The research reported in this document has been sponsored by Electronics Research Directorate, Air Force Cambridge Research Center, Air Research and Development Command.
## ERRATA SHEET

<table>
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<tr>
<th>Figure No.</th>
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<tr>
<td>21</td>
<td>Add &quot;of&quot; after month.</td>
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<tr>
<td>22</td>
<td>Add &quot;18 Mc/s&quot; after title of figure.</td>
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<td>23</td>
<td>Add &quot;12 Mc/s&quot; after title of figure.</td>
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<tr>
<td>24</td>
<td>Insert &quot;Figure 24A&quot; before the title, &quot;Comparison of Received Signal and Ground-scatter, 12 Mc/s, December 8, 1958&quot;. Change &quot;24&quot; to &quot;24B&quot; on title of bottom figure.</td>
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<tr>
<td>42)</td>
<td>Under the column &quot;Figure No.&quot; substitute 14 for 6.</td>
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<td>43)</td>
<td>&quot;date&quot; should read &quot;data&quot;.</td>
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<tr>
<td>54 Line 4</td>
<td>Should be, &quot;The diurnal variation in chorus activity at Kotzebue is similar . . . .&quot;</td>
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<td>59 Line 8</td>
<td>Change &quot;24&quot; to &quot;24B&quot;.</td>
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<td>87 Line 7</td>
<td>Bottom line of footnote, &quot;( \leq 0.5 )&quot; should read &quot;( \geq 0.5 )&quot;.</td>
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GEOPHYSICAL INSTITUTE
OF THE
UNIVERSITY OF ALASKA

ARCTIC PROPAGATION STUDIES AT TROPOSPHERIC
AND IONOSPHERIC MODES OF PROPAGATION

FINAL REPORT
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Prepared for
ELECTRONICS RESEARCH DIRECTORATE
AIR FORCE CAMBRIDGE RESEARCH CENTER
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C. T. Elvey, Director
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ABSTRACT

Two types of direct scatter from the F region are identified on the records from the oblique incidence sweep-frequency sounder located at College, Alaska. One type of echo appears to come from randomly distributed, field-aligned irregularities in the ionosphere and the other from discrete patches of irregularities. The former is essentially a nighttime phenomenon, while the latter occurs mostly during the day. From these direct scatter modes we can obtain an estimate on the horizontal and the vertical extents of the irregularities. Analysis of the data for the past year has shown that the randomly distributed irregularities commonly occur in regions having horizontal extents of more than 1000 km. The discrete irregularities appear to extend throughout most of the lower half of the F layer. The sequence of events near sunrise and sunset on a magnetically quiet winter day indicates that solar radiation eliminates the random irregularities and accentuates the discrete irregularities.

Certain phenomena frequently recorded on high latitude ionograms such as Spread F and triple splitting are probably manifestations of backscatter from ionospheric irregularities. The occurrence of Z-traces in College ionograms is studied statistically and it is concluded that the majority, if not all, of the Z-traces are produced by backscatter of the radiation obliquely incident in the direction of the magnetic zenith.

Fixed frequency oblique incidence soundings on frequencies of 12, 18 and 30 mc/s made at College, Alaska show both direct backscatter from the E and F layers and F layer propagated backscatter from the ground. The 12 mc/s soundings made during 1956 have been re-scaled under this contract.
to extract the available information concerning direct backscatter echoes at ranges below 1000 km. The direct backscatter echo from the F layer (1F echo) has a large diurnal maximum at approximately 1800 AST and a smaller maximum at 0400 AST. 1F echoes are observed at ranges from 500 to 1000 km, usually occurring at approximately one-half the range of the 2F echo. The azimuth distribution of the 1F echo has a maximum centered on magnetic north.

Direct backscatter from the E layer (1E echo) occurs in the range interval of 200 to 800 km with a maximum between 300 and 500 km. The azimuth distribution maximum is centered on magnetic north and the diurnal distribution shows maxima from 0000 to 0200 AST and 0300 to 0400 AST.

F layer propagated backscatter from the ground (2F echo) is investigated using both the 12 mc/s 1956 soundings and soundings on 12, 18 and 30 mc/s obtained during 1958. Histograms showing the diurnal distribution of 2F echo occurrence on 12 mc/s for 1956 and 1958 are essentially the same, and illustrate solar effects on the F layer. The behaviour of the regular 2F echo on 12, 18 and 30 mc/s for a typical day in December 1958 is illustrated by a series of PPI photographs.

The results obtained during an experimental investigation of the drift motions of auroral ionization are summarized, and certain properties of the luminous aurora established by photo-electric measurements reviewed.

Some preliminary observations of solar radio emission at 65 mc/s are reported.

A technique of estimating the electron densities of the outer ionosphere by the use of nose whistlers is described. The method involves the numerical integration of the whistler dispersion equation after first assuming a model
for the distribution in density. This technique is applied to several
whistlers which occurred on 19 March 1959 resulting in estimates of electron
densities between four and five earth's radii.

The temporal variations in the occurrence of chorus during the IGY
at College and Kotzebue, Alaska are studied.

The results of an investigation of the effect of latitude on the
diurnal maximum of chorus indicate that it is desirable to use a latitude
based on the location of the eccentric dipole rather than the usual geo-
magnetic latitude for the study of chorus.

The mathematical theory of longitudinally propagated whistlers in a
magnetic dipole field is developed. The usual method for deriving electron
density distributions in the exosphere from nose whistler observations by
means of assumed distribution functions is criticized and shown to be
ambiguous and subjective. A systematic method which avoids subjective
assumptions is described. The whistler propagation problem is reduced to
an integral equation and a first order principal value solution is obtained
by using an approximate form of the equation. Higher order solutions may
then be derived by an indicated iterative procedure.

Five short-term transpolar transmission tests conducted jointly by the
Geophysical Institute and the Norwegian Defence Research Establishment
during 1956-59 are described briefly. Some preliminary results of a
transarctic propagation study on 12, 18 and 30 mc/s made by the Geophysical
Institute in cooperation with the Kiruna Geophysical Observatory, Sweden,
are reported. Simultaneous backscatter soundings of the polar region from
College, Alaska and recordings of the forward propagated signal at Kiruna,
Sweden are used to deduce the propagation conditions and modes. The 12 mc/s
and 18 mc/s pulse transmissions from College were received at Kiruna over
80% of the time during the month of December 1958. Groundscatter echoes from the polar regions indicated that a three-hop mode occurred 52% of the time on 12 mc/s and 49% of the time on 18 mc/s. Similarly, a two-hop mode occurred 9% of the time on 12 mc/s and 12% of the time on 18 mc/s. A signal was recorded at Kiruna 19% of the time without any corresponding groundscatter being observed from College. This could indicate propagation by a one-hop high ray (Pedersen) mode or by a lateral mode.
I. OBLIQUE SWEEP-FREQUENCY SOUNDINGS (H. F. Bates).

Introduction. During the last year a modified C-4 sweep-frequency sounder has been used for oblique incidence backscatter studies of the ionosphere near College, Alaska. Slow sweeps (6 minutes duration) with long pulses (600 microseconds duration) were made regularly every 15 minutes over the 1-25 mc/s frequency range of the equipment. The radiation (10 kw peak power) was beamed north and south using first sloping-V and later rhombic antennas. The observations have shown that direct backscatter from the F layer is a common phenomenon in the auroral zone, and occurs more frequently than F layer propagated groundscatter echoes for our equipment parameters. In fact, the majority of the long range echoes that we record above the vertical incidence critical frequency, but below the oblique incidence penetration frequency, appear to be direct scatter from the F region. This contrasts with the situation at lower latitudes where similar observations show that groundscatter echoes propagated by the F layer prevail, although direct backscatter echoes from F layer irregularities have been observed, preferably during the night. The shift in the relative importance of direct backscatter from the F layer and groundscatter propagated by the F layer indicates that the ionosphere is characterized by a greater degree of roughness and more pronounced electron density irregularities in the auroral zone than at lower latitudes. This conclusion remains true when the differences in absorption between high and low latitudes are taken into account. It is generally accepted both from theoretical considerations and VHF experiments that the ionospheric irregularities on the scale seen at VHF tend to assume an ellipsoidal shape with their major axes aligned parallel to the direction of
force of the earth's magnetic field. It is not clear to which extent the larger scale irregularities seen by high frequency waves appear as field aligned, but HF radar studies at College have demonstrated that at least the auroral E layer ionization has this property. At 12 mc/s the E layer irregularities associated with aurora are aspect sensitive and give echo returns only when the angle of incidence is within 25 degrees of normality to the direction of the magnetic field lines. Similar field-aligned irregularities in the F layer must be expected to show a greater degree of aspect sensitivity due to the increase in characteristic scale-length from the E to the F layer. In the arctic ionosphere the field lines are nearly vertical, so the irregularities will tend to have their major axes oriented almost vertically. The preferred direction of scatter for incident radio waves will be on a conical surface of revolution about the major axis of the ellipsoid. The vertex angle of the cone will be twice the complement of the angle of incidence. For normally incident waves the preferred direction of scatter will therefore be in the plane normal to the major axis. Strictly speaking the scattering geometry has been established only for cylindrical irregularities in the Born approximation, i.e. for the case when the frequency of the incident radiation is large compared with the plasma frequency of the scattering cylinders. But since the angle of maximum backscatter for such under-dense columns is the same as the angle of reflection from a corresponding metallic cylinder, it appears permissible to extrapolate the result to the intermediate case where the frequency approaches the plasma frequency and the columns become almost dense to the incident radiation.

In this report we consider two echo types commonly observed with the College oblique sweep-frequency sounder both of which have been identified as direct backscatter from field-aligned irregularities in the F layer. Figure
7B shows a simultaneous recording of the usual groundscatter echo returned via the F layer and a frequently observed F layer echo. The groundscatter echo appears above the F layer echo. The mechanism which gives rise to the groundscatter echo is well understood, and has been analyzed in detail by Peterson\textsuperscript{5} for the case of a plane earth and ionosphere. The pulse propagates over the triangular path transmitter - F layer - ground and a fraction of the energy scattered by the impact with the ground returns over the same path. At a given frequency only the pulses traveling on or near the least-time path contribute appreciably to the echo. Consequently the leading edge of the groundscatter echo is sharply defined while the amplitude of the echo builds up during approximately a period of one pulselength and thereafter declines. The resulting echo is delimited to a characteristic, fairly narrow range interval. As the transmitting frequency is raised, the range of the leading edge of the echo increases linearly with frequency, departing tangentially from the second order vertical incidence trace. These features are all evident in the upper P'-f trace of Figure 7B. The departure from linearity near the upper frequency end is an effect of the curvature of the earth and the ionosphere. Following Eckersley this echo is denoted 2F to indicate that the complete path involves two F layer reflections. The lower echo in Figure 7B has an appearance similar to the groundscatter echo but departs tangentially from the first vertical incidence trace at half the slope of the groundscatter echo. Thus the lower echo has the characteristics of least-time focussed backscatter returned from the vicinity of the midpoints of the oblique groundscatter paths. In other words, the echo represents direct backscatter from the F layer originating at increasing range with frequency. It is convenient to use the notation lF for this backscatter
mode.* One can think of two possible ways in which direct backscatter could be produced from the vicinity of a reflection point in the high-latitude F layer:

1. scattering from any irregularity near the point where the vertical component of the propagation vector is reduced to zero, or
2. scattering from field-aligned irregularities at normal or near-normal incidence to the direction of the major axis.

In view of the results of a recent investigation by Pitteway\textsuperscript{6} theory tends to discredit the first possibility and favor backscatter from field-aligned irregularities. Pitteway found that weak irregularities would not appreciably enhance scattering from the level of reflection compared with other levels. The question can be settled conclusively from the experimental results. If the backscatter takes place at the reflection point, then, barring layer tilts, the range of the direct scatter echo at any frequency should be exactly one half the range of the groundscatter echo. But if the backscatter is from field-aligned irregularities then the deviation of the field lines from the vertical should lead to a LF slope slightly less than one half the slope of the 2F trace when sounding north but slightly greater than one half the 2F slope when sounding south. Such deviations from a 1:2 ratio between the slopes of the LF and 2F echoes are observed for soundings to the north and south. We conclude that the LF echo is due to least-time focussed backscatter from field-aligned irregularities randomly distributed over a considerable region of the F layer. We note that the LF type of backscatter is appropriately termed weak backscatter because nearly strict normal incidence of the radiation on the field-aligned irregularities combined with least-time focussing is required to produce observable echoes.

\*More precisely, least-time focussed LF or "weak" LF backscatter.
Once the backscatter mechanism has been established, the range-frequency characteristics of individual echoes can be used to determine the height of the scattering irregularities and the extent of the region containing scattering elements. An analysis of the available observations shows that the irregularities responsible for the IF echoes occur at actual heights between 300 and 500 kms. The horizontal north-south extent of the scattering region is found to be of the order of 1000 to 2000 kms. The IF echo is observed regularly at night and also during the day in disturbed periods, and may tentatively be associated with particle ionization.

The frequency of the IF echoes leads one to expect that at times stronger irregularities will occur which cause strong backscatter not dependent on strictly normal incidence or least-time focussing. Direct backscatter from the F layer of this kind is often observed and some typical echoes are shown in Figure 5. The echo has an essentially constant range with increasing frequency. Sometimes it appears simultaneously with the IF backscatter echo as in Figure 5A and at other times by itself as shown in Figure 5F. The echo can be assigned a lower cut-off frequency $f_L$, and an upper cut-off frequency $f_U$ which is near the oblique penetration frequency (see Figure 3). The constant range echo joins the IF echo at the upper cut-off frequency. This constant range echo is explained in terms of strong backscatter from a single, field-aligned irregularity in the F layer. The lower cut-off frequency corresponds to the lowest part of the irregularity capable of causing observable backscatter and the upper cut-off frequency corresponds to the highest frequency for which an oblique path will meet the irregularity at almost normal incidence. Analysis of the constant range echoes permits one to determine the vertical extent of that part of the irregularity which is below the F2 maximum. It is found that
usually the vertical extent is between one half and three quarters of the half-thickness of the F layer. The constant range echo is typically a daytime phenomenon.

An insight in the fine-structure of the arctic F layer can be gained by studying the temporal variations in the occurrence of IF and constant range backscatter echoes. It has been noted that typically the IF echo is a nighttime and the constant range echo a daytime occurrence. During sunrise and sunset periods one often observes transitions from one echo form to the other. An examination of the detailed behavior leads to the conclusion that the nighttime F layer is characterized by weak field-aligned irregularities spaced fairly closely over large regions of the ionosphere and that the sunlit F layer tends to have strong and isolated field-aligned irregularities.

Theory and Observations. The following primitive model is proposed to explain the backscattered echoes that we observe. Geometrical optics for a plane, horizontally stratified layer are used throughout; the earth's magnetic field and the collisional losses in the ionosphere are neglected.

Consider that the ordinary F layer has embedded in it thin, vertical columns of additional ionization. As we noted above, for direct backscatter the preferred direction of incidence upon a column will be perpendicular to the major axis of the column; hence for the case of vertical columns, the preferred direction for the wave is horizontal. Since any ray that is horizontal in the ionosphere is in the process of being refracted back to earth, only energy at frequencies below the oblique incidence penetration frequency will be backscattered by such a column.

Assume now that the column extends through only part of the layer as in Figure 1. It will be illuminated only by frequencies above some lower cut-off frequency \( f_L \) because a frequency below \( f_L \) cannot penetrate to the height of
the column. Thus direct backscatter can be obtained only in a band of frequencies for this simple model.

Next we shall examine the echo returned from a single column that is illuminated by a short pulse of energy at some particular frequency. The wave penetrates the layer at all angles of incidence less than the critical angle; therefore the perpendicularity requirement upon the column cannot be satisfied, and there is no appreciable scatter at those angles.

Peterson showed that for groundscattered echoes there is a strong focusing effect in the ionosphere for the path of least time. He showed, further, that the angle of incidence of the path of least time upon the layer is slightly greater than the critical angle, and that the virtual height of reflection is a constant for all possible frequencies or angles of incidence.

This analysis is directly applicable to the problem of direct scatter, because the assumption that the energy is scattered from the ground is not a decisive factor in the theory. The method Peterson used was to calculate the path of minimum transit time to the midpoint of the path; this is precisely our present problem.

The least-time focussing effect strongly enhances the echo traveling the path of minimum time, so if the scattered energy is relatively weak, only the least-time focussed echo will be detected. Figure 2 shows the range of the leading edge of this echo as a function of the frequency. Figure 7A shows such an echo recorded experimentally. Following the Eckersley-Peterson notation, this is called the 1F mode.

The direct scattered 1F echo and the groundscattered 2F echo follow the path of minimum transit time, and the 1F echo is backscattered from the midpoint of the path of the 2F echo. Thus for this simple model the range of the
2F echo is precisely twice that of the 1F echo at any given frequency. Figure 7B is an excellent example of the two occurring simultaneously.

In general the F region irregularities will occur in patches. Let us assume that such a patch of irregularities exists at some oblique range from the observer. Let us assume further that the boundary between the patch and the rest of the ionosphere is sharp, and that this boundary is perpendicular to the direction we are sounding.

If the boundary is sharp enough, it will backscatter part of the incident energy. As the frequency is increased above $f_L$, the equivalent range of the echo will remain essentially constant until the path of minimum time is reached, then the range will increase very sharply with frequency. This increase will be very difficult to record in the presence of noise and interference, unless the echo is exceptionally strong; thus on the sweep-frequency equipment we will not, in general, see the echo above the frequency $f_U$ at which it is tangent to the least-time path curve, as shown in Figure 3. Figure 5D shows the echo recorded experimentally.

These two types of direct echoes are useful in that the horizontal and the vertical extents of the irregularities in the F region can be estimated from them. From the 1F echo we can determine the horizontal extent of the irregularities that lie near the layer maximum. The calculation of the path of least time shows that its virtual height is a constant for all frequencies; with this fact plus Martyn's theorem the calculation of the horizontal extent is then a simple matter; Figure 4 shows the geometry for this calculation.

Martyn's theorem states that any two frequencies $f_1$ and $f_2$ that are reflected from the same virtual height are related by the following equation:

$$f_1 \cos \theta_1 = f_2 \cos \theta_2$$

(1)
The frequency in Figure 2 at which the least time path branches off the vertical incidence trace is \( f_t \), and at the branch point the angle of incidence is zero, so we have,

\[
f_t = f_1 \cos \theta_1 = f_2 \cos \theta_2
\]  

(2)

The horizontal extent \( d \) is then given by,

\[
d = h_0' \left( \tancos^{-1} \frac{f_t}{f_2} - \tancos^{-1} \frac{f_t}{f_1} \right)
\]  

(3)

In Figure 5D the following values may be read,

\[
\begin{align*}
h_0' & = 300 \text{ km} \\
f_2 & \approx 20 \text{ mc/s} \\
f_1 & \approx 12 \text{ mc/s} \\
f_t & \approx 9 \text{ mc/s}
\end{align*}
\]

Therefore

\[
d \approx 330 \text{ km}
\]

To estimate the vertical extent of the irregularities, we proceed as follows. Consider a vertical column extending downward in the F region as in Figure 1. If the angle \( \Delta \theta \) is small, then \( \theta \) can be used as the angle of incidence for all of the paths to the column.

In the discussion above \( f_u \) is the frequency at the tangent point between the LF and the constant range echoes, so we can use the secant law to find the angle of incidence, \( \theta \).

\[
f_t = f_u \cos \theta
\]  

(4)

Next we find the vertical incidence frequency \( f \) that is associated with \( f_L \) by the secant law, assuming that the angle of incidence is the same as in Equation (1).

\[
f = f_L \cos \theta
\]  

(5)
The angle of incidence can be eliminated between Equations (4) and (5), and the result is Equation (6).

\[ f = \frac{f_L}{f_U} \]  

(6)

Martyn's theorem states that both \( f \) and \( f_L \) are reflected at the same virtual and actual heights. For vertical incidence upon a parabolic layer we can show that the virtual distance traveled in the layer is approximately twice the actual distance for all frequencies such that \( f \leq 0.8 f_c \). Thus to obtain the actual height of the lower edge of the irregularities, one first scales \( f_L, f_U, \) and \( f_c \) from the record and calculates \( f \) using Equation (3).

The next step is to scale the virtual heights for the frequencies \( f \) and \( f_c \) from the vertical incidence trace and divide their difference by two to obtain the thickness.

The value for the vertical extent of the irregularities obtained in this manner is actually a minimum value. For example we have assumed that \( f_L \) is due only to the bottom edge of the vertical boundary of the patch, but in fact it may be mostly equipmental. The antenna pattern probably greatly influences \( f_L \).

Furthermore if the irregularities extend throughout that part of the F region below the least-time path, there appears to be no reason why they should not extend above that. In fact we believe that the probability is high that when irregularities are seen in the neighborhood of the least-time path, they will be present throughout much of the F region vertically above the midpoint of the least-time path involved. One reason for this belief is the low conductivity along the field lines that tends to greatly elongate the irregularities.

The value \( f_c \) is usually very difficult to scale accurately, especially if the irregularities do not extend overhead. An alternate and very crude
procedure for obtaining an estimate of the thickness of the patch is as follows. Assuming a parabolic layer with a reasonable half-thickness, one can calculate the thickness using just $f_U$ and $f_L$. For example if the layer thickness is 100 km, then we obtain the following thicknesses and distances between the lower edges of the layer and the patch.

<table>
<thead>
<tr>
<th>$\frac{f_L}{f_U}$</th>
<th>Thickness</th>
<th>Height Above Layer Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>45 km</td>
<td>5 km</td>
</tr>
<tr>
<td>0.50</td>
<td>40</td>
<td>10</td>
</tr>
<tr>
<td>0.75</td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>

From Figure 6C we obtain the following approximate values.

\[
\begin{align*}
  f_L &= 9 \text{ mc/s} \\
  f_U &= 22 \text{ mc/s}
\end{align*}
\]

The patch is at least 40 km thick and extends to within approximately 5 km of the lower edge of the F region.

Most of the records examined to date indicate that when the constant range echo exists, the patch of irregularities producing it extends throughout most of the region below the least-time path, indicating that the irregularities probably extend vertically throughout much of that region of the F layer.

The sequence of events during the transition periods near sunrise and sunset may lead to a better understanding of the arctic F region.

Here we are using the terms sunrise and sunset in a somewhat loose manner to indicate a period of the day rather than a precise time. The region we are sounding into may contain both sunlit and dark portions at any given level, and of course, the time of sunrise or sunset at any given level varies with the height. The most serious difficulty, however, is how to define sunrise or
sunset at a particular point. They might equally well be defined as the time when a particular point is illuminated by a ray that is tangent to some elevated layer, such as the ozone layer, rather than as the time the ray is tangent to the earth.

During the winter day in quiet periods the vertical incidence trace is clear and normal. Various constant range versus frequency echoes may exist in addition to the vertical incidence traces, but the IF echo is usually absent. The constant range echoes appear to be primarily direct echoes from discrete patches of F region irregularities.

During the transition periods of sunrise or sunset, however, the situation is quite different. Figures 5 and 6 contain the sequence of events that was recorded during the day of December 16, 1958, as observed from College, Alaska.

Figure 5A, taken at 0635 AST (150° WMT), shows a well defined IF echo plus a direct or fixed range echo at a slant range of 1500 km. The vertical incidence trace is spread and very poorly defined.

In Figure 5B, recorded at 0720, we note that the IF echo no longer connects with the vertical incidence trace, indicating that the irregularities overhead have disappeared. The vertical incidence trace is clearer than it was.

By 0806, Figure 5C, the vertical incidence trace is definitely clearer, and the critical frequency has increased. The IF echo does not appear between 8 and 13 mc, and in fact appears only at ranges greater than the 1000 km range of the fixed range, direct F layer echo. The latter echo is diffuse, indicating that the scattering region is not sharply defined as yet.

At 0906, Figure 5D, the fixed range echo has moved in to 900 km and has become sharp and well defined. Again we note that the IF echo exists only at ranges greater than that of the fixed range echo. The vertical incidence trace is much clearer, and the critical frequency has increased to approximately 9 mc.
By 0950, Figure 5E, the fixed range echo has moved out to 1100 km, and the extraordinary critical frequency is about 11 mc. The 1F echo appears only beyond the fixed range echo.

By 1105, Figure 5F, the 1F echo has apparently disappeared, and we have the more or less normal daytime record.

The sunset sequence of events is essentially the reverse of the sunrise sequence, except that the speed of occurrence is somewhat greater.

Figure 6A, taken at 1435, is a reasonably normal daytime record. The vertical incidence echoes are clear, and there are constant range F region echoes at 1200 and 1500 km. Between 13 and 15 mc 2F groundscatter is present but very weak. The extraordinary critical frequency is approximately 13.8 mc.

At 1550, Figure 6B, the constant range F region echo has decreased in range to 1100 km, and it now shows the characteristic high frequency cut-off associated with the 1F echo. Again the vertical incidence traces are clear, and the 2F echo is present. The critical frequency has decreased about half a megacycle.

The records in Figures 6B to 6F were taken fifteen minutes apart, indicating the speed of occurrence of the events. In Figure 6C the strongest direct echo is at 1000 km, but a weak one has also appeared at 800 km. The critical frequency has decreased several hundred kilocycles. The vertical incidence traces are still clear.

Figures 6D, 6E, and 6F show this sequence of events continuing. The range of the fixed range echoes decreases, the critical frequency decreases, and the 1F echo appears at a progressively shorter range, but always at a longer range than the direct echo.

Figure 6G was taken at 1750, an hour after Figure 6F. By this time the 1F echo was well established and had merged with the vertical incidence trace.
A weak 3F (N-type least time, direct scatter mode) echo extended from 9 to 13 mc. The vertical incidence trace was spreading, and the extraordinary critical frequency was approximately 9 mc.

Apparently when the F region is illuminated by the sun, the irregularities exist in comparatively small patches. These patches apparently must be in the form of sheets aligned along the field lines because an echo returned from such a patch is generally sharp and well defined with no IF echo present, indicating that the horizontal extent of the patch is at most comparable to half the pulse width times the speed of light, or about 100 km.

In the region of the F layer where there is no insolation, the irregularities are distributed much more generally. In fact solar radiation appears to either eliminate or to greatly reduce such irregularities during quiet periods.

During the transition periods illustrated, the IF echo existed only at a range greater than that of the fixed range echo. This appears to be generally true for the winter records and indicates that the F region is vertically stratified into a northern and a southern region. The southern part is relatively free of irregularities, while the northern part contains patches of randomly distributed, field aligned irregularities. The boundary between the regions appears to be sharp, as though there were an actual discontinuity in the ion density between the two regions.

**Typical P'-'f Records.** The records shown in Figure 7 are included to indicate the general type of records that we obtain.

Figure 7A is the usual nighttime IF echo from the north. The maximum slant range is 1600 km, indicating that the horizontal extent of the irregularities is at least 1500 km, extending north from directly overhead. The cutoff at the high frequency end is partly equipmental.
Figure 7B is one of our best examples of 1F and 2F echoes occurring simultaneously.

Figure 7C is a rather common early morning type of record. As yet we do not know what causes the constant range echo at 500 km. There are several other weak echoes present which are unidentified. The weak echo between 800 and 1200 km, and 9 to 13 mc, respectively, may be a 2F echo.

Figure 7D shows some strong but unidentified echoes. The short range echo may be slant Eₙ. Absorption has apparently caused the disappearance of the low frequency end of the echoes. This type of record is fairly common.

Figure 7E is an example of a diffuse or spread 2F or groundscattered echo from the south. This echo appears to branch off the extraordinary trace, although the resolution is too poor for a definite conclusion.

Figure 7F is a good example of another type of 2F echo that we see. This echo is sharp and appears to branch off the ordinary ray. Again, this last point is uncertain.

Figure 7G shows several echoes from the south. The 1F is weak, but the 2F is strong and sharp. A 4F echo is weak but clear. This is a fairly typical early evening record. On most of these records the 2F echo appears to branch off the ordinary vertical incidence trace.

Figure 7H shows a peculiar echo at 1200 km range between 3 and 6 mc that we have recorded several times. The retardation is the difficult part to explain. Even for oblique incidence penetration of the E layer, the retardation appears to be excessive. The record otherwise is a typical daytime record, containing several weak echoes.

The last record, Figure 7I is an extremely interesting and somewhat puzzling record. A weak 1F echo and the first, second, and third multiple
vertical incidence reflections are present, but the interesting echo is the one that extends from 4 mc and 1200 km to 11 mc and 3600 km. It behaves as a least time focussed 3F echo should, except that it apparently connects to the z-trace of the third multiple of the vertical incidence trace. One will also note that it is relatively strong as compared with the IF. Furthermore the corresponding one hop echo does not exist, indicating that one reflection from either the ionosphere or the ground is required. This is not an isolated occurrence, as we have at least a dozen examples of this echo.

Most of the records we obtain include parts of one or more of the echoes shown above. Generally the echoes are weak and the resolution poor, so that scaling is at best difficult. This situation is further aggravated during disturbed periods when the absorption increases. For this reason the identification of the modes of propagation requires extensive observation and progresses slowly.

**Equipment.** The Ionospheric Recorder, Model C4, arrived in July, 1957, and by the end of August it was installed in its present location. Two sloping-V antennas, aimed at 17° true bearing, and the associated feed lines were constructed during the remaining good weather in September. The trouble-shooting of the C4 itself began in November, and was carried on continuously until automatic operation was started in April, 1958. From then until the present one technician has devoted at least half-time to keep it running. The sounder now operates approximately 75 percent of the time.

In October 1958 two rhombic antennas aimed at 5° true bearing were put into operation, and the efficiency of the equipment was measurably increased. Groundscattered echoes were a rarity with the V-antennas, but are observed regularly with the rhombics.
Several modifications have been necessary to convert the equipment for use as an oblique incidence sounder. The various changes are listed below.

Past experience both here and at lower latitudes indicates that the optimum pulse length for low and medium power is between one-half and one millisecond; for that reason we increased the pulse length from 100 to 600 microseconds.

Increasing the pulse length decreases the bandwidth of the transmitted pulse so the receiver bandwidth may be narrowed with a consequent increase in the signal to noise ratio of the returned echo. In order to reduce the bandwidth of the C4 receiver a third i-f strip with center frequency at 260 kc and bandwidth 5 kc was installed.

The range originally displayed on the recording was either 500, 1000, or 4000 km. The sweep circuits have been modified to provide any desired range between 1500 and 6000 km.

The original range marks which were 100 km apart have been changed to give either 200 or 400 km marks by the addition of two binary dividers. The range marks have also been broadened so that they will record more prominently on the 1500 to 6000 km sweeps that are now available.

Finally the range marks and the video output are mixed in a squaring amplifier that is adjusted to clip at an arbitrary level. In this manner a weak echo records almost as prominently as a strong one, and much of the noise is removed from the signal.

The C4 may function adequately as a vertical incidence sounder, but represents a marginal equipment for oblique incidence sounding. In the latter service every unit has to operate at its maximum efficiency at all times; and even a slight reduction can cause a complete loss of data. One of the main difficulties with the C4 is that too many of its circuits were designed to
operate at their maximum ratings or capabilities. As two examples, consider
the high voltage power supply and the final amplifier of the transmitter. In
each case the tubes used in these units are operated at or above their maxi­
mum ratings, so tube life is short.

Further the design and the construction of specific circuits and units in
the equipment reflect lack of care, poor engineering practices or hasty work.
For instance: use of inadequate insulation on the high voltage leads in the
HV power supply and bundling of the leads into a single cable. Many break­
downs occurred until we completely rewired the unit. Other minor items in­
clude wiring errors, cold solder joints, and the lack of matching of screw
holes. Some circuits or circuit elements that are normally prone to trouble
cannot be reached without major disassembly. For example the replacement of
a relay in the control unit requires the dismantling of half the chassis of
the unit.

Probably fifty percent of the time lost in the past six months was due to
the camera jamming. We hope that the installation of an idler on the take­
up sprocket will finally solve this particular difficulty.
II. VERTICAL SWEEP-FREQUENCY SOUNDINGS (L. Owren).

Vertical incidence soundings of the ionospheric layers over College are carried out routinely with a C-3 sweep-frequency recorder under a contract with the National Bureau of Standards. The resulting ionograms are filed in the archives of the Geophysical Institute and are available for studies under other research contracts.

Many features appearing in the College ionograms are manifestations of direct backscatter from the ionosphere although an understanding of their nature may not result from the vertical incidence soundings alone but rather from such soundings combined with other experimental techniques. At this time we would like to draw attention to the frequently observed phenomena of spread F and third or z-branches in the F layer ionograms both of which may be aspects of direct backscatter.

(a) Spread F Echoes. There is a growing body of evidence that when the College oblique incidence soundings indicate direct F layer backscatter from nearly overhead, the vertical incidence sounder will record spread F traces. Thus the common nighttime oblique IF echo illustrated in Fig. 7A is generally accompanied by a spread F vertical incidence record. The oblique IF echo is interpreted as least-time focussed backscatter from field-aligned F layer irregularities. This leads to the tentative conclusion that spread F is an effect of backscatter from such irregularities. A comprehensive analysis of the available experimental evidence will be required to put this conclusion on a firm foundation. An investigation of the relationship between occurrence of spread F in the College vertical incidence soundings and oblique incidence backscatter as well as radio star scintillations has been started and the results will be reported at a later date.
(b) Z Echoes. Inspection of the College ionograms has shown that during certain periods z-traces are observed frequently and consistently in the daytime F2 layer recordings. During the month of January 1955 z-traces appeared sometime every day except two, on one of which the sounder was inoperative. F2 layer z-traces were observed on 29 days between 0800 and 1800 local time and Es layer z-traces during 6 nights between 1930 and 0230 local time. Similarly during February 1955 F2 layer z-traces were observed on all days except three when high absorption blanketed the recordings while Es layer z-traces were observed on five nights. During such periods of frequent occurrence of the z-wave component it is often possible to scale the z-wave critical frequency from the C-3 soundings throughout several hours.

During January 1955 profiles of $f_zF2$ could be obtained from the soundings made at 15 minute intervals for periods of four hours or more on thirteen days. The best profile was scaled from the 13 January ionograms when the z-wave critical frequency could be observed at each recording from 0930 to 1645 inclusive, i.e. for seven and a half hours, except for absorption at 1045 and equipment off-time at 1145 (and following the 1645 observation). The sequence of $f_zF2$ profiles obtained during the period 1-15 January 1955 from College vertical incidence soundings is illustrated in Fig. 8. The symbols appearing on the profiles have the following meaning: crosses indicate periods of absorption, slant lines show absorption in the region of the critical frequency, a zig-zag line (6 January 1315) indicates interference, while the symbol "C" denotes equipment off-time. A histogram of the virtual heights for the F2 layer z-traces during January 1955 showed 210 km to be the most frequent height with a sharp lower cut-off at 200 km and only few heights exceeding 240 km.
Two different mechanisms have been proposed for the explanation of triple splitting (simultaneous appearance of z, o and x branches) in vertical incidence soundings (see Ratcliffe, The Magneto-Ionic Theory, Cambridge 1959, Sec. 13.5 and 17.3). The mechanism advanced independently by Eckersley and Rydbeck in 1950 produces the z-branch by frictional coupling between the ordinary and extraordinary wave near the level of reflection of the o-wave when the direction of propagation is nearly parallel to the magnetic field lines. The z-wave is generated by collisional transfer of energy from the ordinary to the extraordinary mode and is reflected at the second ionospheric reflection level of the x-wave existing above the o-wave reflection level. For vertical incidence soundings this mechanism limits the occurrence of F layer z-traces to high geomagnetic latitudes unless much larger values of the F layer collisional frequency be assumed than indicated by measurements based on other methods.

In 1950 Scott reported z-traces in Canadian high latitude soundings which passed through the E and Fl ordinary wave critical frequencies ($f_{0E}$ and $f_{0Fl}$) without retardation. He concluded that the z-mode could not be generated by the collisional coupling process mentioned but must be propagated independently in the ionosphere. Scott proposed that the z-trace is produced by backscatter from a rough ionosphere of part of the energy which propagates parallel to the magnetic lines of force. Thus the observed z-traces would indicate backscatter of the waves obliquely incident in the direction of the magnetic zenith rather than z-mode reflection of vertically incident waves. Scott also noted that the Canadian observations showed more occurrences of $f_{zF2}$ for the auroral zone stations than for stations further south or north. A qualification was made regarding a possible underestimation of z-traces.
from the station north of the auroral zone due to masking of the $f_{x}F2$ by frequent occurrence of spread echoes.

Ellis\(^9\) has investigated the backscatter hypothesis in more detail both theoretically and experimentally. He measured the angle of arrival of $z$-echoes at the intermediate latitude station Hobart, Tasmania (geomagnetic latitude $51^\circ$S, magnetic dip $72^\circ$). Ellis found that the angle of arrival in the magnetic meridian corresponded to that which would make the return (and incident) radiation parallel to the magnetic lines of force at the reflection level of the oblique $o$-wave, indicating that the backscatter interpretation was the correct one for his station. We note that backscatter along this particular path of incidence is essential because the obliquely reflected $z$-wave or scatter radiation in other directions cannot penetrate the $o$-wave reflection level as downcoming waves. Although the oblique backscatter mode does not necessarily depend on collisional energy transfer from the $o$-wave to the $z$-wave and back, such frictional coupling at the $o$-wave reflection level will clearly make the backscatter mechanism more efficient since then nearly longitudinal as well as strictly longitudinal waves may contribute. In fact, Ellis interpretes the observed short-time variations of 1-2 degrees in the angles of arrival as the effect of collisions. A series of measurements on $z$-echoes made by Ellis\(^10\) during the months of March, April, May and August 1954 showed that the true height of scattering varied between 200 and 214 kms with a mean height of 210 kms.

The oblique backscatter mechanism may well be the only one responsible for the appearance of $z$-traces in intermediate latitude soundings. In high latitudes the situation need not be so clear cut. In particular, if it is found that collisions are essential for the production of $z$-traces by oblique backscatter as well as by vertical incidence coupling of wave modes, both
mechanisms may contribute to the appearance of these traces in soundings from high latitude stations such as College. A clarification of the actual situation would make it possible to use observations of z-traces to measure variations in the degree of roughness or collisional frequency in the F layer. The original intention was to collect a representative statistical material on the z-traces by sufficiently extensive and careful scaling of the College ionograms for selected periods during a sunspot cycle. Because of lack of funds and shortage of trained personnel this program had to be discontinued after scaling of only a few months including March 1949, April 1954, January and February 1955. In order to provide a somewhat broader base for discussion we have taken advantage of the fact that since January 1957 the f-plots prepared from the C-3 soundings are supposed to include entries on the critical frequencies of the z-traces. Unfortunately the College scalers seem to have included the z-traces in a consistent manner only during the first ten months of 1957 and thereafter no more than sporadically until recently. Even the 1957 data are probably not comparable with the other scalings since the latter were made with special attention to the z-traces by the head of the C-3 sounder section while the 1957 z-trace scalings were made by the regular scaling technicians as part of the general ionogram reductions. Thus the smaller number of z-traces observed monthly during 1957 as compared with the other four months mentioned could well signify that only the more prominent were noticed and entered in the f-plots rather than an actual decrease in the frequency of occurrence. The material on which the discussion of the z-traces and the conditions of their appearance will be based is assembled in tabular form on the following page.
Table 1. Occurrence of $f_z$ at College

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>$f_zF2$</th>
<th>$f_zF1$</th>
<th>$f_zEs$</th>
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<td>March</td>
<td>192</td>
<td>28</td>
<td>1</td>
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<td>1954</td>
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<tr>
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<td>February</td>
<td>344</td>
<td>0</td>
<td>8</td>
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<td>0</td>
</tr>
<tr>
<td></td>
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<td>Jan-Oct</td>
<td>392</td>
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</table>

Total 1480 167 27

Remarks: This table shows the number of times a $z$-component critical frequency $f_z$ was scaled from the 15 minute interval ionograms during the month indicated. The $f_zE$ were observed at night excepting one noon occurrence in April 1954. All occurred in sporadic E and none in a regular E layer.
Table 2. Virtual heights of F2 layer when $f_{\text{F2}}$ observed

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<tr>
<th>$h' \text{ km}$</th>
<th>200</th>
<th>210</th>
<th>220</th>
<th>230</th>
<th>240</th>
<th>250</th>
<th>260</th>
<th>270</th>
<th>280</th>
<th>290</th>
<th>300</th>
<th>310</th>
<th>320</th>
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</tr>
<tr>
<td>Feb 1955</td>
<td>19</td>
<td>65</td>
<td>57</td>
<td>52</td>
<td>37</td>
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</tr>
<tr>
<td>Jan 1957</td>
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<td>4</td>
<td>6</td>
<td>3</td>
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<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
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</tr>
</tbody>
</table>

Remarks: The table shows the number of times a given value of $h'$ was recorded for the bottom of the F2 layer when $f_{\text{F2}}$ was present. The $h'$ values were scaled only for the three months indicated. During the winter months these minimum virtual heights for the F2 region will closely approximate the true height of the bottom of the layer, and also indicate the true height from which the $z$-echo originates.

Table 2A. Monthly median values of $h'\text{F2}$ for College (or Tromsø)

<table>
<thead>
<tr>
<th>Time</th>
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<th>Feb '55</th>
<th>Jan '57</th>
<th>Feb '57</th>
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<tr>
<td>00</td>
<td>290</td>
<td>(320)</td>
<td>(355)</td>
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<tr>
<td>01</td>
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<td></td>
</tr>
<tr>
<td>02</td>
<td>330</td>
<td>---</td>
<td>(340)</td>
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</tr>
<tr>
<td>03</td>
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<td>$\leq$ 340</td>
<td>(290)</td>
<td></td>
</tr>
<tr>
<td>04</td>
<td>(310)</td>
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<td>(260)</td>
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<td>(350)</td>
<td>(340)</td>
<td>260</td>
<td></td>
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<td>$\leq$ 300</td>
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<tr>
<td>23</td>
<td>300</td>
<td>(320)</td>
<td>(315)</td>
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</tr>
</tbody>
</table>

Remarks: $h'\text{F2}$ values were not scaled for College in 1957, and the $h'\text{F}$ values for Tromsø are used as the best available substitute.
Table 3. Distribution of $f_z F_2$ over 1 mc/s frequency intervals

<table>
<thead>
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<th>Month</th>
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<th>3-4</th>
<th>4-5</th>
<th>5-6</th>
<th>6-7</th>
<th>7-8</th>
<th>8-9</th>
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<th>10-11</th>
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<td>199</td>
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Remarks: Each frequency interval includes values from X.0 through X.9 mc/s. Thus 1-2 includes critical frequencies from 1.0 through 1.9.

In the following Table 4 the distribution of the observed $f_z F_2$ over diurnal time intervals as well as frequency intervals is considered. The time intervals used are "Morning" from 0300 through 0945 (denoted 03-10), "Noon" from 1000 through 1345, "Afternoon" from 1400 through 1745, "Evening" from 1800 through 2045 and "Night" from 2100 through 0245, all in local time (150° W.M.T.).
Table 4. Distribution of $f_e F_2$ over time and frequency intervals

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| 03-10 | 9   | 13  |     |     |     |     |     |     |      |       |       | 22  |
| 10-14 | 0   | 34  |     |     |     |     |     |     |      |       |       | 34  |
| 14-18 | 0   | 82  |     |     |     |     |     |     |      |       |       | 82  |
| 18-21 | 5   | 54  |     |     |     |     |     |     |      |       |       | 59  |
| 21-03 | 1   | 1   |     |     |     |     |     |     |      |       |       | 2   |
| Sum   | 15  | 184 |     |     |     |     |     |     |      |       |       | 199 |

| Jan '55 |     |     |     |     |     |     |     |     |      |       |       |     |
| 03-10 | 0   | 8   | 12  | 1   | 0   |     |     |     |      |       |       | 21  |
| 10-14 | 0   | 3   | 66  | 114 | 15  |     |     |     |      |       |       | 198 |
| 14-18 | 4   | 22  | 64  | 39  | 2   |     |     |     |      |       |       | 131 |
| 18-21 | 2   | 1   | 0   | 0   | 0   |     |     |     |      |       |       | 3   |
| 21-03 | 0   | 0   | 0   | 0   | 0   |     |     |     |      |       |       | 0   |
| Sum   | 6   | 34  | 142 | 154 | 17  |     |     |     |      |       |       | 353 |

| Feb '55 |     |     |     |     |     |     |     |     |      |       |       |     |
| 03-10 | 0   | 7   | 18  | 4   | 0   |     |     |     |      |       |       | 29  |
| 10-14 | 0   | 0   | 34  | 96  | 25  |     |     |     |      |       |       | 155 |
| 14-18 | 0   | 5   | 52  | 75  | 10  |     |     |     |      |       |       | 142 |
| 18-21 | 2   | 15  | 1   | 0   | 0   |     |     |     |      |       |       | 18  |
| 21-03 | 0   | 0   | 0   | 0   | 0   |     |     |     |      |       |       | 0   |
| Sum   | 2   | 27  | 105 | 175 | 35  |     |     |     |      |       |       | 344 |

| Jan '57 |     |     |     |     |     |     |     |     |      |       |       |     |
| 03-10 | 0   | 0   | 0   | 0   | 0   |     |     |     |      |       |       | 0   |
| 10-14 | 0   | 0   | 0   | 0   | 0   |     |     |     | 4     |       |       | 4   |
| 14-18 | 0   | 0   | 0   | 1   | 1   |     |     |     | 2     |       |       | 4   |
| 18-21 | 7   | 5   | 1   | 2   | 0   |     |     |     | 0     |       |       | 15  |
| 21-03 | 0   | 0   | 0   | 0   | 0   |     |     |     | 0     |       |       | 0   |
| Sum   | 7   | 5   | 1   | 3   | 1   |     |     |     | 6     |       |       | 23  |
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<td>5</td>
<td>22</td>
<td>39</td>
<td>122</td>
<td>167</td>
<td>7</td>
<td>5</td>
<td>2</td>
<td>18</td>
<td>4</td>
<td>392</td>
</tr>
</tbody>
</table>

Remarks: Each frequency interval includes values from X.0 through X.9 mc/s.
Table 5. Distribution of recorded f-min values over 0.5 mc/s intervals when $f_{zF2}$ present.

<table>
<thead>
<tr>
<th>Month</th>
<th>1.0</th>
<th>1.1-1.5</th>
<th>1.6-2.0</th>
<th>2.1-2.5</th>
<th>2.6-3.0</th>
<th>3.1-3.5</th>
<th>3.6-4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar 1949</td>
<td>122</td>
<td>21</td>
<td>30</td>
<td>17</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Apr 1954</td>
<td>175</td>
<td>8</td>
<td>10</td>
<td>5</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Jan 1955</td>
<td>109</td>
<td>88</td>
<td>81</td>
<td>53</td>
<td>16</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>Feb 1955</td>
<td>134</td>
<td>54</td>
<td>62</td>
<td>82</td>
<td>16</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1957</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jan</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Feb</td>
<td>27</td>
<td>5</td>
<td>12</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Mar</td>
<td>18</td>
<td>1</td>
<td>5</td>
<td>9</td>
<td>2</td>
<td>11</td>
<td>2</td>
</tr>
<tr>
<td>Apr</td>
<td>9</td>
<td>3</td>
<td>19</td>
<td>5</td>
<td>2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>May</td>
<td>1</td>
<td>5</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Jun</td>
<td>3</td>
<td>9</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Jul</td>
<td>17</td>
<td>15</td>
<td>19</td>
<td>8</td>
<td>1</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Aug</td>
<td>19</td>
<td>12</td>
<td>17</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sep</td>
<td>20</td>
<td>16</td>
<td>15</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Oct</td>
<td>8</td>
<td>5</td>
<td>8</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Jan-Oct</td>
<td>131</td>
<td>80</td>
<td>104</td>
<td>42</td>
<td>14</td>
<td>17</td>
<td>4</td>
</tr>
</tbody>
</table>

Remarks: f-min is defined as the lowest frequency at which echoes are observed on the ionogram. It may be used as a measure of the non-deviative absorption in the lower ionosphere (D-layer) provided the radiated power and the receiver gain of the ionosonde remains constant. The value 1.0 mc/s corresponds to the low frequency limit of the C-3 sounder and signifies no detectable non-deviative absorption.
Table 6. Distribution of values of College 3-hourly K-index for period when $f_z F_2$ present

<table>
<thead>
<tr>
<th>Month</th>
<th>K = 0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>Sum</th>
<th>Variable</th>
</tr>
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<tr>
<td>1957</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jan</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Feb</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>22</td>
<td>1-4</td>
</tr>
<tr>
<td>Mar</td>
<td>1</td>
<td>4</td>
<td>6</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>13</td>
<td>1-5</td>
</tr>
<tr>
<td>Apr</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td></td>
<td></td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>May</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Jun</td>
<td>2</td>
<td>5</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td></td>
<td></td>
<td>11</td>
<td>1-2</td>
</tr>
<tr>
<td>Jul</td>
<td>2</td>
<td>9</td>
<td>9</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td>26</td>
<td>2-0</td>
</tr>
<tr>
<td>Aug</td>
<td>2</td>
<td>5</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td></td>
<td>31</td>
<td>3-0</td>
</tr>
<tr>
<td>Sept</td>
<td>1</td>
<td>8</td>
<td>4</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td>17</td>
<td>4-1 2-4 1-2</td>
</tr>
<tr>
<td>Oct</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td>19</td>
<td>51</td>
<td>46</td>
<td>24</td>
<td>10</td>
<td>1</td>
<td>1</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>

Remarks: This table shows the number of times per month a given K-index value was scaled from the College magnetograms for the 3-hour period during which the $f_z F_2$ was recorded. "Variable" means that the period when $f_z F_2$ was present fell on two adjacent 3-hour periods having different K-indices, both of which are indicated.

Table 7. Distribution of largest daily sum of K-index over day before, on, and following $f_z F_2$ observations in 1957

<table>
<thead>
<tr>
<th>Day /</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-1</td>
<td>3</td>
<td>5</td>
<td>7</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>7</td>
<td>4</td>
<td>9</td>
<td>5</td>
<td>46</td>
</tr>
<tr>
<td>D</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>28</td>
</tr>
<tr>
<td>D+1</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>4</td>
<td>31</td>
</tr>
</tbody>
</table>

Remarks: This table gives the number of cases per month when the daily sum of the K-index was largest the day before the $f_z F_2$ observation (D-1), on the day of observation (D), and the day after the observation (D+1).
We shall now state three propositions based on the two different mechanisms for the generation of the z-echo outlined above. A comparison of the hypotheses and their experimental consequences with the tabulated statistical material should make it possible to draw at least tentative conclusions regarding the way the z-echoes are produced in the ionosphere over College.

**Proposition 1.** The z-echoes are generated by frictional coupling between the ordinary and the extraordinary mode of vertically incident waves according to the Eckersley-Rydbeck theory. If so, considering the decrease in collisional frequency with height, we should expect that the z-echo would appear preferentially in the E layer and more frequently in the F1 than the F2 layer when both are present. The z-echo would be expected to appear in the F layer only when the true height of the layer is low.

**Proposition 2.** The z-echoes are generated by backscatter of obliquely incident waves from ionospheric irregularities according to the Scott-Ellis theory. The generation of the echoes is independent of collisions. If this hypothesis is correct the echoes should appear preferentially in whichever layer has the larger degree of irregularities of the most favorable scalelength compared with wave frequency. The true height of the layer should be unimportant except for the possible effect of height on scalelength.

**Proposition 3.** The z-echoes are generated by oblique backscatter from irregularities according to the Scott-Ellis theory, and the generation is aided by collisions. The echoes should appear in whichever layer has the larger degree of irregularities and preferentially at times when there is evidence of some absorption. The (non-deviative) absorption cannot be heavy since this would cause blanketing of the echoes. Further, in a given layer, the z-traces would tend to be present mostly when the actual or virtual height of the layer is low.
When we examine the Tables 1-7 in light of these propositions we can immediately conclude that Proposition 1 is false. The z-echoes observed in the E, F1 and F2 layers occurred in the ratios

1 : 5 : 50

and moreover all the E layer z-echoes except one occurred at night in sporadic E clouds and the one daytime occurrence was also in Es ionization. Therefore an oblique incidence backscatter mechanism is definitely indicated.

No final choice can be made between the propositions 2 and 3 from the available observational data. Table 2 shows that the virtual (and actual) height of the bottom of the F layer is generally low when the z-echoes appear. On the other hand the most frequent f-min value is 1.0, indicating no detectable non-deviative absorption. The 3-hourly College K-indices most frequently recorded in the periods when z-echoes occurred are K = 1 and 2, again indicating relatively quiet conditions. Probably both of the propositions 2 and 3 are valid. At times the z-echoes will appear by oblique backscatter without the aid of collisions, while at other times their appearance depends on collisions as well as the presence of scattering irregularities.

In this connection it is interesting to note that on two occasions (4 and 5 October 1957) when the z-echoes were particularly well developed and a comparison could be made with riometer absorption measurements, the z-echoes occurred in a quiet period immediately preceded and followed by periods of relatively high absorption. On 4 October a period with 1 1/2 db of absorption at 30 mc/s having a peak value of 3 db occurred around 1000 followed by a second period at 1500 with 2 db of absorption (peak 2 1/2 db). The z-traces were observed between 1200 and 1400. On 5 October there were periods of 1 1/2 db absorption at 1030 and 1500 while the z-trace occurred at 1415.
Conclusions. Most of the z-traces observed have critical frequencies between 3 and 7 mc/s and are recorded in the F layer, preferably during the daytime or evening. Z-traces from the E layer have been noticed mostly at night and only in connection with dense sporadic E clouds. The z-echoes tend to appear in quiet periods between lesser disturbances, or before and after disturbed periods. The available observations indicate that the z-echoes are generated by oblique backscatter from irregularities in the F and E layer and not by vertical incidence reflections from the regular layers.

The statistical study here reported was made to guide the design of a special experiment on the nature of the z-echoes.
III. OBLIQUE FIXED-FREQUENCY SOUNDINGS (R. D. Huncucker and R. A. Stark).

A program of oblique incidence backscatter sounding of the ionosphere at fixed high frequencies using the rotating antenna and PPI display technique has been pursued by the Geophysical Institute since the end of 1955. It is well known that this technique permits a single station to obtain information on the propagation conditions of the ionospheric layers out to distances of 1000 to 2000 km from the transmitter. The earlier series of soundings were made on the single frequency of 12 mc/s between November 1955 and January 1957 under Signal Corps Research Contract Nos. DA-36-039 SC-56739 and SC-71137. In August 1957 the Geophysical Institute received and installed an IGY 3-frequency sounder for 12, 18 and 30 mc/s. This sounder was operated from September 1957 through 15 April 1959 under Contract No. AF 19(604)-1859 excepting the period 1 July through 31 December 1958 when IGY funds were available through NSF Grant No. Y/6.28/292.

The 12 mc/s sounder was constructed locally with the specific aim of exploring the arctic and subarctic ionosphere, and in particular the effects of auroral ionization on propagation conditions. The operational parameters of the sounder were selected accordingly and a high resolution PPI display system was used. The IGY 3-frequency sounders were designed to survey very large regions of the ionosphere by means of a limited number of stations, and the operational parameters as well as the low resolution display systems were unfavorable for sounding the ionosphere in and near the auroral zone. As part of the IGY network, the College station could take no steps to improve the operational characteristics until IGY terminated.

Two types of backscatter have been studied under this contract:
(a) Direct scatter from the E and F layers of the ionosphere
(b) Groundscatter propagated via the F layer.
The direct scatter studies require high resolution and our analysis is based entirely on the film records obtained with the 12 mc/s sounder during 1956. The analysis of these records performed under Signal Corps sponsorship and presented in Final Report, Task B, October 1957, Contract No. DA-36-039 SC-71137 was concerned exclusively with echoes returned from auroral ionization or the ground via the ionosphere at ranges exceeding 1000 km. The film records were rescaled under the present contract, AF 19(604)-1859, in order to extract the available information concerning the direct ionospheric backscatter at ranges below 1000 km.

The results on F layer propagated groundscatter reported below are based on the film records from the IGY 3-frequency backscatter sounder. For the purpose of comparing the 1956 and 1958 groundscatter observations we have included as Fig. 12 a drawing which was prepared for the Signal Corps Final Report mentioned above in addition to the Figs. 13 and 14A-P prepared for the present report. The figures 12 and 13 are supplementary in that Figure 12 shows the seasonal variation of F layer propagated groundscatter on a single frequency, while Figure 13 shows the frequency variation in a single season. Thus a complete picture can be obtained by comparison of the two figures.

IIIa. Direct-Scatter Ionospheric Echoes

The echoes may be divided into two groups: direct-scatter from irregularities at E region heights, and direct-scatter from irregularities at F region heights. Such echoes are referred to as IE and IF echoes respectively. The observations were made in March, September, October and November of 1956 at 12 mc/s.

The most complete data were secured in October. The March and September data are incomplete, due largely to CW interference which was very consistent.
at certain hours of the day, and the November data were of poor quality due largely to over-exposed film. Halation about the echoes made this film difficult to scale accurately and particularly to separate echoes which were close together.

Figures 9 through 11 are plotted from the October observations and other months are discussed with respect to these histograms.

**1F Echoes**

1F echoes represent direct scatter from irregularities at F region heights. Whether these echoes are from field-aligned irregularities or from discontinuities in the horizontal layer, is not clear at present.

The diurnal distribution of the occurrence of 1F echoes, measured in terms of the number of minutes echoes were present, is plotted in Fig. 9B. The plot shows that the 1F echoes appear mostly in the afternoon or early evening and during the night or early morning hours.

The 1F echoes which were recorded on the 12 mc/s radar, have been compared with vertical incidence soundings at College. Unfortunately, the two equipments look at different parts of the ionosphere. The C-3 vertical incidence sounder records zenith conditions while the radar at oblique incidence investigates a region from a few hundred kilometers up to several thousand kilometers away.

Usually the vertical incidence sounder at College records Spread F echoes from approximately 1900 until 1000, local time. 1F echoes are not seen during the day when the F region is usually fairly quiet. During the night, when extremely spread echoes are often recorded on the vertical incidence equipment, 1F echoes are reduced in number, but this may be due to blanketing by Es or confusion with 2Es echoes, since strong 2Es echoes are observed at ranges from 600 to 1000 km. Usually very strong 1E echoes are also seen during this period.
If a simple model of the F region is constructed, assuming only solar influence, IF echoes recorded on the radar are observed to move in the direction of the formation and breakup of the layer. IF echoes are observed in the north in late afternoon and move in a westerly direction. They are also observed in early morning and again move in a westerly direction. The azimuth distribution by hourly intervals is plotted in Figure 10B.

IF echoes are observed at ranges from 500 to 1000 km. The echoes usually occur at approximately one-half the range of the 2F echoes. In general, the movement of the IF echo follows very closely the movement of the 2F (F layer propagated groundscatter) echo. As an example as the 2F echo increases in range and moves to the southwest in the late afternoon, the IF echo in the north increases in range also and moves in an easterly direction always remaining in the gap of the 2F echo ring.

The range and azimuth distributions for the IF echoes are shown in Figure 10B and 11B. Figure 11B is particularly interesting. In scaling the data, a number of factors, such as general ionospheric conditions, particular disturbances, fading rates and other echo characteristics such as length of life, motion and simultaneous occurrences were taken into account in separating IE and IF echoes from other echoes. The range distributions histogram tends to bear out the accuracy of the separation since the distributions represent the approximate half power points at the layer heights involved. At an assumed height of about 100 km, the half-power points are approximately 300 and 500 km in range. The IE echoes decrease sharply in number after 500 km. At a height of 300 km, the half-power points are approximately 500 and 900 km. The measured vertical lobe of the antenna centers around 30 degrees with half power points at 15 and 45 degrees.
IE Echoes

IE echoes are observed in the range interval of 200 km to 800 km. Of these 60% occur at ranges less than 500 km, while 85% of the echoes occur at ranges of 600 km or less. The minimum range sensitivity of the equipment is about 200 km therefore no echoes would be observed at shorter ranges. The range distribution is shown in Fig. 11A. The radiation pattern of the Yagi antenna used reduces the possibility of seeing low angle echoes except in cases where the echoes are quite strong.

Figure 10A shows the azimuth distribution of the IE echo for the month of October 1956. Since the E layer irregularities are thought to be associated with auroral events it is not surprising that the maximum of IE echo occurrence is near magnetic north. It should also be remembered that since the irregularities are considered to be field-aligned, the perpendicularity requirement for backscatter is more nearly fulfilled when the radar is pointed toward magnetic north. The possibility of backscatter from other directions is indicated by the existence of IE echoes to the south in Fig. 10A. Since during auroral disturbances the auroral activity is sometimes present at the zenith and to the south and if, in fact, the IE echoes are associated with auroral activity their presence in this direction is reasonable. It was found that most of the echoes observed in the south were seen during the period from 2000 to 0300 local time and the azimuth distribution showed a southern motion during the onset of the active auroral period at night. A closer study of the IE backscatter from aurora moving from north to south through the zenith shows that radio echoes are received on 12 mc/s only when the angle of incidence on the field lines is within 25 degrees of the perpendicular.
The diurnal distribution of Figure 9A shows a maximum from midnight to 0200 local time. This follows the distribution of visual aurora observed at College. In general however, the resemblance of a particular echo to a visual aurora is very poor. In many cases the visual aurora is seen in a different part of the sky than the radar echo. The relation improves during the later stages of the auroral display. Most echoes tend to be more stable than visual aurora and have a longer life. The average lifetime for all echoes of this type is about five minutes, but some have a lifetime of 10 to 20 minutes with relatively little change in intensity or shape. The shorter lived echoes, those which change from minute to minute, are much more closely associated with visual auroral forms and are usually seen during auroral breakup. In a few instances visual observations during a display have confirmed echo motions similar to movement of the auroral form.

No consistent east to west or west to east echo motion has been observed. There are approximately equal numbers of echoes in both directions. However there is a general north to south echo movement during the onset of the aurora and the reciprocal motion during the later stages of the display.

The number of echoes observed varies greatly from day to day during disturbed periods, as many as 250 minutes of echoes per hour may be observed, or an average of more than four separate echoes per minute. During quiet periods, the number may drop to a few echo-minutes per hour. Occasionally, several days with relatively few echoes may be observed. Although not shown on the histogram, 1E echoes have been observed at all hours of the day, but in relatively small numbers.
The results of the 1956 investigation of F layer propagated groundscatter at 12 mc/s are shown in Figure 12A. The histograms are based on 185 days of usable PPI records. The evaluation is made in terms of echo minutes which seems more meaningful than a mere enumeration of occurrences without regard to duration.

The solar control of the F layer ionization is apparent from the seasonal shift in the diurnal starting and ending time for the 2F echoes. The midday depression or "bite out" in the occurrence of the echoes is attributed to the corresponding daytime maximum in ionospheric absorption.

The diurnal distribution of 2E_s echoes during 1956 is shown in Figure 12B which indicates clearly the importance of the nighttime E_s ionization for high latitude HF propagation. No particular seasonal trend was found in the diurnal distribution of the 2E_s echoes.

The behaviour of the regular 2F groundscatter echoes on 12, 18 and 30 mc/s for the period of 25 Nov. to 20 Dec. 1958 is summarized below. These data were scaled from the 16 mm film data records obtained with the IGY backscatter sounder. Data loss due to interference was negligible on all three frequencies during the period when 2F echoes were observed.

As contrasted with the auroral and 2E_s echoes, the behaviour of the 2F groundscatter echoes is quite simple and regular, making them very easy to identify utilizing low resolution PPI data only. The 2F echoes generally appear early in the morning in the east as a weak echo covering an arc of 30° to 60°. As the morning progresses, the echo decreases in range, increases in intensity and moves into the southern azimuths. Around local noon the echo reaches its maximum intensity and minimum range and covers the southern 180°
or more of the PPI presentation. Some days it extends to all azimuths, forming an eccentric circle. In the afternoon the sequence is reversed, the echoes increasing in range, decreasing in intensity and arc length and finally moving off the PPI in the West in the late afternoon or early evening.

The regular behaviour of the 2F echoes is best illustrated in Table I which shows the range in kilometers to the nearest part of the 2F echo for a typical day in December 1958.

<table>
<thead>
<tr>
<th>Frequency (mc/s)</th>
<th>Morning (0800AST)</th>
<th>Noon</th>
<th>Afternoon (1500AST)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>1500 km</td>
<td>1000 km</td>
<td>1300 km</td>
</tr>
<tr>
<td>18</td>
<td>2000 km</td>
<td>1500 km</td>
<td>1500 km</td>
</tr>
<tr>
<td>30</td>
<td>2500 km</td>
<td>2000 km</td>
<td>2000 km</td>
</tr>
</tbody>
</table>

The hourly averages of echo-minutes of 2F echoes are shown in Figure 13. These histograms cover the month of December 1958. If the 12 mc/s histogram of Figure 13 is compared with the histogram for December 1956 in Figure 12A, it is seen that the diurnal distributions are essentially the same. The mean Zurich Provisional Relative sunspot numbers for Dec. 1956 and Dec. 1958 were 185.5 and 185.2 respectively which indicates that solar influence on the ionosphere was essentially the same for both periods of observation.

Figure 14A through P shows the development of 2F groundscatter echoes on three frequencies: 12, 18 and 30 mc/s for 20 December, 1958. This particular day is an example of the diurnal development on a quiet day.

In the PPI photographs the 24 hour clock shows the time of the observation in Universal time. Alaska standard time (150° WMT) is 10 hours earlier. The
three frequencies are displayed as follows:

upper left PPI: short-range 18 mc/s presentation (not functioning)
upper right PPI: long-range 12 mc/s presentation
lower left PPI: long-range 18 mc/s presentation
lower right PPI: long-range 30 mc/s presentation

The PPI presentations appear square because of malfunctioning of the sine-cosine potentiometer in the CRT sweep circuit. The range markers occur every 500 km and the maximum range displayed is 4500 km. Geomagnetic north is at the top of the PPI presentation. The radial lines present on some of the PPI photographs are due to interference from CW stations near the operating frequencies of the sounder.

DESCRIPTION OF ECHOES

<table>
<thead>
<tr>
<th>TIME (AST)</th>
<th>FIGURE NO.</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0821</td>
<td>6-A</td>
<td>18 mc/s - Weak echo appears in the east at 2200 km, covering a sector of about 30°. Echo in north at 2300 km is probably direct F-scatter IF or sunlit auroral type.</td>
</tr>
<tr>
<td>0844</td>
<td>6-B</td>
<td>12 mc/s - Weak echo appears at 1600 km in the azimuth sector 110°-170°.</td>
</tr>
<tr>
<td>0859</td>
<td>6-C</td>
<td>12 mc/s - Weak echo moves in to 1500 km covering 110°-180° sector. 18 mc/s - Echo intensity increases slightly and covers 80° sector in the southeast at a range of 2000 km.</td>
</tr>
<tr>
<td>0925</td>
<td>6-D</td>
<td>30 mc/s - Weak echo appears at 2700 km (090°-150°).</td>
</tr>
</tbody>
</table>
0954  6-E

12 mc/s - Echo intensity moderate, range 1300 km (090°-200°). At 0954 an echo appears at 1500 km (010°-080°) and increases in intensity to "strong" in two minutes. Echo at 1700 km (200°-250°) probably part of 2F groundscatter echo.

18 mc/s - 4F echo at 2800 km in south.

12 mc/s - Continuous echo from 300° to 260°
Range: North - 1400 km
Southeast - 1200 km
Southwest - 1400 km

18 mc/s - Development of normal 2F echo
30 mc/s - Development of normal 2F echo

1007  6-F

1030  6-G

Continued echo development on all three frequencies. Some cw interference in northeast sector on 18 mc/s. Possibly 4F echo in north on 12 mc/s with some Es activity at 700 km in northeast.

1100  6-H

12 mc/s - Echo intensity-strong; azimuth-continuous except for gap in the northwest.
Range: About 100 km shorter in the north than in the other directions.

18 mc/s - Strong echo (070°-250°) at a range of 1500 km. Weak, short-duration (4 min) echo at 1400 km (330°-020°). Probably propagated auroral echo.

30 mc/s - Strong echo (060°-220°)
Range: East-2400 km
South-2200 km
DISCUSSION OF RESULTS

The development of 2F groundscatter echoes on 12, 18, and 30 mc/s shown in the preceding series of PPI photographs for the day of 20 December 1958 illustrates the "normal" diurnal development of these echoes as well as some anomalies in the development.

The month of December 1958 was characterized by quite high F layer critical frequencies. The College ionosonde indicated F layer critical frequencies ranging from 5 mc/s at 0800 up to 12 mc/s at 1400 on 20 December.
Both groundscatter and direct backscatter echoes were present during most of the period of observation. The groundscatter echoes follow the usual pattern of development for the first hour, i.e., appearing in the east as a weak echo at approximately 2000 km range and moving into the southern half of the PPI with accompanying echo intensity increase and decreasing range. At 0954 on 12 mc/s the 2F echo in two minutes moved into the northeastern sector of the PPI scope and increased in intensity from "weak" to "strong". This illustrates the rapidity of change of ionization in the arctic ionosphere.

Another rapid change in the extent of the 2F echo occurred from 1121 through 1125 on 18 mc/s. The 2F echo spread into the northwest sector in course of five minutes and shortly thereafter developed into almost a continuous ring type echo.

The movement of the 2F echoes in the afternoon followed the usual pattern of development. The last photo (taken at 1349) shows well-developed 2F groundscatter echoes on all three frequencies. There also appears to be some 1F or 2Es echo activity in the north on 12 mc/s. The PPI photo at 1349 was the last of the series since the antenna ceased rotating due to mechanical difficulties.

Observations made with the C-4 sweep-frequency oblique incidence sounder located at College have been studied and attempts have been made to correlate these observations with the fixed frequency backscatter records. It appears that each sounder is illuminating a different part of the ionosphere and the equipment parameters (receiver sensitivity, power output, antenna radiation patterns, etc.) are so different as to make this comparison very difficult. In comparing the sweep frequency and fixed frequency observations for 20 Dec. 1958 the only simultaneous occurrence of a particular echo on both sounders
was at 0820. At this time the fixed frequency sounder showed an echo in the north at 2300 km on the frequency of 18 mc/s. The sweep frequency sounder also showed an echo in the north at 2200 km in the frequency range of 12 to 21 mc/s. These simultaneous observations make it probable that the echo was produced by direct backscatter from the F layer.
Fig. 1. Geometry of Constant-Range Backscatter.
Fig. 2. Range-Frequency Dependence of IF Backscatter.

Fig. 3. Range-Frequency Plot of Constant-Range Echo Joining IF Echo.
Fig. 4. Geometry of IF Backscatter.
Fig. 5. Morning Sequence of Records
16 December, 1958.
Fig. 6. Afternoon Sequence of Records
16 December, 1958.
Fig. 7. Typical $P'$-f Records.
Fig. 8. College $f_2 F2$ profiles 1-15 January 1955.
Fig. 9. Diurnal Distribution of 1E and 1F Echoes October 1956.

Fig. 10. Azimuth Distribution of 1E and 1F Echoes October 1956.
Fig. 11. Range Distribution of 1E and 1F Echoes October 1956.
Fig. 12A. Diurnal Distribution of 2F Echoes.
Fig. 12B. Diurnal Distribution of $2E_s$ Echoes.
Fig. 13. Diurnal Distribution of 2F Echoes on 12, 18, 30 Mc/s December 1958.
Fig. 14 A-D. 2F Echo Development on 12, 18, 30 Mc/s 20 December 1958.
Fig. 14 E-H. 2F Echo Development on 12, 18, 30 Mc/s 20 December 1958.
Fig. 14 I-L. 2F Echo Development on 12, 18, 30 Mc/s 20 December 1958.
Fig. 14 M-P. 2F Echo Development on 12, 18, 30 Mc/s 20 December 1958.
TASK B. AURORAL ECHOES AT RADAR FREQUENCIES

DRIFT MOTIONS OF AURORAL IONIZATION (B. Nichols).

The experimental study of drift motions and the interpretation of the results has been described fully in Scientific Report No. 1, AF 19(604)-1859, July 1957. The purpose, techniques and results of the investigation may be summarized as follows.

The purpose of the experimental observations was to determine the direction and speed of the drift motions of auroral ionization. In doing so, additional information concerning the general nature of auroral ionization was obtained.

Measurements were taken at College, Alaska, during the winter and spring of 1956-57, using CW transmitters. By locating the transmitters at Eielson Air Force Base, it was possible to separate the transmitters and the receivers by 42 kilometers along a geomagnetically east-west line. The basic technique used was to examine the frequency spectra of radio echoes from the aurora at 106 mc/s and 41.15 mc/s. A comparison of the results obtained at 106 mc/s and 41.15 mc/s showed that the frequency shifts are proportional to the transmitted frequency, as would be expected of Doppler shifts.

By measuring the spectra of the echoes received from east and west of geomagnetic north at the same time, it was possible to determine the following:

(i) That the motions are generally horizontal and in the geomagnetic east-west plane; and

(ii) That the speeds of the motions vary from 350 meters per second to 2,000 meters per second.
On the basis of the experimental results and the published literature, it was shown that the electron drift motions in the aurora are of the same order of magnitude and direction as the motions of the electrons in the ionospheric current system required to explain magnetic disturbances. These electron motions produce the Doppler shifts that are responsible for the well-known rapid fading of auroral radio echoes. The fading of radar auroral echoes is therefore associated with the increased electric fields which drive the currents in auroral regions.

Following a review of the available information concerning general motions in the ionosphere, motions of the visible aurora, and motions inferred from magnetic storms, it was shown that the drift motions of auroral ionization do not constitute a separate and distinct group. Instead, they are found at the upper end of a continuous curve of increasing speed of motions with increasing magnetic disturbance. The intense ionospheric currents that produce the magnetic disturbances are found to be associated with both increased electron density and increased speed of motion.

In an examination of the amplitude of VHF radio auroral echoes, the basic premises of the theory of scattering by nonisotropic irregularities produced by turbulence\(^4\) were found to be satisfactory. However, the numerical values of the parameters suggested by Booker require revision. In particular, the results obtained here indicate that the mean square fractional deviation of electron density is much greater than Booker conjectured on the basis of the then available evidence; in fact, it is greater by two to three orders of ten.
TASK C. DIFFRACTION STUDIES EMPLOYING EXTRATERRESTRIAL RADIATION AND SPACED RECEIVERS

No work was undertaken on this task during the contract period due to lack of equipment, funds and personnel.

TASK D. PREDICTION OF AURORAL AND IONOSPHERIC STORMS

I. PHOTOELECTRIC MEASUREMENTS OF AURORA (W. B. Murcray)

The photometric studies of auroral luminosity undertaken under this contract were fully described in Scientific Report No. 2, AF 19(604)-1859, September 1958. We therefore limit our report to the following summary.

The auroral radiation, 3914 Å, received from the entire sky on a horizontal diffusing plate was monitored continuously during the nights of 1955-56 and 1956-57. The 1955-56 and part of the 1956-57 data were used to obtain a diurnal curve for the sky intensity in this wavelength. The auroral light increases to a broad maximum which lasts from magnetic midnight till dawn. The luminosity was found to correlate fairly well with absorption as inferred from f-min values and with \((f Es)^2\), and very well with the magnetic K-indices.
II. SOLAR RADIO OBSERVATIONS (L. Owren)

Monitoring of solar radio emission at 65 mc/s was started in February 1956 with a temporary equipment previously used for absorption measurements by the extraterrestrial radiation technique. The equipment consisted of a surplus British VHF receiver and two 5-element yagi antennas connected to form a meridian total power interferometer. The recordings were made on an Esterline-Angus graphic instrument. The receiver was not sufficiently stable for reliable long term observations, and work was started early on a better phase-switching receiver to replace it. Due to lack of skilled personnel at first and lack of funds later, the new receiver was never completed. A section of it was used for total power recordings from June 1957 through the spring of 1958 until it failed and the observations were discontinued till funds would be available for its repair and completion.

The solar observations for the period February 1956 through 15 September 1957 have been scaled.

The solar radio observations were used successfully for a local 48-hour prediction of aurora. The local predictions were compared with the forecasts issued at 0800 and 1600 Alaska Standard Time by the North Pacific Radio Warning Service. In general, the solar radio emission appeared to provide a better basis for local prediction of aurora than the forecasts of the Radio Warning Service. Attempts to relate the solar radio emission quantitatively with local indices of auroral and magnetic activity were not successful, partly due to the insufficient reliability of the radio observations.
I. WHISTLER AND CHORUS OBSERVATIONS (J. H. Pope)

INTRODUCTION

Whistlers and chorus are electromagnetic naturally occurring phenomena observed in the 1 to 30 kc portion of the spectrum. Whistlers are perceived as a downward going tone or "swish". Chorus is heard as a multitude of upward tones. Whistlers are caused by electric discharges such as lightning. The low frequency radiation from such a discharge may follow geomagnetic line of force to the opposite hemisphere and return producing a frequency dispersion of the original wave packet. The theory and history of whistlers have been given by Storey\textsuperscript{11,12}. The nature of chorus is unknown although Gallet\textsuperscript{13} has presented a hypothesis suggesting the possibility of traveling wave gain along the field lines due to the supposition that the electromagnetic radiation travels at about the same velocity as the incoming solar particles along the field line.

In order to find out what differences may exist in these phenomena between high and low latitudes a receiving station was established at College, Alaska under Contract AF 19(604)-1089 during summer of 1955. The first high latitude whistlers were received by this station and they were found to differ significantly from the low latitude whistlers\textsuperscript{14}. From the low latitude whistlers it had been supposed that the higher the frequency the smaller the propagation time. These high latitude whistlers showed that above a certain frequency the propagation time becomes larger with frequency. The result on a frequency-time plot is roughly a parabola and the whistlers are known as "nose"
whistlers*. The modification to the whistler theory which explains the occurrence of the nose whistler predicted that the nose can be seen at low latitudes by examining the frequency range above 10 kc. This prediction has been verified at several locations\textsuperscript{16}.  

It was found that chorus occurs frequently at high latitudes and that the diurnal maximum occurs in College at about 1400 (150° WMT). This time of maxima is somewhat later than that found at lower latitudes. This fact led to the discovery that the time of diurnal maximum is a function of geomagnetic latitude\textsuperscript{17,18}.  

**INSTRUMENTATION**

The equipment used to receive these low frequency phenomena consists of an antenna, a high gain amplifier and a tape recorder plus other components such as timing units. The instrumentation used prior to March 1958 has been described in more detail in earlier contract reports. The equipments used at College since that date and at Kotzebue between December 1957 and December 1958 inclusive were supplied by Stanford University under an IGY program and have been described in detail by the Stanford group\textsuperscript{19}.  

\* The discovery of the nose whistler has been erroneously attributed to "Helliwell and his co-workers at Stanford University"\textsuperscript{15}. This mistaken assumption is in part attributable to the fact that the theory (developed by "Helliwell and his co-workers") and the experimental verification (obtained by the Geophysical Institute) were published together in a joint paper.\textsuperscript{14}
OBSERVATIONS

The observations made during the period December 1955 to March 1958 inclusive were described and analysis based on these observations reported in Scientific Report No. 4, AF 19(604)-1859.

During December 1957 an IGY whistler station was installed in Kotzebue, Alaska using the Stanford IGY whistler receiver. This station was in nearly continuous operation until the end of December 1958.

In order to standardize the College station for IGY purposes, an IGY receiver was installed during January 1958. The old station continued in operation until the end of March 1958 providing a three month overlap of the two stations. The data recorded by these two receivers were essentially compatible, however, timing difficulties inherent in the design of the IGY receiver lead to uncertainties in the times of operation. Hence the data received on the old equipment are used in the analysis for the period when it is available.

In October 1958 a remote site, free from power line harmonics, became available for use as a whistler station. The old whistler equipment was installed at this site and the two equipments (one at College and the other at the low noise site) were operated for a period of about one month. The IGY receiver was then moved to the low noise site and the two equipments operated at the same site for about two weeks. The results showed a large improvement in the number of whistlers received and in the chorus received.

For compatibility between the data received before and after the move, it is desirable to obtain a quantitative determination of the improvement. Unfortunately instrumentation difficulties made an accurate estimate impossible. The results indicate that this factor is probably between 2 and 4.
During the IGY both stations operated on the two minute per hour sampling schedule specified for IGY whistler stations.

The tapes from the two stations are monitored at College and the results tabulated on a standard IGY date log. A subjective estimate of the strength is made of the whistlers and chorus received. The strength scale used is comprised of the integers 0 to 5. In using these indices consideration must be given to their subjective nature. To determine their reliability a number of tapes have been monitored twice by the same person and some of them by different individuals. The results indicate some discrepancy on an hour to hour basis but good agreement on a daily sum basis. Therefore in statistical studies it is desirable to use daily sums rather than hourly indices.

AN ESTIMATE OF THE OUTER-IONOSPHERE ELECTRON DENSITY USING NOSE WHISTLERS

The first whistler recordings made at College, Alaska exhibited two new characteristics not known from lower latitude observations. The first of these characteristics is that above some frequency, called the "nose frequency", the frequency increases with time instead of decreasing. The second is that the whistler is composed of many separate traces, each successive trace having a lower nose frequency.

The explanation for the difference in shape from the low latitude whistlers has been given by Helliwell\textsuperscript{14} and independently by Ellis\textsuperscript{20}. In deriving the dispersion law, Storey\textsuperscript{11} assumed that the gyromagnetic frequency (\(g\)) is small compared with the observing frequency (\(f\)). Using this assumption he obtained a simple expression for the group refractive index (\(\mu\)) as obtained from the Appleton-Hartree formula assuming longitudinal propagation. The relation
giving the time (t) required for a frequency component of a whistler to propagate is given by

\[ t = \frac{1}{2c} \int_{\text{path}} \mu \, ds = D/f^{1/2} \]

where

\[ D = \frac{1}{2c} \int_{f_H^{1/2}} f_o \, ds \quad f_o = 8.97 \times 10^3 N^{1/2} \text{ cps} \]

D is a constant for a particular whistler. The value of \( g \) at the outermost part of the high latitude geomagnetic field line is not large compared with \( f \). Thus the assumption used is not applicable. Removing this assumption, the correct equation for \( \mu \) is

\[ \mu = \frac{1}{2} \frac{f_o \, g}{f^{1/2} \, (g-f)^{3/2}} \]

and

\[ t = \frac{1}{2c} \int_{f_H^{1/2}} \frac{f_o \, g}{f^{1/2} \, (g-f)^{3/2}} \, ds \]

The second characteristic has not yet been satisfactorily explained. The decrease in nose frequency \( (f_n) \) with time makes it necessary to assume that each trace has traversed a different path. Those with the lower nose frequencies having taken a longer field line than those with higher nose frequencies.

**Calculation of Electron Densities**

Since the dispersion \( D \) depends on \( f_o \) and consequently on the electron density \( N \) it would seem that it should be possible to calculate this density from measurements on conventional whistlers. In general it is not possible. Since the originating impulse may have occurred anywhere within 1000 miles or more of the station, the path length is not accurately known. The nose whistlers provide a means of determining the path taken since \( f_n \) depends mostly on \( g \).
which is determined by the particular field line along which propagation takes place. Thus a measurement of $f_n$ and the time for any frequency should provide an estimate of the ion density.

It is necessary to integrate the expression for the time ($t$) along the field line. Let $L$ be the latitude measured from the equator and $L_o$ the latitude of the end of the field line.

$$t = \frac{1}{c} \int_0^{L_o} \frac{f_0 \cdot g}{f^{1/2} \cdot (g-f)^{3/2}} \, ds$$

where

$$f_n = f_e R^{-3} (1 + 3 \sin^2 L)^{1/2}$$

$$ds = R \cos^2 L (1 + 4 \tan^2 L)^{1/2} \, dL$$

$f_e =$ the value of $f_n$ at the equator = 0.87 mc/s

$R =$ the distance between the earth's center and $ds$

The integral may be evaluated numerically using an assumed function for the electron density distribution over the path of propagation. The function for $f_0$ must be considered. Gallet\textsuperscript{13} has used the assumption that

$$\frac{N}{H} = a \text{ constant along a field line or approximately } N \text{ is proportional to } \frac{1}{R^3}.$$  For the purposes of the integration let $N = \frac{K^2}{R^3}$.

From the above equation we obtain

$$\frac{ctf}{b} \left( \frac{b^{3/2}}{K} \right) = 8.97 \times 10^3 \int_0^{L_o} \frac{1}{(R')^{3/2}} \frac{\left( \frac{f}{g} \right)^{1/2}}{\left( 1 + \frac{f}{g} \right)^{3/2}} \, ds'$$

where

$$b = R \sec^2 L_o$$

$$ds' = \frac{ds}{b}$$

$$R' = \frac{R}{b} = \sec^2 L_o$$

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The gyro-frequency \(g\) is a function of position on the field line while \(f\) is a parameter between 0 and \(\varepsilon_{\text{min}}\). Performing the integration for various values of \(f\) provides the \(t\) versus \(f\) curve. It would seem necessary to specify the particular field line involved in order to obtain the values of \(g\) and to perform the integration for each field line desired. By selecting \(f\) to be some fraction of the value of \(g\) in the plane of the equator it is possible to remove the dependence of the integral on the particular field line involved. Thus it is possible to eliminate the labor of performing the numerical integration for each field line of interest.

The above integration was performed numerically. For the function \(N = \frac{k^2}{R}\) it was found that

\[
\frac{f_n}{\varepsilon_{\text{min}}} = 0.45
\]

The \(\frac{t_n b^{3/2}}{k}\) versus \(f_n\) curve (Figure 15) was obtained by integration using \(\frac{f}{\varepsilon_{\text{min}}} = 0.45\) from which by measurement of the values \(f_n\) and \(t_n\), \(\frac{k^2}{b^3}\) can be determined.

On 19 March 1959 a number of whistlers containing nose components were recorded in which the initiating spheric can be identified. These whistlers are shown in Figure 16. The times of occurrence are approximately 0836, 0837, 1035, 1235 and 1435 UT. The systematic behaviour of these whistlers makes it desirable to attempt ion density estimates using these whistlers to find out if any systematic changes in the ion densities took place during the six hours.

For each component for which \(f_n\) and \(t_n\) can be identified the value for \(\frac{k^2}{b^3}\) (the ion density at the midpoint of the path) was obtained. These results
are shown in Figure 17. The average values of $k^2$ were obtained for each whistler. The functions $\frac{k^2}{R^3}$ are shown in this figure for each of the values of $k^2$. Although there is considerable scatter in the data points, it is clear that they fail to follow the $\frac{1}{R^3}$ distribution. The agreement from whistler to whistler in the values obtained indicates that at least within experimental error the ion densities in the region considered were constant with time during the six hour period.

The assumptions used are:

1. Whistlers follow the geomagnetic field lines
2. The various components in the multiple whistler are due to a multiple path propagation such that those branches with lower nose frequencies have taken longer field lines
3. The nose whistler law holds
4. The ion density varies with distance from the center of the earth as $\frac{1}{R^3}$.

Assumption 1 may not be strictly true as indicated by Maeda and Kimura but it is probably a reasonably good approximation. The results indicate that assumption 4 may not hold except as a 1st order approximation. A slightly steeper drop off in ion density is indicated, if so, then the densities given are too large and the distances too short. One other consideration is that because of the discrete nature of the individual components in the whistler the ionization may be in the form of field aligned tubes, or shells instead of monotonically decreasing with distance.
ANALYSIS OF CHORUS OBSERVATIONS

Temporal Variations

Chorus activity at College was shown to have pronounced diurnal and seasonal variations. The data for 1958 are in substantial agreement with the earlier work. The Kotzebue data show similar variations. Both stations show a winter maximum in the seasonal variation. The Kotzebue station however has a strong summer maximum. A tabulation of these values is given in Table I. The values for College after November 1958 are divided by three to normalize for the improvement obtained at the low noise site.

The diurnal variation in chorus activity is similar to that of College except that the maximum occurs at about 1300 (165° WMT) while the College peak occurs at about 1400 (150° WMT). Figure 19 shows plots of these two diurnal variations for the 13 month period December 1958 to December 1959 inclusive for comparison. The two curves have comparable amplitudes, but the College curve is somewhat broader than that of Kotzebue towards the morning hours. This broading may be attributable to the morning secondary peak discussed in an earlier report which is prominent during the winter months. This curve is weighted somewhat in favor of the winter months because the amplitude of the seasonal curve is large during the winter and because the data for two Decembers are included.

Correlations

The correlation between chorus and magnetic activity at College shows a seasonal variation. To find out if this effect continues and to compare with a station of slightly lower latitude the monthly coefficients of correlation have been obtained for the chorus activity at College versus magnetic activity at College and for the chorus activity at Kotzebue versus magnetic...
activity at College. The indices of magnetic activity used are daily K index sums. The daily chorus indices are obtained by summing the hourly values of chorus strength. The coefficients of correlation between chorus activity at College versus that at Kotzebue were also obtained. These results are tabulated in Table II. It is seen that the correlation between chorus at the two stations varies randomly about 0.5. The correlation between College chorus and magnetic activity shows the usual positive and negative seasonal variation while that for the Kotzebue chorus is negative only once and then not significantly so. The latter correlation does have large variations which agree in phase with the variations in the correlation of College chorus.

The correlation for College chorus and magnetic activity differs from that reported earlier in the positions of maxima and minima. While the first winter maximum and spring minimum are in their normal positions the summer maximum, fall minimum and second winter maximum occur somewhat too early. It is found that the average College K index daily sums (tabulated in Table II) depart from normalcy in the same manner. It has been suggested that the correlation between College chorus and magnetic activity tend to be negative during periods of generally high magnetic activity. This agreement in the departure in the normal seasonal variation of both quantities gives support to this suggestion.
<table>
<thead>
<tr>
<th>Date</th>
<th>Average daily chorus index College</th>
<th>Average daily chorus index Kotzebue</th>
</tr>
</thead>
<tbody>
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<td>Dec '57</td>
<td>9.3</td>
<td>3.8</td>
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<tr>
<td>Jan '58</td>
<td>14.8</td>
<td>11</td>
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* Divided by three to normalize for site noise improvement.
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<tr>
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<td>-</td>
<td>-</td>
<td>22.3</td>
</tr>
</tbody>
</table>
EFFECT OF LATITUDE ON THE DIURNAL MAXIMUM OF CHORUS

It is known that chorus, or "dawn" chorus, exhibits a pronounced diurnal variation in its occurrence and that different stations show different local times for the diurnal maxima. These maxima have been shown to be a function of geomagnetic latitude by Allcock and independently by Pope.

The data used in these studies represented samples taken at three-hourly intervals with a consequent limitation in time resolution (excepting those obtained by the College station). The availability of data from a large number of stations with a time resolution of one hour during the IGY makes it desirable to reconsider the latitude effect.

The data were obtained in various ways. The Geophysical Institute operated field stations at College and Kotzebue. The data for Dunedin, Wellington, Stanford, Boulder, Seattle, Anchorage and part of those from Unalaska were supplied by IGY Whistlers - West. The data from Bermuda, Washington D.C., Norwich, Mont Joli, Knob Lake and part of those for Unalaska were supplied by IGY Whistlers - East. The Cambridge point was obtained from Storey's doctoral dissertation. The time of maximum at Saskatoon was supplied by G. Mck. Allcock of New Zealand. The Macquarie result was communicated directly by radio from that station.

With the exception of the last three stations, which used the occurrence of chorus, the diurnal curves were determined from hourly chorus indices. These indices are derived through a subjective estimate of the strength of the phenomenon. Using the strengths can be considered a weighting of the occurrences in favor of those close to the station. The difference between these two techniques of obtaining the diurnal maximum is probably small.
Table III is a tabulation of the various "whistler" stations used in this study along with the various parameters involved.

Figure 18 shows a plot relating the local time of the diurnal maximum to geomagnetic latitude. The arrows attached to the data points indicate the extent and direction of magnetic time correction. In this figure the eastern stations are plotted with solid data points while the western are plotted as open points. It is apparent that the eastern stations tend to the left of the plot while the western tend to the right side. Thus there appears to be an "east-west effect" in the time of diurnal maximum, which is probably a spurious effect.

Maeda\textsuperscript{23} has considered the effect of a distortion of the earth's magnetic field by rotation to explain the westward shift of the cosmic ray equator noted by Simpson\textsuperscript{24}. This westward shift would tend to reduce the east-west effect in the northern hemisphere. The Knob Lake station being closer to the magnetic equator would have a lower latitude while the College station being further from the equator, would have a higher latitude. This qualitative explanation, however, is not successful if the three southern hemisphere stations are considered, since they are all increased in latitude. Therefore, accepting the validity of the data from the southern hemisphere stations, this westward shift of the geomagnetic equator fails to resolve the discrepancy without introducing others.

The use of geomagnetic latitudes derived from dip angles also fails to remove the discrepancy.

More success can be had by use of an eccentric dipole field. Parkinson and Cleary\textsuperscript{25} have computed the position of the eccentric dipole field poles for the epoch 1955. They are 81.0\textdegree N, 84.7\textdegree W and 75.0\textdegree S, 120.4\textdegree W. Owing to
the fact that these poles are not antipodal the problem of computing eccentric geomagnetic latitudes is complicated. A simple approximation can be obtained however by computing the latitudes in each hemisphere separately as if the dipole were centered using the appropriate pole. This approximation will, of course, produce a discontinuity at the equator. The latitudes using this approximation are tabulated and the results plotted in Fig. 18. The magnetic time corrections are also plotted in this figure. It is clear that while some scatter remains the east-west effect has disappeared. In particular, the Knob Lake point is brought into reasonable agreement with the rest of the data.

These results indicate that it is desirable to consider the use of the eccentric dipole field in connection with theories of chorus. Also the paths of whistler propagation may be affected by the eccentric field rather than the centered field, which may be an important consideration from the point of view of conjugate point experiments and electron density computations.
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Station</th>
<th>Geomagnetic Latitude</th>
<th>Eccentric Geomagnetic Latitude</th>
<th>Local Time Maximum</th>
<th>Number of Months</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>College, Alaska</td>
<td>64.9</td>
<td>67.5</td>
<td>14.0</td>
<td>36</td>
</tr>
<tr>
<td>KO</td>
<td>Kotzebue, Alaska</td>
<td>63.9</td>
<td>67.1</td>
<td>13.2</td>
<td>13</td>
</tr>
<tr>
<td>KL</td>
<td>Knob Lake, Canada</td>
<td>66.1</td>
<td>63.2</td>
<td>8.5</td>
<td>4</td>
</tr>
<tr>
<td>UN</td>
<td>Unalaska, Alaska</td>
<td>51.1</td>
<td>54.2</td>
<td>6.4</td>
<td>9</td>
</tr>
<tr>
<td>SE</td>
<td>Seattle, Washington</td>
<td>53.8</td>
<td>54.5</td>
<td>6.3</td>
<td>10</td>
</tr>
<tr>
<td>ST</td>
<td>Stanford, California</td>
<td>43.8</td>
<td>45.7</td>
<td>3.9</td>
<td>7</td>
</tr>
<tr>
<td>BO</td>
<td>Boulder, Colorado</td>
<td>48.9</td>
<td>48.3</td>
<td>5.5</td>
<td>8</td>
</tr>
<tr>
<td>NR</td>
<td>Norwich, Vermont</td>
<td>55.1</td>
<td>52.5</td>
<td>6.0</td>
<td>14</td>
</tr>
<tr>
<td>MJ</td>
<td>Mont Joli, Canada</td>
<td>60.0</td>
<td>57.1</td>
<td>7.5</td>
<td>9</td>
</tr>
<tr>
<td>WA</td>
<td>Washington, D.C.</td>
<td>50.2</td>
<td>47.8</td>
<td>3.4</td>
<td>10</td>
</tr>
<tr>
<td>BE</td>
<td>Bermuda</td>
<td>43.7</td>
<td>40.7</td>
<td>2.7</td>
<td>7</td>
</tr>
<tr>
<td>CA</td>
<td>Cambridge, England</td>
<td>54.7</td>
<td>52.1</td>
<td>6.0</td>
<td>3</td>
</tr>
<tr>
<td>SA</td>
<td>Saskatoon, Canada</td>
<td>60.5</td>
<td>60.3</td>
<td>9.6</td>
<td>1</td>
</tr>
<tr>
<td>MQ</td>
<td>Macquarie Island</td>
<td>60.2</td>
<td>64.4</td>
<td>11.0</td>
<td>-</td>
</tr>
<tr>
<td>DU</td>
<td>Dunedin, N.Z.</td>
<td>50.5</td>
<td>54.3</td>
<td>4.9</td>
<td>3</td>
</tr>
<tr>
<td>WE</td>
<td>Wellington, N.Z.</td>
<td>45.2</td>
<td>48.9</td>
<td>4.2</td>
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</tr>
</tbody>
</table>
CONCLUSIONS

A technique has been described which may enable one to measure the electron density of the outer ionosphere to heights reached by whistlers. In developing this technique a method was sought by which a large number of whistlers can be analyzed in order to make statistical studies of the electron density variations. The method presented satisfies these conditions. Unfortunately its accuracy is seriously impaired without an accurate determination of the time of the causative impulse.

The causative tweek is seldom identified with whistlers recorded at College and Kotzebue, Alaska. Therefore, for statistical studies, it seems desirable to modify the technique so that the results are independent of the time of origination or to find a method of deducing the time without a location on the sonagram of the originating impulse.

While the nature of whistlers has been essentially established, virtually nothing is known regarding the origin of chorus. Thus the results of studies of temporal variations and correlations of chorus at all latitudes are significant. The temporal variations at the latitude of College, Alaska have been determined. The dependence of the diurnal variation on the geomagnetic latitude has been shown to have a later local time of maximum with higher latitude. The correlation between chorus and magnetic activity at College has a complicated seasonal variation which implies that the observed chorus depends on a third phenomenon. It seems probable that this third phenomenon is closely related to ionospheric absorption but there is not sufficient data in a reduced form to determine the validity of this supposition.
Fig. 15. The Time-Integral as a Function of Nose Frequency.
Fig. 16. Sonagrams of Some Whistler Trains Which Occurred on 19 March 1959.
Fig. 17. Electron Density Versus Distance from Earth's Center as Determined from the 19 March 1959 Whistler Trains.
Fig. 18. The Latitude Effect in the Time of Diurnal Maximum of Chorus.
Fig. 19. Diurnal Variations in College and Kotzebue Chorus.
II. WHISTLER PROPAGATION (L. Owren)

DEDUCTION OF THE ELECTRON DENSITY DISTRIBUTION IN
THE EXOSPHERE FROM NOSE WHISTLER OBSERVATIONS

1. INTRODUCTION

The accepted explanation of the whistling atmospherics occurring in the audio frequency spectrum is that they represent an electrical impulse which has been dispersed by propagation through the ionized medium of the upper atmosphere\(^ {26,27} \). The electrical impulse originates from a lightning discharge in the troposphere. When the impulse reaches the ionosphere, part of the energy may be transferred into a longitudinal mode of propagation which constrains it to follow a line of force of the earth's magnetic field. The longitudinally propagated wave packet returns to the earth's surface near the conjugate magnetic point of the initial impulse. Since the wave packet has traversed a medium where the refractive index depends on frequency (and the mode of propagation), it arrives dispersed. When the whistler is fully developed, the wave packet contains frequency components both above and below the frequency suffering the smallest time delay over the propagation path, and both ascending and descending tones are heard. The curve for the time delay as a function of frequency then has a roughly parabolic shape. Such a whistler is referred to as a nose whistler and the frequency corresponding to the minimum time delay as the nose frequency. Sometimes a nose whistler is composite, with the time versus frequency spectrum consisting of a sequence of parabolas characterized by turning points of increasing time delay and decreasing nose frequency. This phenomenon has been interpreted in terms of a filamentary structure in the electron density distribution in the exosphere. The filaments are assumed to be
aligned with magnetic lines of force and the initial impulse causes wave packets to propagate simultaneously along neighboring, but separated paths. It should be pointed out that the wave frequencies involved in whistler propagation are below the gyromagnetic frequency of the ionized medium. As the wave frequency approaches the gyromagnetic frequency, the group velocity decreases rapidly and the energy of the wave field is dissipated by electronic collisions. Therefore the frequency spectrum of a whistler is confined between zero frequency and the lowest gyromagnetic frequency on the path of propagation.

The most important aspect of whistler investigations is perhaps that the observed dispersion curve is directly related to the electron density distribution along the path of propagation. Since the central part of the path may be at considerable distance from the earth, whistler observations give information about the electron densities in regions of the exosphere which otherwise are accessible only by space rockets. In principle, a systematic study of whistler observations made over a range of latitudes should permit a mapping of the electron density contours over a large region of the exosphere and provide information on the seasonal and yearly changes. The whistlers observed in high latitudes are particularly interesting because their propagation paths extend to between 4 and 6 earth's radii. Every group engaged in whistler investigations has made efforts to derive from their observations the wanted information about the electron density in the parts of the exosphere traversed by the paths ending near their respective latitudes. But because of the inherent mathematical and observational difficulties of the problem, the yield has so far been meager, and the results mostly qualitative only. The mathematical problem
consists in inverting the integral for the group path of propagation which is directly related to the observed propagation time for each frequency component. This integral has as its integrand the group refractive index and is extended over the path of propagation. The expression for the group refractive index, which follows readily from the magneto-ionic theory, is a function of the wave frequency, the gyromagnetic frequency and the unknown electron density. The two latter quantities are, of course, point functions. The resulting integral equation for the unknown electron density function is non-linear and apparently too involved to permit solution by presently known techniques. In view of this the approach has been to use an assumed electron density distribution function, and obtain solutions which match the observed dispersion curves for the assumed form of the function. Various simple forms of the distribution function such as a constant, a linear function, an exponential or a polynomial have been used.

Consideration of the expression for the group refractive index will show that the unknown electron distribution function enters as a weighting factor of the integrand. Thus the overall, roughly parabolic, shape of the dispersion curve does not depend on the electron distribution function, and the latter only serves

(a) to select the path (field line) of propagation

(b) to give a best fit to the observed dispersion curve for this path.

The path selection is made from the relationship between the whistler nose frequency and the minimum gyromagnetic frequency along the path. These two quantities are proportional and the value of the factor of proportionality lies between 1/3 and 1/2 depending on the electron density distribution. When a model for the electron density distribution has been selected, the path of propagation is fixed. A best fit to the observed dispersion
curve is then obtained by variation of the value of the electron density at the midpoint of the path. Clearly every reasonable model will permit a "best fit" by selection of an appropriate value of the electron density at the midpoint (geomagnetic equator). There can be no objective way of deciding which of several different models best reproduces the observed dispersion curves. Hence, when assumed electron distribution functions are used, there is no way of determining a unique electron density distribution. Therefore the method of numerical evaluation and fitting with assumed distribution functions is ambiguous and the results of such an analysis depend on an arbitrary, subjective physical assumption regarding the electron density distribution over the path of propagation.

It is the purpose of this communication to replace this unsatisfactory technique by a more systematic method avoiding subjective assumptions. A provisional form of the electron density distribution function is derived by solving an approximate form of the integral equation and thereafter iterative procedures used to obtain the final form. The success of the method depends on how well the simplified integral approximates the exact integral and on the convergence of the iterative procedure. We shall show that under certain conditions, which are likely to be satisfied in practice, the exact integrand may be expanded in a convergent series. The first term of the expansion will be dominant if the conditions are well satisfied, and the series rapidly convergent. If the series expansion is permissible, the exact integral can be reduced to a Fredholm integral equation of the first kind with a singular and unsymmetric kernel. It is possible to invert this integral equation and obtain a principal value solution. It may be noted that at least in some of the attempts at solving with assumed distribution functions only this simplified form of group path integral were used.
In Section 2 we derive the series expansion form of the group path integral and discuss under which conditions it is convergent. In Section 3 it is shown how the Fredholm equation which approximates the group path integral, may be inverted and a principal value solution obtained. Finally an iterative procedure is outlined which may be applied to obtain more accurate solutions, provided the first order solution is consistent with the basic assumption.

2. THE WHISTLER INTEGRAL AND ITS APPROXIMATION

The group path of a wave packet propagating in an ionized medium under the influence of a magnetic field is given by

\[ P' = cT(\omega) = \int_{\text{path}} n'(\omega, x, N) \, ds \]

where \( c \) = velocity of electromagnetic radiation in free space
\( \omega \) = wave frequency (angular)
\( x \) = gyromagnetic frequency (angular) of electron
\( N \) = electron density
\( s \) = path length

\( T(\omega) \) is the group time of propagation while \( n' \), the group refractive index, is defined by

\[ n' = \frac{c}{U} = \frac{\partial (\omega n)}{\partial \omega} = n + \omega \frac{\partial n}{\partial \omega} \]

with \( U \) = group velocity and \( n \) = refractive index.

Let \( p(s) \) denote the plasma frequency at any point \( s \) on the path,

\[ p^2(s) = \frac{e^2 N(s)}{4\pi^2 mc^2} \]

where \( e \) = charge of electron, \( m \) = mass of electron, \( \epsilon_0 \) = capacitivy of free space.
In whistler propagation studies it is convenient to specify the frequencies in kilocycles per second. Then,

\[ p = 9 \frac{N}{\sqrt{2}} \text{ kc/s} \quad \text{when } N \text{ is the number of electrons per cubic centimeter.} \]

\[ x = 2800 B \text{ kc/s} \quad \text{when the magnetic flux density, } B, \text{ is given in gauss.} \]

By a well-known result of the magneto-ionic theory the refractive index of an ionized medium for strictly longitudinal propagation with collisions neglected is

\[ n^2 = 1 - \frac{p^2}{\omega^2 + \omega x} \quad (4) \]

When the wave frequency \( \omega \) is smaller than the gyrofrequency \( x \) so that \( (x/\omega) > 1 \), the plus sign in (4) corresponds to a decreasing refractive index for increasing \( (p/\omega) \), while the minus sign gives an increasing refractive index for increasing \( (p/\omega) \). It is the latter case which is appropriate for whistlers. When we select the minus sign in equation (4), the wave is labelled an extra-ordinary wave for \( (p/\omega) < 1 \) but an ordinary wave for \( (p/\omega) > 1 \). The whistler mode of propagation is therefore to be labelled as an ordinary wave.

Application of equation (2) leads to the following expression for the group refractive index

\[ n' = \frac{c}{U} = \frac{1}{2} \omega^{-1/2} \frac{px}{(x - \omega)^{3/2}} \frac{1 + 2h}{(1 + h)^{-1/2}} \quad (5) \]

where

\[ h = \frac{\omega(x - \omega)}{p^2} , \quad \theta = \frac{x - \omega}{x} , \quad 0 \leq \theta \leq 1 \quad (6) \]
Provided \( p^2 > \omega(x - \omega) \), or \( h < 1 \), at every point along the path of propagation in the ionized medium, the last parenthesis may be expanded in a binomial series. The resulting equation may be written as

\[
\frac{c}{U} = \frac{1}{2} \omega^{-1/2} \frac{px}{(x - \omega)^{3/2}} (1 + (2\theta - \frac{1}{2}) h - (\theta - \frac{3}{8}) h^2 + \ldots)
\]

Consider the implication of \( p^2 > \omega(x - \omega) \).

The product \( \omega(x - \omega) \) is zero for \( \omega = 0 \) and \( \omega = x \). Therefore, for a given value of \( x \), \( \omega(x - \omega) \) must have a maximum when \( \omega = \frac{1}{2}x \).

The condition \( p^2 > \omega(x - \omega) \) may therefore be restated as

\[
(8) \quad p^2 > \frac{1}{4} x^2
\]

But the wave frequency \( \omega \) cannot exceed the smallest value of \( x \) along the path. Denote this minimum value of \( x \), which occurs at the midpoint of the path (geomagnetic equator), by \( x_o \). Then

\[
(9) \quad p^2 > x_o(x - x_o)
\]

Over the inner part of the path \( x \) is much larger than \( x_o \), so there the condition is equivalent to

\[
(10) \quad p^2 > x_o x
\]

or

\[
(10a) \quad N > \frac{x_o x}{81}
\]

The situation is therefore as follows. In order to make use of the series expansion and equation (7), the plasma frequency \( p(s) \) must at any point \( s \) on the path of propagation exceed the larger of

\[
(x_o(x - x_o))^{1/2} \quad \text{and} \quad \frac{1}{2}x(s).
\]
Over the inner part of the path (closest to the earth) this is equivalent to saying that the local plasma frequency must exceed the geometric mean of the local gyromagnetic frequency and the minimum gyromagnetic frequency encountered on the path.

Provided $\omega^2$ is much larger than $\omega(x - \omega)$, the expression for the group refractive index is well approximated by the first term of (7)

\begin{equation}
\frac{c}{U} \simeq \frac{1}{2} \omega^{-1/2} \frac{px}{(x - \omega)^{3/2}}
\end{equation}

and the approximate integral for $cT(\omega)$ reads

\begin{equation}
cT(\omega) = \frac{1}{2} \omega^{-1/2} \int_{-s_1}^{s_1} \frac{px}{(x - \omega)^{3/2}} \, ds
\end{equation}

We now make the following assumptions:

(i) The earth's magnetic field may be represented by a dipole field.

(ii) The plasma frequency, i.e. the electron density distribution along a field line, is symmetric about the geomagnetic equator.

Since we have used equation (4) to obtain the expression (12) for $T(\omega)$ we have also implicitly assumed that

(iii) The whistler wave-packet propagates in a strictly longitudinal mode, i.e. is tied to a particular field line.

(iv) Electronic collisions may be neglected.

Let a whistler wave packet start at the point $-P_1$ in the southern hemisphere in the geomagnetic latitude $-L_1$ and let it be observed after one passage at the conjugate point $P_1$ in the geomagnetic latitude $L_1$ in the northern hemisphere.
Then the observed dispersion is given by

\[(13) \quad \chi_T(\omega) = \frac{1}{2} \omega^{-1/2} \int_{-1}^{1} \frac{p(x)}{(x - \omega)^{3/2}} \, ds\]

or

\[(13a) \quad \chi_T(\omega) = \omega^{-1/2} \int_{-1}^{1} \frac{p(x)}{(x - \omega)^{3/2}} \, ds\]

because \(x(s)\) and \(p(s)\) are even functions (symmetric about the geomagnetic equator). In fact

\[(14) \quad x(s) = \text{constant} \cdot R^{-3} (1 + 3 \sin^2 L)^{1/2} \]

\[= \text{constant} \cdot R_0^{-3} (1 + 3 \sin^2 L)^{1/2} \cos^{-6} L\]

where \(R\) is the distance from the dipole center to the point \(s\) on a dipole field line, \(R_0\) is the equatorial distance, and \(L\) the geomagnetic latitude of \(s\).

An element of arc along the field line is given by

\[(14a) \quad ds = R_0^{-1} (1 + 3 \sin^2 L)^{1/2} \cos L \, dL.\]

In order to cast equation (13) in the desired form, we must use the gyromagnetic frequency \(x\) as the independent variable, and introduce

\[ds = \left(\frac{ds}{dx}\right) \, dx\]

Equation (13) now assumes the form

\[(15) \quad f(\omega) = \int_{x_0}^{x_1} k(x - \omega) g(x) \, dx\]
where \( x_0 = x(s = 0) \) and \( x_1 = x(s_1) \) while

\[ f(\omega) = c\omega^{1/2} T(\omega) \]

\[ k(x-\omega) = \left| x-\omega \right|^{-3/2} \]

\[ g(x) = px \frac{ds}{dx} \]

In (15b) we have replaced \((x-\omega)^{-3/2}\) by \(\left| x-\omega \right|^{3/2}\). The replacement of the parenthesis by an absolute value sign is permissible since \(\omega\) never exceeds \(x_0\), the minimum value of \(x\), and the kernel \((x-\omega)^{-3/2}\) is therefore non-negative on the interval \((x_0, x_1)\). Formally equation (15) is a Fredholm integral equation of the first kind where the function \(g(x)\) is unknown.

The function \(\frac{dx}{ds}\) is continuous and \(x\) has a stationary point \(\frac{dx}{ds} = 0\) at \(s = 0\). Therefore \(\frac{ds}{dx}\) is not defined at \(x = x_0\) and tends to infinity as \(x^{-1/2}\) when \(x\) approaches \(x_0\). Since a solution \(g(x)\) of the integral equation must remain finite for all values of \(x\) on the closed interval \(x_0 \leq x \leq x_1\), this implies that \(p(x)\) approaches zero at least as \(x^{1/2}\) when \(x\) approaches \(x_0\). Such a behavior of \(p(x)\) violates our assumptions, and can be shown to be a consequence of neglecting the effect of the collisions at and near \(x = x_0\). Therefore we use the expedient of redefining \(\frac{ds}{dx}\) on the segment \(x_0 + \delta \leq x \leq x_0\) such that \(\frac{ds}{dx}\) remains finite. This may be accomplished by putting

\[ \frac{ds}{dx} = \text{constant} = \left(\frac{ds}{dx}\right)_{x_0 + \delta} \]

everywhere on \((x_0 + \delta, x_0)\) and selecting for \(\delta\) the smallest positive number which permits the condition

\[ p^2 > x_0(x - x_0) \]

or

\[ p^2 > \delta x_0 \]

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to be satisfied. Physically this means that we are replacing the actual electron density distribution in the neighborhood of the geomagnetic equator by a thin layer of half-thickness

$$\Delta s = s(x_0 + \delta) - s(x_0)$$

where the electron density varies more slowly than prescribed by the function $x \frac{ds}{dx}$ near $x = x_0$. The necessity of redefining $\frac{ds}{dx}$ near the midpoint of the path indicates that the assumption of strictly longitudinal propagation is an idealization which breaks down at that point. When $\frac{ds}{dx}$ is redefined as indicated, $g(x)$ is a well-behaved function on $(x_0, x_1)$ since $x \frac{ds}{dx}$ is continuous and bounded while $p(x)$ may be assumed to be a sectionally continuous function with at most a finite number of ordinary discontinuities on $(x_0, x_1)$. The observed dispersion $T(\omega)$ may be represented by polynomials so $c \omega^{1/2} T(\omega) = f(\omega)$ is well-behaved on $(x_0, x_1)$.

The kernel $|x - \omega|^{-3/2}$ is unsymmetric and singular because of the infinite singularity at $\omega = x_0$. The kernel is non-integrable on the closed interval $(x_0, x_1)$. This implies that only a principal value solution of the integral equation may be obtained. The feature which gives hope of finding a solution is that the integral equation is of the convolution form.

3. INVERSION BY A FINITE FOURIER TRANSFORM

A principal value solution of the integral equation (15) may be obtained by:

(i) introduction of an integrable kernel which by a limiting operation reduces to $k(x - \omega) = |x - \omega|^{-3/2}$;
(ii) use of the convolution form of the integral equation and the finite Fourier transform technique (cf. Churchill, Operational Mathematics).

In connection with the latter it is convenient to transform the range of variation from the interval \((x_0, x_1)\) to \((0, \pi)\).

Thus,

\[
(17) \quad f(W) = \int_{0}^{\pi} k(W + X) g(X) \, dX
\]

where

\[
X = \frac{\pi}{x_1 - x_0} (x - x_0), \quad W = \frac{\pi}{x_1 - x_0} \omega
\]

(18) Let \(h(T) = \frac{T}{1} \exp (-T^2/2)\)

\[
= - \frac{\pi}{\Theta} \frac{d}{dT} \left( \text{ERF} \left( \frac{\Theta}{|T|^{1/2}} \right) \right)
\]

Clearly \(h(T)\) has the required property

\[
(19) \quad \lim_{\Theta \to 0} h(T) = k(T)
\]

and is integrable over \((0, \pi)\).

Now define \(h(X)\) and \(g(X)\) in \((-\pi, 0)\) by odd periodic extensions, and the integral equation assumes the proper convolution form for a finite range of variation

\[
(20) \quad f(W) = \int_{-\pi}^{\pi} h(W + X) g(X) \, dX = h(-W) \ast g(W)
\]

Take the Fourier cosine transform of both sides,

\[
(21) \quad C_N(f) = C_N(h \ast g) = -2 h_s(N) g_s(N)
\]
The inverse operation yields

(22) \[ g(X) = -\frac{2}{\pi} \sum_{N = 1}^{\infty} \frac{f_C(N)}{h_S(N)} \sin(NX), \quad 0 \leq X \leq \pi \]

where \( f_C(N) \) is the Fourier cosine transform of \( f \)

(23) \[ f_C(N) = \int_{0}^{\pi} f(T) \cos(NT) \, dT \]

taking \( f(T) = 0 \) outside its range of definition. Similarly, \( h_S(N) \) is the Fourier sine transform of \( h \)

(24) \[ h_S(N) = -2N \exp\left(-\frac{\theta^2}{4}\right) \int_{0}^{\pi} \frac{\cos(NT)}{T^{1/2}} \, dT + O(\theta^2) \]

In the limit \( \theta \to 0 \) this becomes the Fourier sine transform of \( k \)

(25) \[ \lim_{\theta \to 0} h_S(N) = k_S(N) = -2 (2\pi N)^{1/2} C(\pi N) \]

where \( C(\pi N) \) denotes the Fresnel cosine integral which is a tabulated function (cf. Jahnke and Emde, Tables of Functions).

The principal value solution of the integral equation (15) is

(26) \[ p(X) = (2\pi^3)^{-1/2} (X \frac{d}{dX})^{-1} \sum_{N = 1}^{\infty} \frac{f_C(N)}{N^{1/2} C(\pi N)} \sin(NX), \quad 0 \leq X \leq \pi \]

This solution has a convenient form for numerical evaluations.
4. ITERATIVE IMPROVEMENT OF THE SOLUTION

Consider equation (7)

\[
\frac{c}{u} = \frac{1}{2} \omega^{-1/2} \frac{px}{(x - \omega)^{3/2}} \left(1 + \left(2\theta - \frac{1}{2}\right)h - \left(\theta - \frac{3}{8}\right)h^2 + \ldots\right)
\]

and the resulting integral

\[
\int_0^{s_1} (x - \omega)^{-3/2} (px) \, ds
\]

\[
+ \int_0^{s_1} \frac{px}{(x - \omega)^{3/2}} \left((2\theta - \frac{1}{2})h - \left(\theta - \frac{3}{8}\right)h^2 + \ldots\right) \, ds
\]

The second integral can be evaluated term-by-term using the first mean value theorem and the first order expression obtained for \( p(x) \).

Thus we have

\[
f(\omega) + \sum_{k=1}^{\infty} t_k(\omega) = \int_{x_0}^{x_1} k(x - \omega) g(x) \, dx
\]

and the first order solution obtained by neglecting the contributions from the higher order terms

\[
\sum_{k=1}^{\infty} t_k(\omega)
\]

can be systematically improved by an iterative procedure.
TASK F. INVESTIGATION OF IONOSPHERIC ABSORPTION AS A FUNCTION OF PROPAGATION FREQUENCY

No work has been undertaken on this task under the present contract because similar work was pursued by the Geophysical Institute with support from other agencies.
I. TRANSPOLAR TRANSMISSION TESTS 1956-58 (L.Owren and R.D. Hunsucker)

Early in 1956 the Norwegian Defence Research Establishment and the Geophysical Institute agreed to cooperate in a program of test transmissions across the north polar region in order to explore the propagation conditions. The first propagation test was made during the month of July 1956. The original plan called for continuous transmission of a 3 kw frequency-shift teletype signal on .3.3 and 7.7 mc/s from Fairbanks, Alaska and a 5 minute-per-hour transmission of a 5 kw continuous wave signal on 5.9 mc/s from Harstad, Northern Norway. In addition the Alaska receiver stations were to monitor the 100 kw broadcast transmissions on 629 kc/s from Vigra in Southern Norway. Receiver stations were set up at College and Barrow in Alaska, and at Harstad, Norway as well as on West Spitzbergen, Svalbard, which is a Norwegian dependency. As the test progressed modifications had to be made in the original plan. The 3.3 mc/s transmission from Fairbanks had to be cancelled because of interference with other services. The Norwegian receiver stations were unable to pick up the 7.7 mc/s transmission, and on 12 July this was replaced by a 6 kw pulse transmission on 12.3 mc/s beamed from College to Northern Norway. This signal was immediately picked up and identified by the Spitzbergen station.

The College receiver station was unable to identify the 5.9 mc/s transmission from Harstad, but Barrow succeeded after coming into operation on 13 July. The signal was never well received even at Barrow. Completely negative results were obtained on the Vigra MF transmissions both at Barrow and College.
A supplementary program for monitoring Norwegian and Russian MF and HF broadcast transmitters in the frequency range from 0.5 to 22 mc/s was put in effect at College on 6 July and at Barrow on 13 July. Good results were obtained on the Norwegian short-wave transmissions at 17.825 mc/s from Fredrikstad, Southern Norway.

The July 1956 test showed clearly the superiority of pulse signals over the FSK and CW types of transmission, and further indicated that future tests should be concentrated on frequencies in the HF band.

Because of various circumstances the next transmission test could not be made till the last week of July 1957. Only the College pulse transmitter operating at 11.772 mc/s was available for this test except that during the last day of the 7 day test period a College 30.64 mc/s pulse transmitter was added. The July 1957 test was unsuccessful because heavy radio interference blocked the reception at Ski near Oslo of the 12 mc/s signal while the 30 mc/s signal was not heard at Ski.

A third test transmission was made from 30 September through 1 October 1957 using College pulse transmissions on 11.634, 17.877 and 30.64 mc/s. No report was received from the Norwegian Defence Research Establishment regarding the outcome of this test.

The fourth and fifth transmission tests were conducted on 16-17 January and 13-14 February 1958. Pulse transmissions from College on 6, 12, 18 and 30 mc/s with 4 kw peak power and receiver stations on Spitzbergen, Harstad and Ski were used for the January-February 1958 tests. The NDRE found the 11.634 mc/s frequency to be satisfactory but the 17.877 mc/s unsuitable. NDRE also objected to the use of frequencies as high as 30.64 mc/s and suggested that 24.025 mc/s, a Norwegian allocation, be used instead in later programs. We complied with this request by starting construction of a 24 mc/s pulse transmitter similar to the 12, 18 and 30 mc/s units.
The Kiruna Geophysical Observatory also participated in the January and February 1958 tests with encouraging results. In particular it was found that the 12 mc/s signals could be picked up even when the antenna was rotating; in fact the pulse emission from College could be received during the whole rotation cycle. Later it was found that the 18 mc/s pulse transmission could similarly be received over half the rotation cycle. The 30 mc/s signals were also found to be detectable at Kiruna but intermittently rather than regularly. The Kiruna Geophysical Observatory thereafter set up a program of continuous monitoring of the College pulse transmissions on 12, 18 and 30 mc/s which went into effect on at least two frequencies in May 1958.

On 22 July 1958 Dr. Leif Owren of the Geophysical Institute, who was visiting in Oslo, met with Finn Lied, Director of the Norwegian Defence Research Establishment, and some members of his staff to discuss the situation. It was agreed to regard the test transmissions during 1956-58 as being of exploratory nature concerning the proper techniques and frequencies for transpolar propagation studies. It was further agreed that NDRE should take steps to set up three receiver stations in Norway, at Ski, Harstad and on Spitzbergen, for continuous recording of the College pulse signals on the five frequencies of 6, 12, 18, 24 and 30 mc/s. It was planned that after one year of recording, the Norwegian signal strength observations and the simultaneous College backscatter soundings on the same five frequencies should be analyzed jointly, preferably at the Geophysical Institute, College, Alaska. Work is in progress to realize these plans.

The College transmissions on 12, 18, 24, and 30 mc/s have been recorded at Kiruna utilizing a rhombic antenna connected to a communication receiver modified for pulse reception. The receiver output is displayed on an oscilloscope, and recorded photographically.

The Kiruna signal-strength and College backscatter data for the month of December 1958 have been analyzed and the probable propagation modes identified. The transpolar propagation is characterized by a predominant three-hop mode and a less often observed two-hop mode. It is possible that a one-hop (Pedersen) mode is responsible for the propagation part of the time. Figure 20 shows the transpolar propagation path.

Observations

Six hundred seventy-two hours of simultaneous recordings of received signal-strength at Kiruna and groundscatter echoes observed at College for the month of December 1958 were available for analysis at the time of writing.

Approximately 30% of the 672 hours of data were lost due to short-wave interference on the frequencies being used and the usual equipment failures. At Kiruna, interference accounted for the following data loss: 12 mc/s - 12%, 18 mc/s - 10%, 30 mc/s - 14%. The loss due to interference at College was slightly higher on 12 mc/s and 18 mc/s for the corresponding period. Equipment failures accounted for approximately 15% of the loss of data at College and Kiruna.

The great-circle transpolar propagation path between College, Alaska and Kiruna, Sweden is approximately 5300 km. Groundscatter observed from College appearing within ± 30° of the Kiruna azimuth in the 1000 to 1900 km range interval was interpreted as the first hop of a three-hop mode.
Similarly, groundscatter in this direction in the 2000 to 3000 km range interval was considered as the first hop of a two-hop mode.

Periods of high signal strength at Kiruna were sometimes observed during the interval 07-18 U.T. when there were no groundscatter echoes in the direction of propagation. This could indicate that the echoes were present but were below the receiver sensitivity threshold or that a one-hop Pedersen propagation mode was operative. The histogram for 18 mc/s in Figure 24 illustrates this condition during the interval 12-15 U.T.

When the College transmissions were "readable"* at Kiruna, groundscatter echoes from the polar region indicated the relative occurrence of the following propagation modes:

<table>
<thead>
<tr>
<th>Propagation Mode</th>
<th>Percent of time when mode occurred</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12 mc/s</td>
</tr>
<tr>
<td>Three-hop</td>
<td>65%</td>
</tr>
<tr>
<td>Two-hop</td>
<td>11%</td>
</tr>
<tr>
<td>No indication</td>
<td>24%</td>
</tr>
</tbody>
</table>

(polar groundscatter absent)

Figure 21 shows the average signal-strength at Kiruna for the month of December 1958 for 12 mc/s and 18 mc/s. The pronounced "dip" at 1500 U.T. in the 12 mc/s and 18 mc/s histograms occurs during the period of maximum interference at both Kiruna and College. The diurnal maximum of D-layer absorption in the region north of College also occurs during this interval.

*The Kiruna signal-strength data are recorded photographically and scaled at arbitrary levels ranging from 0 to 3. A "readable" signal is taken as one of strength ≤ 0.5 on this scale.
The hourly total of echo-minutes for two and three-hop groundscatter observed on 12 mc/s is shown in Figure 23. It is apparent that the two-hop mode occurs less frequently than the three-hop mode and that their diurnal maxima do not coincide. The period from 1300 U.T. to 1800 U.T. represents the time of maximum loss of data due to interference.*

Similarly, the 18 mc/s diurnal variations in total echo-minutes of two and three-hop groundscatter are shown in Figure 22. Again, the two-hop mode is seen to be less prevalent than the three-hop mode. The period of maximum loss of data due to interference occurs from 1400 U.T. to 1800 U.T.

Data for two selected days are displayed in Figure 24. The Kiruna hourly average signal-strength is compared with two and three-hop groundscatter on 12 mc/s and 18 mc/s. These days were chosen because echo observations of all three categories were present and the data loss due to interference was relatively low.

The 12 mc/s presentation does not show a definite correlation between the presence or absence of groundscatter echoes and the Kiruna signal-strength level. On 18 mc/s, however, such a correlation appears to exist as can be seen from Figure 24.

Discussion of Results

It should be pointed out that the fixed-frequency sounder data are displayed on a PPI presentation and consequently, quantitative echo intensity is not recorded. For the present investigation, the number of echo-minutes per hour in the region of interest has been compared with the average hourly signal-strength at Kiruna.

*Diagonally marked areas denote periods of maximum interference.
The diurnal variation of groundscatter echoes in the polar region is summarized in Table 2. This table indicates that for 12 mc/s and 18 mc/s, the three-hop mode occurs both day and night and the two-hop mode is predominately a daytime mode, Alaska time, with a maximum around local noon. The time of minimum occurrence of three-hop and two-hop echoes for 12 mc/s is centered around local midnight.

There is a possibility that some of the echoes observed in the 1000 to 1900 km interval could be direct backscatter from the F region. The sweep-frequency investigation at oblique incidence reported under Task A, Section I, shows that these echoes occur in the 400 km to 1800 km region in the north and are associated with irregularities of electron density at heights from 350 km to 500 km. Not enough simultaneous sweep-frequency and fixed-frequency data were available at the time of writing to positively identify these echoes as direct backscatter, however.

**TABLE 2**

**Diurnal Variations of Groundscatter Echoes in the Polar Region**

<table>
<thead>
<tr>
<th>Propagation Mode</th>
<th>Maximum Occurrence 12 mc/s</th>
<th>Maximum Occurrence 18 mc/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three-hop</td>
<td>1000-1300, 1900-2300, 0100-0200</td>
<td>0900-2200 (1300, 1600, 2100) (1100-1700)</td>
</tr>
<tr>
<td>Two-hop</td>
<td>1000-1700, 1900-2000, 22-23 01-02</td>
<td>1100-1300, 1600-2000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Propagation Mode</th>
<th>Minimum Occurrence 12 mc/s</th>
<th>Minimum Occurrence 18 mc/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three-hop</td>
<td>05-07 (QRM)</td>
<td>23-02</td>
</tr>
<tr>
<td>Two-hop</td>
<td>03-10 (QRM)</td>
<td>20-03</td>
</tr>
</tbody>
</table>

Notes: All times are A.S.T. (150° WMT)  
**Underlined** time intervals denote peak activity.
The absorption effects mentioned earlier are based on the assumption of a "take-off" angle of 15° for the radiation leaving College and a height of maximum absorption of 60 km. According to the riometer data secured by H. Leinbach, the values of absorption in this region are typically quite high during the diurnal period when low average signal strength is observed at Kiruna and a minimum of polar groundscatter echoes observed at College on 12 mc/s.

The possibility of lateral scattering in the ionosphere, producing propagation in a horizontally deviated path should also be considered. Investigators\(^\text{29}\) in Japan have found that signals from Europe can be received in Japan followed by lateral deviation of about 20° at times when F-layer propagation along the great circle is not possible.

DISCUSSION OF TABLE 2

I. 12 mc/s

A. Three-Hop Mode. For a three-hop transmission mode assuming a take-off angle of approximately 15°, the radiation would pass through the absorption zone north of College. The maximum absorption occurs at 05-08 AST which probably causes the "dip" in observed polar backscatter echoes at 05-07 AST. The Kiruna signal strength is also at a minimum value at 0500 AST.

The periods of maximum occurrence of three-hop backscatter are near local\(^*\) noon, midnight, and early morning (0300-0400). Strong signals are also recorded at Kiruna during these periods. As to why the three-hop mode should be preferred during these periods it is not clearly understood.

*Local time is here taken as the time at the midpoint of the first-hop of the observed mode of propagation.
B. Two-Hop Mode. The main maximum of two-hop backscatter echoes occurs during the corresponding maximum for the three-hop mode, but lasts about four hours longer. This occurs during the afternoon and evening 1300-2000 local time.

It should be pointed out that the backscatter data are hourly averages during the month and do not imply the simultaneous existence of two-hop and three-hop backscatter echoes.

The take-off angle for a two-hop mode is approximately 6°, which would indicate that the radiation for this mode would not pass through the zone of maximum absorption. There appears to be an absence of two-hop backscatter during the period 03-10 AST but this is also the period of maximum data loss due to QRM.

II. 18 mc/s

A. Three-Hop Mode. On 18 mc/s the main maximum of echoes occurs during the late afternoon College time (1300-1900 AST) which corresponds to high signal strength recorded at Kiruna.

The minimum backscatter is observed at 0100-0400 College time (just before local sunrise). The Kiruna signal strength is high during this period.

The simultaneous observations at 18 mc/s of Kiruna signal strength and backscatter soundings at College for 4 December 1958 (Figure 24) show a good correlation between strong signals and echo-minutes of two-hop and three-hop backscatter.

B. Two-Hop Mode. The maxima for the two-hop mode on 18 mc/s occur in the afternoon and evening College time (1400-1700 AST) during times of relatively strong signal at Kiruna.

No two-hop groundscatter echoes are observed near midnight College Time (2300-0600 AST) as might be expected.
POSSIBILITY OF ONE-HOP OR LATERAL PROPAGATION MODE

No polar groundscatter echoes were observed at College during 24% of the time when a readable signal was recorded at Kiruna at 12 and 18 mc/s. This means that the backscatter soundings gave no direct indication of the probable transpolar propagation mode during 19% of December 1958 while the propagation modes apparently were directly indicated 61% of the time, and no signal was propagated 20% of the time. The absence of groundscatter echoes from the polar region when signal transmission takes place may be explained in several ways such as (i) due to the scattering properties of the Arctic Ocean, or (ii) propagation by a one-hop high ray mode, or (iii) off-great circle propagation by a lateral mode.

(i) The first possible explanation is that for certain angles of incidence or in certain regions the ice-covered Arctic Ocean acts as a good reflector but a poor scatterer of the incident HF radio waves. Thus the presence or absence of ground scatter would depend on geometrical factors such as the height of the reflecting layer in the ionosphere and the location of the ground impact area. If this hypothesis were correct we should expect the gaps in the 2F groundscatter rings so frequently observed to be centered on geographic north (see Figure 20). A closer examination of the backscatter records both for 1956 and 1958 reveals however that the gaps are consistently centered on geomagnetic rather than geographic north. This indicates that properties of the ionosphere such as electron density gradients in the magnetic meridian plane rather than the reflecting and scattering properties of the earth's surface are responsible for the gaps. Since at College the bearing of geomagnetic north is 27 degrees east of geographic north, an unambiguous discrimination between the two directions is possible even for the fairly wide (about 60°) horizontal beamwidth of the rotating antenna polar diagrams.
(ii) A second possible explanation involves one-hop propagation modes. A tilted-layer mode of the type established by the Stanford University group cannot be invoked since groundscatter from the impact area near the receiving station would be expected. However one-hop propagation by a high ray or Pedersen mode is a distinct possibility. The energy spread and absorption suffered by the groundscatter radiation over the return path from Kiruna to College might well reduce its intensity below the threshold of detection and account for the absence of groundscatter echoes at times when the signals are received with fair strength over the forward path. We note in this connection the one-hop high-angle propagation of radio waves at frequencies between 27 and 33 mc/s over the Ottawa-Slough path of 5300 km reported by Canadian workers. A difficulty posed by this explanation is that although the signal propagation takes place by the high ray mode, one would still expect the transmitting station to observe the groundscatter from the low ray mode intercepted by the earth. This objection may be set aside if it can be assumed (or established) that the low ray mode is subjected to higher absorption than the high ray mode by passage through the auroral D-layer absorption zone on one or preferably both sides of the path.

(iii) The third possibility is propagation from College to Kiruna by a lateral scatter mode, similar to the mode observed by Japanese workers, rather than a great circle mode. In connection with this alternative it is interesting to note that the 12 mc/s backscatter soundings at College during 8 months of 1956 showed that long-range backscatter echoes from auroral ionization (in northern azimuths) occurred on the average 19.5% of the time, distributed with 11% during the daytime and 8.5% during the night.
The observations presently available for the transpolar propagation path are neither qualitatively nor quantitatively adequate for a determination of the propagation modes. The work undertaken to date indicates that in addition to simultaneous recordings of the amplitudes of the forward propagated signal and backscatter from the ground, information on fading rates as well as multipath and lateral propagation are required.

COMPARISON WITH VERTICAL INCIDENCE SOUNDINGS AT COLLEGE

Scaled vertical incidence ionospheric soundings at College, Alaska for the month of December 1958 were available for comparison with the backscatter and signal strength data. The hourly values of F2 layer 3000 km MUF were tabulated and compared with the other observations. There was no apparent relation between high MUF and observed signal at Kiruna.
Fig. 20. College-Kiruna Propagation Path (5300 km) Range in Thousands of Kilometers.
Fig. 21. Average Signal Strength at Kiruna, Sweden for month December 1958.
Fig. 22. Total Echo-Minutes of Groundscatter for December 1958.
Fig. 23. Total Echo-Minutes of Groundscatter for December 1958.
Fig. 24. Comparison of Received Signal and Groundscatter 18 Mc/s 4 December 1958.
REFERENCES


APPENDIX

EQUIPMENT PARAMETERS

A. 12 mc/s Backscatter Sounder

Frequency

12.305 mc/s

Transmitter characteristics:

Power output
6 kilowatts, peak

Pulse duration
600 microseconds

Pulse repetition frequency
50 pulses per second

Antenna

Height above ground
0.5 wavelength

Type
3-element Yagi

Beamwidth

Horizontal
50° between 3 db points

Vertical
36° between 3 db points

Front-to-back ratio
12 db

Rotation period
1 RPM

Receiver bandwidth
3 kc/s
### B. Three Frequency IGY Sounder

<table>
<thead>
<tr>
<th>Description</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequencies utilized</td>
<td>12 mc/s, 18 mc/s, 30 mc/s (simultaneous)</td>
</tr>
<tr>
<td><strong>Transmitter characteristics:</strong></td>
<td></td>
</tr>
<tr>
<td>Power output</td>
<td>4 kilowatts, peak</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>2 milliseconds</td>
</tr>
<tr>
<td>Pulse repetition frequency</td>
<td>18.75 pulses per second</td>
</tr>
<tr>
<td><strong>Antenna</strong></td>
<td></td>
</tr>
<tr>
<td>Height above ground</td>
<td>0.6 wavelength on each frequency</td>
</tr>
<tr>
<td>Type</td>
<td>3-element Yagi on each frequency</td>
</tr>
<tr>
<td><strong>Beamwidth</strong></td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td>59° between 3 db points</td>
</tr>
<tr>
<td>Vertical</td>
<td>36° between 3 db points</td>
</tr>
<tr>
<td>Front-to-back ratio</td>
<td>18 db</td>
</tr>
<tr>
<td>Rotation period</td>
<td>1 RPM</td>
</tr>
<tr>
<td><strong>Receiver Sensitivity</strong></td>
<td></td>
</tr>
<tr>
<td>Receiver Bandwidth</td>
<td>6 kc/s</td>
</tr>
<tr>
<td><strong>Receiver Bandwidth</strong></td>
<td></td>
</tr>
</tbody>
</table>

0.10 μv. for 1:1 S/N ratio
PUBLICATIONS, REPORTS AND CONFERENCES

A. Papers


B. Research Notes


C. Scientific Reports

B. Nichols, "Drift Motions of Auroral Ionization."

W. B. Murcray, "Photometric Studies of Auroral Luminosity and Its Connection with Some Atmosphere Ionization Phenomena."

H. F. Bates, "The Height of F Layer Irregularities in the Arctic Ionosphere."

Scientific Report No. 4, April 1959, Contract No. AF 19(604)-1859.
J. H. Pope, "An Investigation of Whistlers and Chorus at High Latitudes."

*Radio Propagation Laboratory, Stanford University.
D. Conference Papers

Seventh Alaska Science Conference, Juneau, Alaska, September 1956:
W. B. Murcray, "Photometric Observations of Auroral Activity during the Winter 1955-56".

J. H. Pope, "Audio Atmospherics in Alaska."

Eighth Alaska Science Conference, Anchorage, Alaska, September 1957:
J. H. Pope, "On the Correlation between Chorus and Magnetic Activity."

Ninth Alaska Science Conference, College, Alaska, September 1958:
H. F. Bates, "HF Sweep Frequency Backscatter Sounding in the Auroral Zone."

Conference on Arctic Communication, National Bureau of Standards, Boulder, Colorado, March 1959:
PERSONNEL

The following scientists and engineers contributed to the work on Contract No. AF 19(604)-1859 during the period 15 April 1956 to 15 April 1959.

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R. D. Hunsucker  Assistant in Geophysical Research
C. G. Little  Professor of Geophysical Research, Principal Investigator 15 April 1956 to 15 June 1958.
C. R. Lodge  Consultant, Assistant Professor of Electrical Engineering, San Diego State College.
R. P. Merritt  Associate Professor of Geophysical Research
J. M. Miller  Engineer (Electronics Technician)
W. B. Murcray  Assistant Professor of Geophysical Research.
B. Nichols  Graduate Assistant
Leif Owren  Associate Professor of Geophysical Research, Principal Investigator 15 June 1958 to 15 April 1959.
F. D. Parker  Consultant, Professor of Mathematics, University of Alaska.
J. H. Pope  Graduate Assistant
R. A. Stark  Engineer (Assistant in Geophysical Research).
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