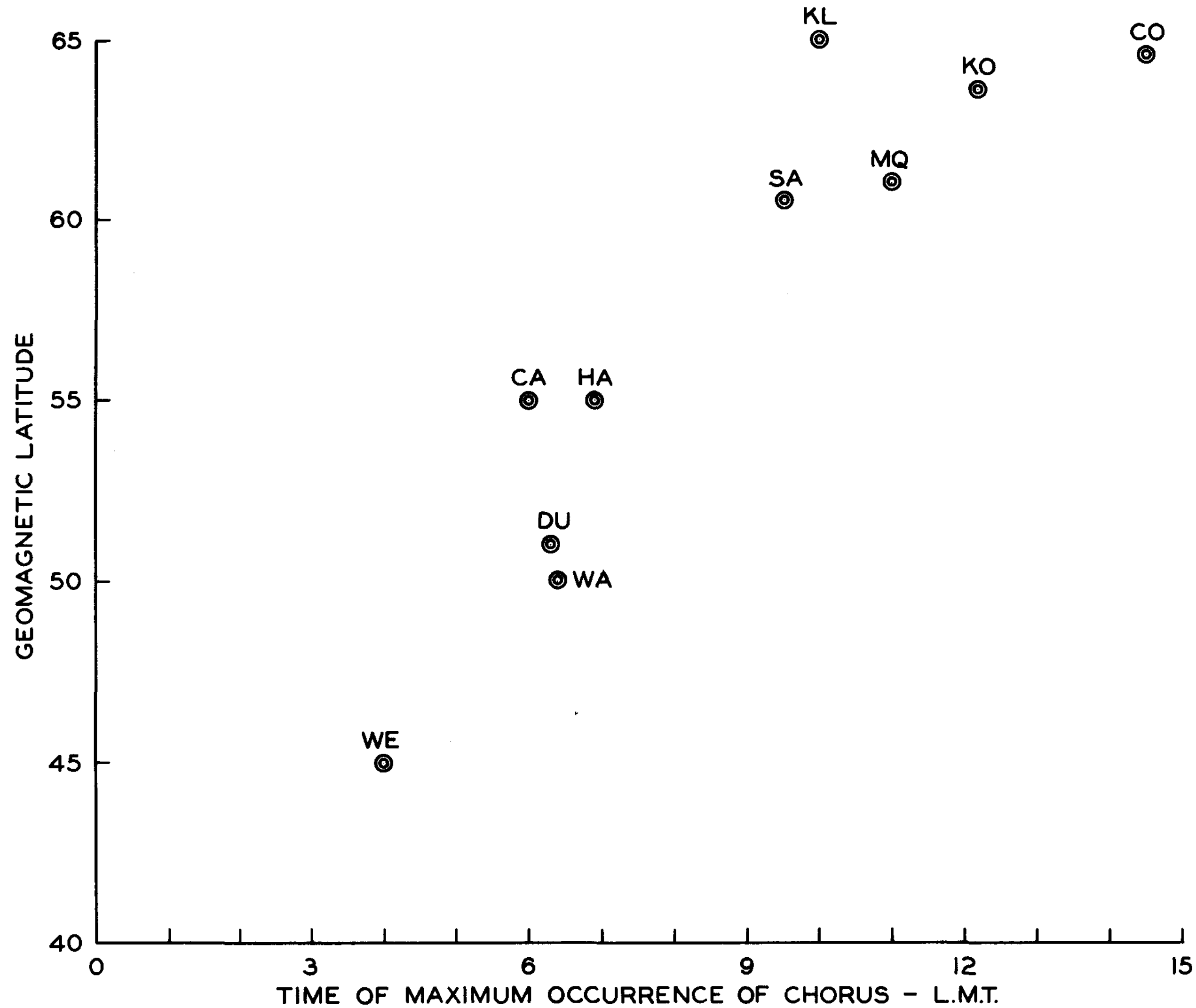


Fig. 12. Time of Diurnal Maximum as a Function of Geomagnetic Latitude.

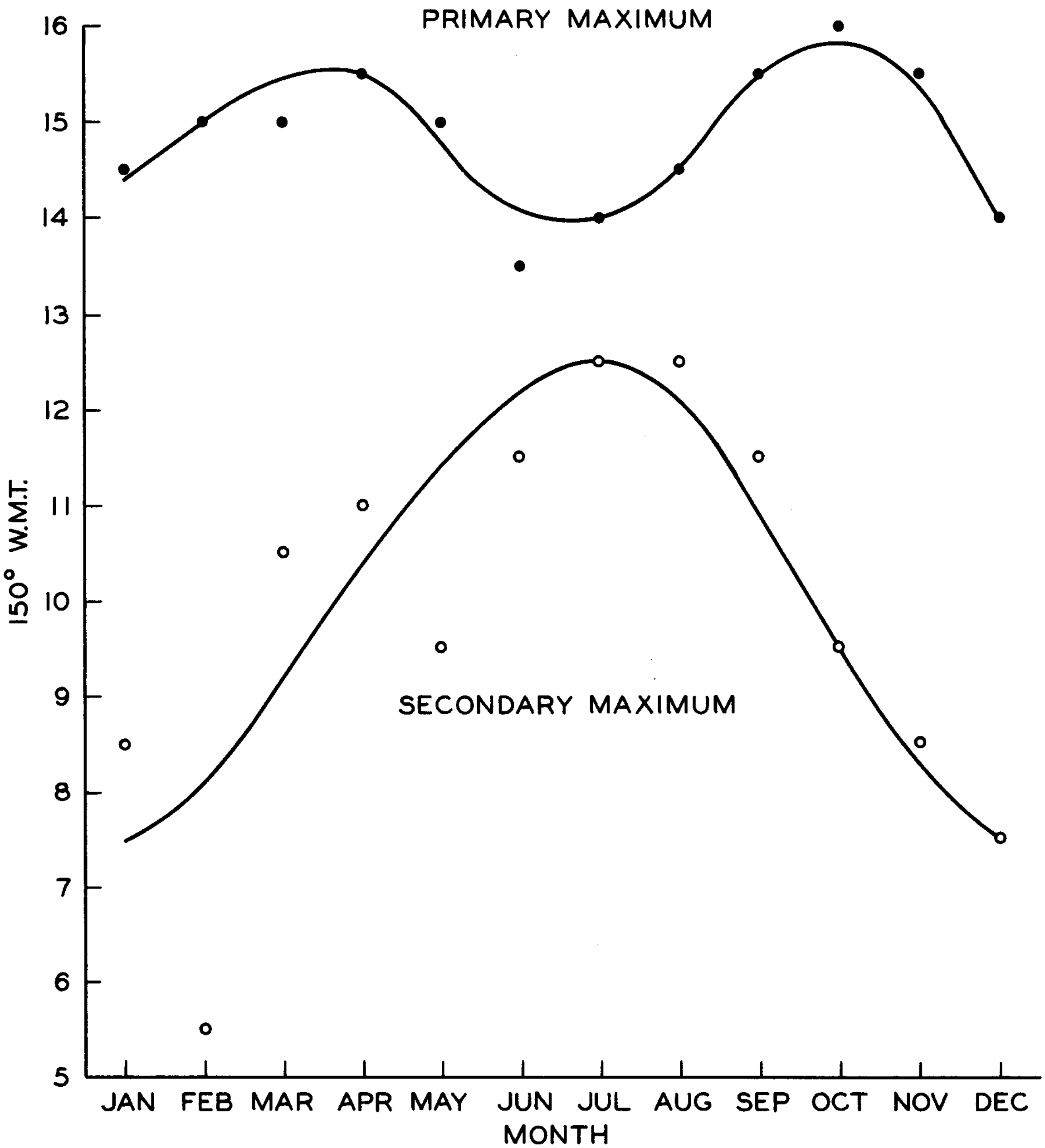


Fig. 13. Primary and Secondary Diurnal Maxima vs. Month.

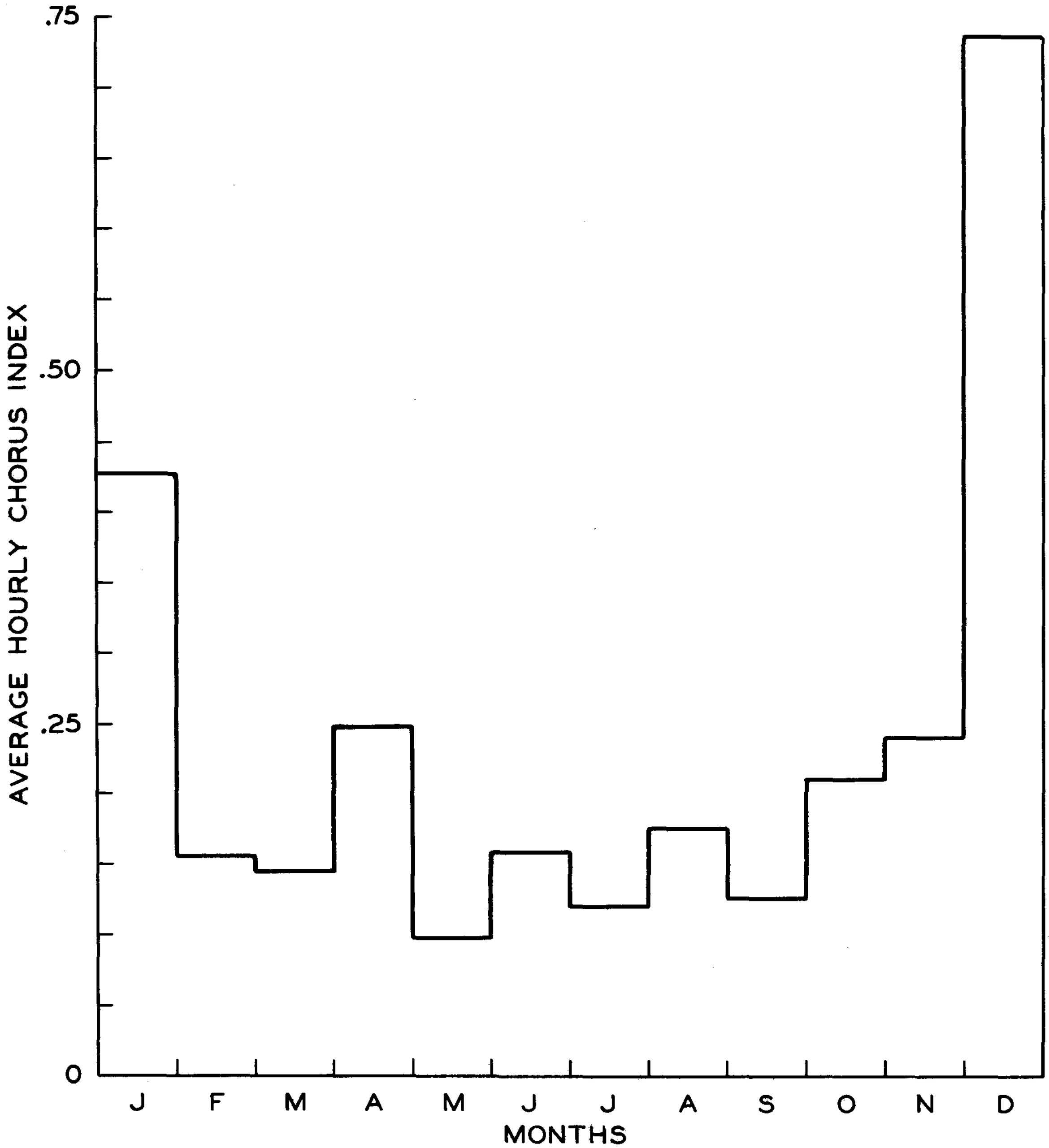


Fig. 14. Seasonal Variation in Occurrence of Chorus.

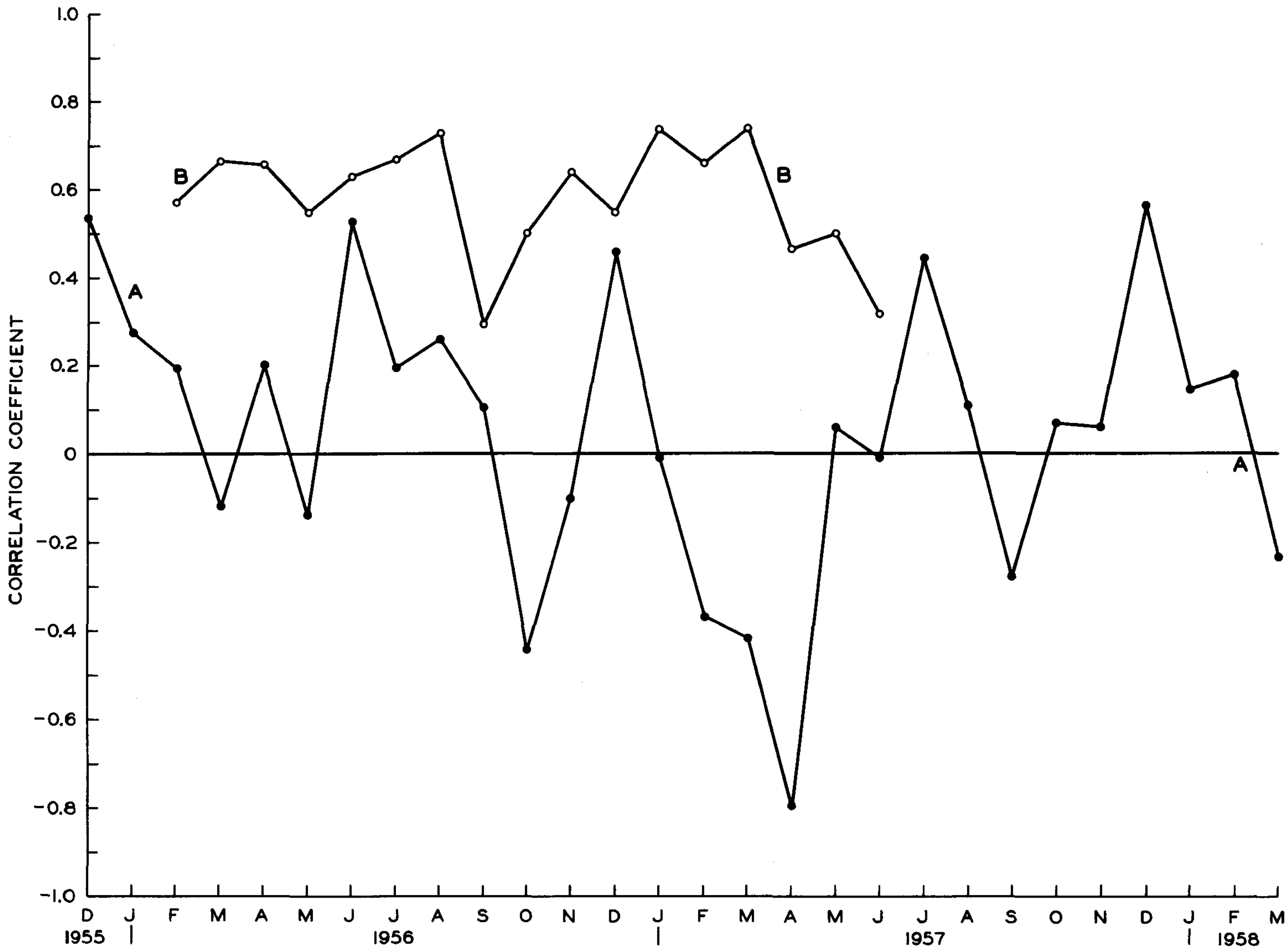


Fig. 15. Correlation Coefficients for (A) Daily Chorus Indexes for College vs. Daily K-index Sums for College, and (B) Daily Chorus Indexes for Washington, D.C. vs. Daily K Sums for Fredericksburg.

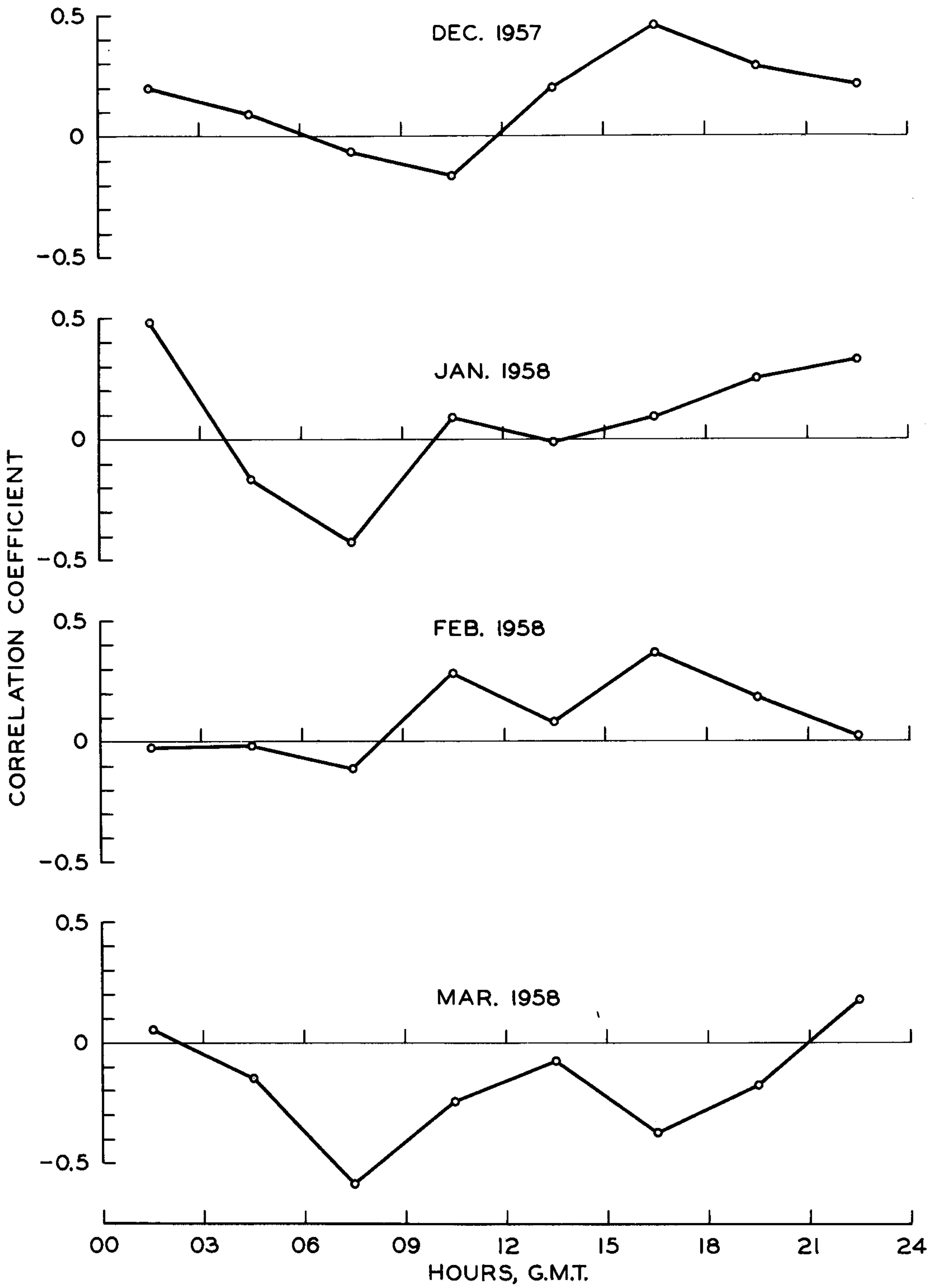


Fig. 16. Diurnal Variation of the Coefficient of Correlation for Chorus Indexes vs. K-indexes.

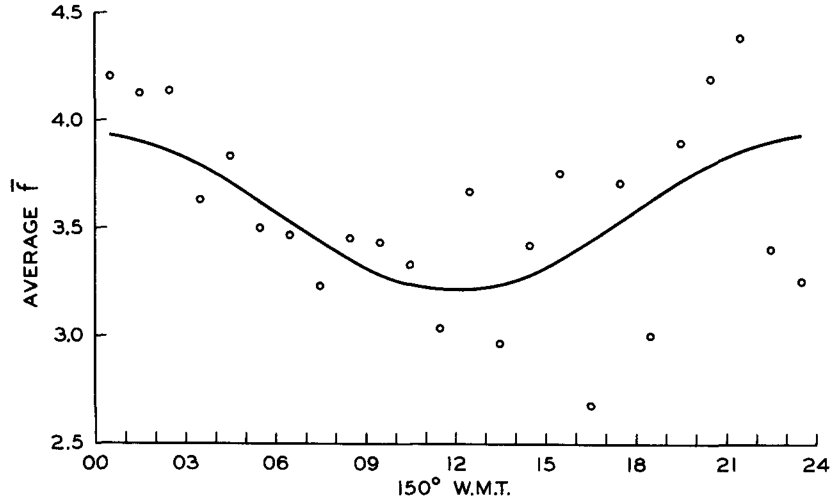


Fig. 18. Diurnal Variation of $\bar{f}$.

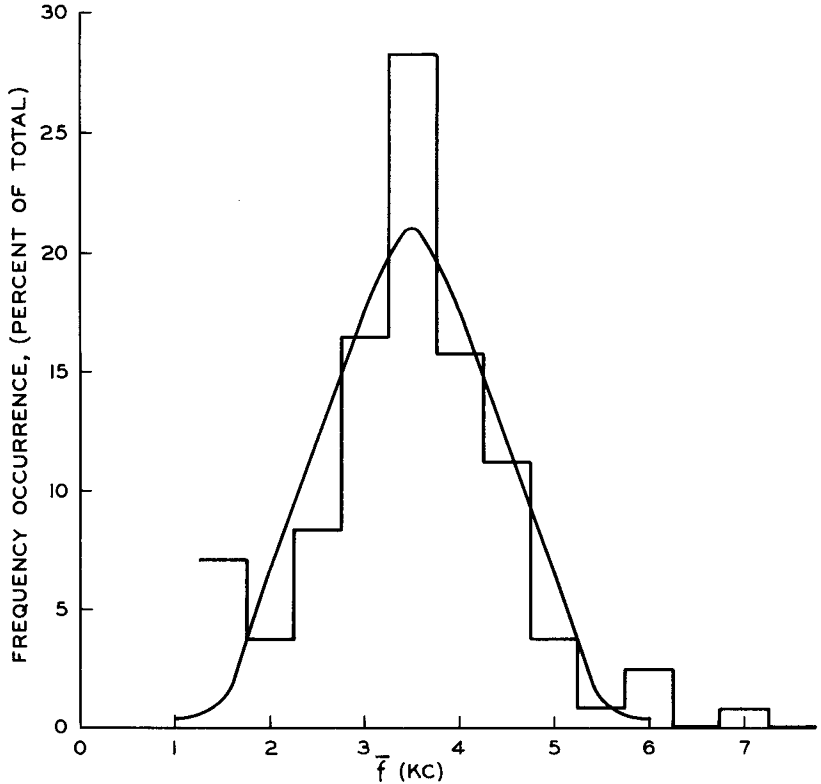


Fig. 17. Occurrence of $\bar{f}$.

DISCUSSION

There are several unsolved problems associated with whistlers. Among them is the cause of the branching of whistlers, that is, the tendency of a single whistler to be composed of many different components each having a different nose frequency. Another is the occurrence of echoes. Why is it that sometimes echoes are prominent and sometimes not, even though many whistlers occur? Whistlers should provide a means for determining the electron density of the outer ionosphere but the solutions to this problem are still quite unsatisfactory.

The nature of chorus is still not known. The traveling wave hypothesis of Helliwell and Gallet[10] seems promising but it is difficult to see how it can explain the diurnal variations or the latitude effect in the time of diurnal maximum.

The nature of the connection with magnetic activity is not clear. The correlation of 0.6 indicates a connection but this value is not as high as the correlations between magnetic activity and other solar particle associated phenomena such as aurora. The strange fluctuation from positive and negative correlation between chorus and magnetic activity observed at College needs to be investigated.

The statistical study of the characteristics of chorus has only been started. One of the problems is to devise simple measurements of the various characteristics. Another is to obtain a consistent classification of the various types observed. Possibly some of these types are phenomena essentially different from chorus. It seems desirable to find how the characteristics and types of chorus change as a function of geomagnetic latitude on a statistical basis.

It would be interesting to study chorus at higher geomagnetic latitudes than that of College to see whether the latitude effect is still applicable. Also it is desirable to consider the region below 1000 cycles to see if chorus occurs in this band.

The study of whistlers and chorus at high latitudes has contributed significantly to the progress in this field. The discovery of the nose whistler and that of the latitude effect in the occurrence of chorus are attributable to high latitude investigation. There is reason to suppose that the study of electron densities using high latitude whistlers will produce significant information concerning the outer atmosphere. In addition, a continued study at high latitudes should contribute to a theory of the origin of chorus and an explanation of the nature of the multiple branching of whistlers.

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Dr. R. H. Helliwell and his group at Stanford University have been helpful in giving technical assistance towards the establishment of the whistler station at College. They also supplied spectral analysis of some of the early tapes before the arrival of the equipment at College, necessary to make these analyses.

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