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Ion-acoustic Waves In Radio Aurora

Jacob Hofstee

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ION-ACOUSTIC WAVES IN RADIO AURORA

by

Jacob Hofstee

Department of Physics

Submitted in partial fulfilment
of the requirements for the degree of
Doctor of Philosophy

Faculty of Graduate Studies
The University of Western Ontario
London, Canada.
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ABSTRACT

That ion-acoustic waves are responsible for at least some of radio-auroral scatter at 40.350 MHz was shown by Hofstee and Forsyth (1969). The bistatic scatter circuits used for that experiment were so arranged that the radio-waves propagated in the plane perpendicular to the magnetic field. However most radio echoes are observed at sites where this condition is not met. To further examine the scattering phenomenon a new scatter circuit also operating at 40.350 MHz was put into operation. In this case the radio-waves propagated in a plane which was some 6° away from the plane which is perpendicular to the magnetic field. The circuit permitted the frequency analysis of the scattered signal. Power spectra were computed for an auroral scatter event that occurred between 1:45 and 2:45 U.T. March 7, 1970. Concurrent magnetograms suggest the presence of an auroral electrojet. The spectra indicate that ion-acoustic waves are again responsible for some of the scattering. On the basis of existing theory the generation of ion-acoustic waves that propagate at angles larger than 1° or 2° to the orthogonal plane requires extremely high electron streaming velocities. How ion-acoustic waves are generated under the
conditions of this experiment is yet to be explained and
certainly requires further investigation.
ACKNOWLEDGEMENTS

The author is indebted to Dr. P.A. Forsyth, not only for proposing an intriguing research topic, but also for his empathy, guidance and advice. Dr. J.W. McGowan, Chairman of the Physics Department is thanked for making available the departmental facilities. The help of Dr. G.F. Lyon, Dr. T.W.W. Stewart, Dr. D.R. Moorcroft and many other members of the Physics Department was greatly appreciated.

A word of gratitude must go to Dr. D. Rice and to the other members of the H F research group as well as to Mr. Brian Lisson, all at the Communications Research Centre, who so willingly aided this research by maintaining the operation of the transmitters.

The author is grateful to Mr. E.I. Loomer of the Dominion Observatory for supplying the magnetograms from Ottawa, Great Whale and Fort Churchill, and also Dr. Syed Ziauddin of Laurentian University for making available the magnetometer records from Sudbury.

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GLOSSARY

aspect angle ≡ the angle between the geomagnetic field and the plane in which a radio-wave propagates, specifically the reciprocal of the vector bisector of the transmitter-scatterer-receiver angle.

bistatic scatter circuit ≡ a transmitter and receiver located at geographically separated points. The transmitter may be operated in a continuous wave mode.

drift velocity (streaming velocity) ≡ the velocity with which the electrons (of, for example, the electrojet) move with respect to the ions.

local acoustic velocity ≡ this is the velocity at which a longitudinal sound wave propagates in the neutral (or ion) component of the plasma. The propagation velocity for ion-acoustic waves is close to this velocity.

radar ≡ implies that the transmitter and receiver of a scatter system are located at the same point, possibly using the same antenna. Most often such a system is used in a pulsed mode.

scatter angle (θ) ≡ in this thesis θ is the angular separation of the transmitter and receiver as seen from the scattering point. In the literature the scatter angle usually employed is equal to 180° - θ° where θ is the angle referred to as the scatter angle in this thesis.
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CHAPTER 1

INTRODUCTION

1.1 Early Work

Reports of the reflection of electro-magnetic energy at radio-wavelengths by auroral ionization appeared as early as 1937 (Appleton 1937). After the Second World War and especially since the peak of the solar cycle in 1947 there has been an increasing scientific study of the characteristics of these radio echoes and the relationship between them and other aspects of aurora. Although Harang and Stoffregan (1938) carried out the first investigation, the first attempts to determine the position of ionization relative to visual aurora was carried out by Lovell, Clegg and Ellyett (1947). It soon became apparent that for a given site, probability of an echo occurring was maximal when the radio-wave propagated at right angles to the geomagnetic field at a height of 100 kilometers. Most echoes are, however, seen from sites where this condition for specular reflection is not met.

Auroral echoes are characterized by a rapid fluctuation of amplitude. Moore (1951) suggested that these rapid changes could be indicative of auroral motion. Information about
motion of, and within, aurora could also be derived by examining the frequency spectrum of the reflected signal. At College, Alaska, Bowles (1954) found that the scattered signal was Doppler shifted. Since this shift did not correspond to a change in range, Bowles interpreted the motion as being upward and downward within auroral structures. Using a Double Doppler radar, McNamara (1955) found regions of ionization moving independently. Sometimes such regions moved in opposite directions simultaneously. McNamara proposed that while the major frequency shift arose from a change in range of an ensemble of echo centres, relatively stationary with respect to each other, part of the scattered energy was thought to be frequency shifted by random motion among the echo centres.

Bowles' (1954) conjecture of motion along the field lines was refuted by Nichols (1957) who simultaneously observed echoes from the east and west. The frequency shifts he observed in the two directions were generally opposed, indicating that the major component of the velocity was in the east-west direction. From the rate of change in range at 48.2 MHz, Lyon and Kavadas (1958) deduced velocities largely in the east-west direction. Westward motion occurred almost entirely before local midnight; eastward motion took place predominantly after midnight. In a period centered at midnight, motion in either direction occurred. These results agreed with those obtained by Bullough and Kaiser (1955) at Jodrell Bank.
Lyon and Kavadas found a statistical relationship between the observed velocities and magnetic disturbances, but no simple relation between the velocity of individual echoes and the magnitude of the magnetic disturbance. The statistical relationship was taken as evidence of the existence of large scale currents. A review by Bullough and Kaiser (1957) of data obtained between 1949-1953 led to the postulation of an east-west current flow. Leadabrand et al (1959) at 400 MHz found consistent east-west motion but no reversal at magnetic midnight. Blevis, Day and Roscoe (1963) observed the average Doppler shift (at 488 MHz) to have a systematic diurnal variation. The direction of apparent motion reversed at the same time as the change in the sign of the magnetic disturbance. The reversal of direction and the night-time minimum of echo occurrence took place about the same time.

1.2 Plasma Waves in Aurora

Bowles et al (1960) examining the frequency spectrum of aspect sensitive echoes from the region of the equatorial electrojet discovered that for vertical incidence the returned spectrum was symmetrical about the transmitted frequency. For all low angles the shift was of the same magnitude but reversed sign between angles to the east and the west. This constant Doppler shift, independent of angle was inexplicable in terms of the horizontal motion of field aligned cylinders of ionization which Booker (1956) had postulated to explain the aspect
sensitivity of auroral echoes. Bowles et al proposed a model in which the irregularities are plane wavefronts for which the wave normals lie in the plane perpendicular to the geomagnetic field. Bowles, Balsley and Cohen (1963) subsequently identified the E region irregularities as plasma ion-acoustic waves. The observed characteristics fitted those required by the mechanism discussed by Farley (1963). Farley determined the necessary conditions for the occurrence of a "two-stream instability" in the presence of an ionospheric electrojet. "A growing wave" leading to the generation of longitudinal ion-acoustic waves could occur in the E region when the electron velocity relative to the ions exceeded only slightly the local acoustic velocity.

That such irregularities occurred in the height and latitude region of the equatorial electrojet was verified by Cohen and Bowles (1963). As well, the intensity was temporally correlated to the horizontal intensity of the geomagnetic field, a measure of the electrojet current. A threshold effect, the abrupt rise of the scattered signal above the noise level, was construed in terms of Farley's theory as the sudden onset of a plasma instability. Noting the similarity between auroral and equatorial echoes Cohen and Bowles pointed out that since an auroral electrojet is thought to flow across the magnetic field at comparable heights to the equatorial electrojet, wave instabilities could occur in the auroral regions.
The existence of an auroral electrojet is not universally accepted. Boström (1964, 1967) and Bonnevier, Boström and Rostoker (1970) have explored models of the auroral current system. Instead of the current system being closed within the ionosphere by currents flowing in the reverse direction at higher and lower latitudes as suggested by Vestine and Chapman (1938), the proposed model (Bonnevier et al 1970) has magnetospheric and ionospheric sections connected by currents flowing along the field lines. (This type of model was first proposed by Birkeland, 1908)). The ionospheric current might be expected to flow near the bottom of a luminous auroral form, along its length. The magnetic field variations predicted by the model appear to be consistent with observed variations. At the ground, however, as Fukushima (1969) points out, the magnetic field variations expected from the two models are equivalent. The difference in the magnetic effect exists above the ionosphere.

The polar (auroral zone) electrojet is thought to have a latitude extent of at least several degrees but exhibits a microstructure (Kamide et al, 1969), being filamentary and/or patchy with each filament having a north-south width of less than 100 kilometers. This is based on variations in the magnetic field at separated stations.

Czechowsky and Lange-Hesse (1970) correlated the auroral scatter data from a number of bistatic circuits with the magnetograms from a north-south line of magnetometers. They
concluded that there was a close correlation between the polar electrojet and V.H.F. backscatter; the geomagnetic deviations coinciding with nearly all details of the amplitude variations of the backscattered signals. The data were interpreted in terms of, and found to be in accordance with, the ion-acoustic wave instability, but the reported data do not preclude other possible explanations.

Leadabrand (1963) and Leadabrand et al (1965) found that their auroral data indicated that at least some of the scattering was by plasma ion-acoustic waves. Abel and Newell (1969) saw a strong tendency toward a constant Doppler shift with azimuth as expected from Farley's two-stream theory. They indicate that the direction of plasma wave-motion plus the height variation of the electrojet current might explain echoes at the magnetic meridian.

On the other hand strong variable frequency dependence had been found by Bullough and Kaiser (1954), Forsyth and Vogan (1957), Lyon and Forsyth (1962). These authors postulated strong scattering and high electron densities. All these interpretations were based on the assumption that auroral scatterers were randomly distributed in space. If a spatially coherent structure can be contemplated the situation changes markedly. Moorcroft (1966), examining the data of Lyon and Forsyth (1962) showed that a portion of the data required such a structure. Moorcroft did not exclude other mechanisms for scattering occurring at different or even at the same
time. At least two types of scatter, one consistent with ion-acoustic waves, were found by Palmer (1967). Amplitude ratios determined from measurements on a common scattering volume observed through two angles (Lyon, 1968) indicated that a coherent structure gave rise to at least some of the observed signals. All of these conclusions were based on relatively indirect evidence concerning the existence of ion-acoustic waves. The most convincing evidence for the existence of such waves in the case of the equatorial ionosphere was a careful measurement of the frequency spectrum of the scattered signal under conditions which permitted the identification of a "line" component. Hofstee and Forsyth (1969) carried out the equivalent experiment for the auroral case and concluded that ion-acoustic waves are responsible for a spatially coherent scattering structure but are not the only source of radio-wave scattering in aurora. The data presented by Hofstee and Forsyth, which is reviewed in the second chapter, was obtained from a pair of bistatic scatter circuits for which the aspect angles were close to 90°. That scatter geometry is attainable only in a limited geographical area in Canada. Indeed it is only in Southwestern Ontario that it is possible to observe a volume in which the aspect angle is close to orthogonality and then to observe from essentially the same locations a volume in which the aspect angle is significantly different from orthogonality. While the probability of echo occurrence, as previously pointed out, is maximal when the aspect angle is 90° significant numbers of
echoes occur where the aspect angle is different from 90°. It was decided to further study auroral scatter employing a circuit where the aspect angle was not 90°. Similar equipment allowing the examination of the spectrum of the scattered signal plus additional improvements to permit location of the scatterers was constructed to further study the scatter of radio waves from the auroral plasma.

1.3 Organization of the thesis

Chapter 3 describes the experimental arrangements making the present experiment possible. The theoretical considerations relevant to the experiment are outlined in Chapter 4. The data obtained in this experiment both from the scatter circuit and from the magnetometers at various locations are laid out in the fifth chapter. The final chapter discusses the meaning of the data as such and draws a comparison between the present data and data from the earlier experiment.
CHAPTER 2

ION-ACOUSTIC WAVES IN THE AURORAL PLASMA

Hofstee and Forsyth (1969) observed a single scattering volume located near 81° West Longitude and 48° North Latitude (Fig. 2.1) from two directions using two closely spaced frequencies (40.346 and 40.350 MHz, respectively) produced by transmitters located at St. Catharines and near Ottawa, Ontario. The bistatic scatter circuits were set up to favour detection of ion-acoustic waves i.e. the aspect angle was close to 90°. As already pointed out this condition is only possible for radio-aurora in a limited area in Canada. Figure 2.2 reproduces the superimposed (112) spectra obtained for the two circuits in the period 5:45 to 6:30 UT February 29, 1968. There are significant signal concentrations for both circuits close to ± 100 Hz. These are noticeable because there is little change of frequency in the line component. That dominating line component present in the spectra for both circuits is strong evidence for the presence of ion-acoustic waves in the auroral plasma.

A different picture, one showing the change of the spectra with time during the 45 odd minutes of the event is presented in Figure 2.3 (A-E). Not all the spectra are presented, only those occurring approximately every two minutes.
Figure 2.1  Circuit Geometry (Ottawa-London; St. Catharines-London)

The common scattering volume is delineated by the half power points of the radiation patterns for the transmitting arrays located at Ottawa and St. Catharines and the receiving array at London. The contours for the most favourable aspect angles are shown. These are 91° for the Ottawa circuit and 90° for the St. Catharines circuit.
Figure 2.2 Circuit Geometry
Figure 2.2 All Spectra

This figure shows superimposed the 112 spectra obtained for that part of the auroral event of February 28-29, 1968 that occurred between 5:45 and 6:30 UT. The two scatter circuits Ottawa-London and St. Catharines-London both had aspect angles close to 90°.
Figure 2.2  All Spectra
The spectra from the first part of the event (5:45 to 6:00 UT) are broad; with for the most part, a positive frequency shift. There is no sign of a "line" component. The positive shift indicating motion toward the receiver suggests that there is a component of motion from west to east. The spectra (6:03 to 6:06 UT) then show the presence of both the line component and the broad component. The line component develops strongly on the Ottawa circuit but appears only briefly on the St. Catharines circuit although there is a positively shifted signal. This development of a line component on the Ottawa circuit without a corresponding component on the St. Catharines circuit is consistent with an electrojet flowing at an angle to the east-west direction. The direction of current flow being from east south east to the west north west. The electrojet intensity would have to be insufficient to allow the generation of ion-acoustic waves propagating at sufficient angles to the electron velocity vector to permit ion-acoustic scatter in the St. Catharines circuit. Some scatter, although not from ion-acoustic waves, and having a positive shift does occur.

At 6:13 UT a negatively shifted component starts to develop on both circuits, indicating motion away from the receiver i.e. the direction of flow of the electrojet has a component directed toward the east. The negatively shifted "line" component is dominant at 6:15 UT although for a short period oppositely moving scattering centres were located within the scattering volume. However by 6:17 UT there is virtually no signal on either circuit. Until 6:23 UT the signal on both
Figure 2.3 A - E Spectral Time History

Selected spectra, separated by two-minute intervals, are shown to illustrate how the spectral characteristics change with time. The centre line of each diagram corresponds to a zero shift in frequency. The left line corresponds to a negative shift of 100 Hz. A negative shift is indicative of motion away from the receiver. The right line represents an upshift in frequency of 100 Hz. The positive shift indicates motion toward the receiver.
Figure 2.3A  Spectral Time History
Figure 2.3D
circuits remains weak. From then until 6:30 UT the spectra are dominated by a positively shifted component on the St. Catharines circuit alone. Whatever signal there is on the Ottawa circuit is insignificant. Remembering that the circuit sensitivity favours the St. Catharines circuit (Fig. 2, Hofstee and Forsyth 1969) and that the direction of "seeing" for the two circuits differ by only 20° the electrojet must have been flowing at a large angle to the east-west direction without sufficient intensity to permit the observation of ion-acoustic scatter on both circuits. At 6:30 UT the signal on the St. Catharines circuit reaches a low point after which a line component begins to arise on the Ottawa circuit as well. Line components persist on both circuits from then until the end of the scatter event. These changes suggest that the electrojet changes its direction of flow back to a more east-west direction and with increased intensity.

Overall during the event the changes are as follows:

(a) the event begins with broad spectra
(b) the development of spectra having a line component
(c) the line component being the only component
(d) the decrease in signal strength before:
   1. the direction of the motion changed
      (i.e. change in sign of the frequency shift)
   2. the line component is stronger on one circuit than the other.

Clearly there are two mechanisms for the scattering of radio energy. At first (the broad spectra) the scattering
could be occurring from irregularities of electron density being convected by the electrojet, thus giving rise to an overall shift in the frequency of the scattered energy plus a broadening of the spectrum caused by motion of the irregularities relative to each other. Once the electrons attain the threshold velocity for the generation of ion-acoustic waves, this mechanism begins to cause scatter. At first however, it is not the dominant mode; not everywhere within the scattering volume have the electrons passed the threshold velocity. As more and more of the electrons are pushed past the threshold velocity the ion-acoustic mechanism dominates and becomes the only mechanism responsible for the scattering. Before a current in the opposite direction becomes dominant the decay of the signal strength from ion-acoustic waves should be expected as the current itself dies away. The changes in signal strength on the two circuits can be seen in terms of the orientation of the electrojet and changes in intensity of the electrojet. The stronger the electrojet the greater the angle (relative to the electron streaming velocity vector) at which ion-acoustic waves can be generated.
CHAPTER 3

EXPERIMENTAL ARRANGEMENTS

Employing the same transmitter location as one of the previous circuits (Ottawa) and a new site near London, the present scatter circuit was set up to have a scatter geometry such that the aspect angle was different from the nearly orthogonal aspect angle of the previous experiment.

New equipment was built which would permit the examination of the frequency spectrum of the scattered signal from two transmitters whose frequencies (40.3500 and 40.3505 MHz) were more closely spaced than those of the earlier experiment.

3.1 The Scatter Circuit

This experiment employed a "double" bistatic continuous-wave radio system. The effective scattering angle was 70°. The geometry of the circuit is shown in Figure 3.1. The contours for the aspect angle at a height of 100 kilometers (as well as the scattering volume as delineated by the half power beam width of the receiving and transmitting antenna arrays) are given in Figure 3.2.

At the transmitting end the antenna arrays had radiation patterns that overlapped partially as was desired, but at the receiving end the effective patterns were such that the receiving antenna patterns were essentially superimposed
Figure 3.1 Ottawa-London Scatter Circuit

The scatter geometry shown is the effective geometry for the experiment described. The transmitter is located at 45.29°N Lat., 75.99° W Long. The receiver is located at 43.9° N Lat. and 81.4° W Long. The scatter geometry is based on calculations for the antenna patterns as outlined in Appendix IIA.
Figure 3.2  Aspect Angles for Ottawa-London Scatter Circuit

The contours for the aspect angles are shown for a transmitter located near Ottawa and a receiver near London. The contours which are effective for this experiment are those which fall within the volume marked out by the half-power points of the effective radiation patterns of the transmitting and receiving antenna arrays.
Figure 3.2
(Appendix II discusses the patterns and gives the calculations for the effective radiation patterns).

3.2 Transmitters

Both the transmitters were located at the Ashton (Live) Site of what was the Defense Research Telecommunications Establishment (DRTE), now the Communications Research Centre. This site, at 45.195° North Latitude and 75.992° West Longitude, is some twenty miles south-west of Ottawa. The transmitters operated at frequencies of 40,350,000 Hz and 40,350,500 Hz radiating about 30 Watts. Both transmitters were provided with fixed directional antenna arrays, each consisting of 4 five-element Yagi antennas mounted 30 feet above the ground, atop telephone poles. The arrays were vertically polarized with an elevation angle of 13°. The effective half-power beamwidth (see Appendix II) was approximately 18°. The arrays were separated by 70.5 feet for minimum interaction and were so oriented that the radiation patterns overlapped. The bearings of the two transmitting arrays then differ by 8°. The northernmost array was driven by the 40,350,000 Hz transmitter; the southernmost by the 40,350,500 Hz transmitter.

3.3 Receiving System

The receiving system was located at the Delaware Radio Observatory, U.W.O.; North Latitude 42.85°, West Longitude 81.40°. This location is approximately twenty miles south-west
Figure 3.3 Transmitting Antenna Arrays

The physical arrangement of the transmitting antennas is given in this figure.

Figure 3.4 Receiving Antenna Arrays

These arrays are physically identical to the transmitting antennas. The array designated as the NE array was installed for possible use in height finding but was not in fact used in the experiment described in this thesis.
TRANSMITTING ANTENNA ARRAYS
CONSISTING OF 4 VERTICALLY POLARIZED 5 ELEMENT YAGI ANTENNAS WITH AN ELEVATION ANGLE OF 13° MOUNTED ON 35' TELEPHONE POLES.

Figure 3.3

RECEIVING ANTENNA ARRAYS IDENTICAL TO TRANSMITTING ARRAYS.

Figure 3.4
Figure 3.5  Receiving System

The block diagram of the receiving system shows the local oscillators driving the mixers of a pair of receivers. The possible outputs from the receiver as well as the other information such as the antenna switch indicator and the time code, which are all recorded, are shown.
Figure 3.5 Receiving System

The block diagram of the receiving system shows the local oscillators driving the mixers of a pair of receivers. The possible outputs from the receiver as well as the other information such as the antenna switch indicator and the time code, which are all recorded, are shown.
Figure 3.5
of London, Ontario. The receiving antenna arrays were physically identical to the transmitting arrays and were similarly arranged (Fig. 3.4), but an additional array was placed 10.53 \( \lambda \) in front of the south-east (SE) array.

The receiving system (Fig. 3.5) initially consisted of a "siamesed" pair of coherent receivers. To attain coherence, oscillators of high stability (about 2 parts in \( 10^8 \) per day) were used in the receiving system and both transmitters. At first one receiver was continuously connected to the SE array. The second receiver was switched between the NE array and the SW array. The switching was accomplished by a co-axial switch driven by a 15 second cam, i.e. the second receiver was switched every 15 seconds between the two arrays. Later this switching arrangement was eliminated by the addition of a third receiver identical to the others. Each receiver was then permanently connected to a single array. All the receivers accepted both transmitted frequencies, which were translated by four conversions to 1,000 Hz and 1,500 Hz. The local oscillator frequencies and the I.F. frequencies are outlined in Figure 3.6. An increase in the received radio frequency (i.e. motion toward the receiver) correspondingly produces an increase in the final I.F. frequency. The higher frequency was removed by a low pass filter; the remaining signal (nominally 1,000 Hz) was detected and recorded on an Esterline Angus graphic ammeter (stripline chart recorder). During auroral events
<table>
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Figure 3.6

The local oscillator frequencies are given as are the various Intermediate Frequencies.
the information in the form of the various audio frequencies was recorded on magnetic tape using a Precision Instrument tape-recorder operated in the F.M. mode at 37.5 inches per second. The tapes were then taken back to the laboratory for analysis. The spectral analysis was carried out on an I.S.A.C. analogue computer.
CHAPTER 4

THEORETICAL CONSIDERATIONS

The Doppler change in frequency \( f_D \) for a moving scatterer in the case of a bistatic scatter circuit is given by

\[
f_D = \frac{2}{\lambda} \frac{\mathbf{v} \cdot \mathbf{k}}{2} \cos \theta \text{ Hz (Appendix 1)}
\]

where \( \mathbf{v} \) = velocity of the scatterer
\( \mathbf{k} \) = unit vector along the bisector of the scatter angle
\( \theta \) = the scatter angle (See Fig.A2.5)

As seen in Chapter 3 the scatter angle for the circuit under consideration is \( 70^\circ \). The transmitted wavelength is 7.43 meters.

\[
i.e. \ f_D = \frac{2}{7.43} \frac{\mathbf{v} \cdot \mathbf{k}}{2} \cos (35^\circ)
\]

\[
= 0.221 \ \mathbf{v} \cdot \mathbf{k} \text{ Hz} \quad \quad \quad \text{Eqn. 4.1}
\]

or \( V = 4.52 \ f_D \text{ m/sec} \quad \quad \quad \text{Eqn. 4.2}
\]

where \( V = \mathbf{v} \cdot \mathbf{k} \) the component of the velocity along the bisector in the case of a "blob" convected along by the electrojet.

For a spectrum of waves in the plasma the system is sensitive only to those waves propagating precisely along the bisector and having a wavelength equal to one half of the
Figure 4.1 (After Farley 1963)

The required electron drift velocity for the generation of ion-acoustic waves is given as a function of the aspect angle for several wavelengths of the ion-acoustic waves. The frequencies indicated would have a wavelength twice that of the ion-acoustic wave since the radar case is assumed.
\[ \hat{K} \cdot \nu_d \ (\text{km/sec}) \]

\[ \nu = 2.6 \times 10^4 \text{sec}^{-1} \]

\[ \nu_i = 1.5 \times 10^3 \text{sec}^{-1} \]

\[ V = \left( \frac{2KT}{m_i} \right)^{\frac{1}{2}} \]

Figure 4.1
component of the wavelength along the bisector. For this scatter circuit ion-acoustic waves would be detected only if the wavelength was close to 3 meters and the direction of motion close to a bearing of 150° or its reciprocal. The velocity of the wave is then given by Eqn. 4.2. The wavelength of 3 meters corresponds to a "transmitted" frequency (backscatter radar case) of ∼ 50 MHz.

From Figure 4.1 (after Farley 1963), the generation of ion-acoustic waves requires that the critical velocity increases slowly with decreasing irregularity wavelength, but increases rapidly as the aspect angle (Farley's α) departs from 90°. Those waves having phase fronts nearly parallel to the magnetic field are the most easily excited. As the aspect angle departs from 90° the greater the electron drift velocity must be to excite waves.

Figure 4.2 (after Farley, 1963) gives the phase velocities of waves corresponding to the drift velocities of Figure 4.1. Waves propagating perpendicular to the magnetic field have velocities just greater than the ion thermal velocity (plasma acoustic velocity). The phase velocity is seen to increase somewhat with a decrease in wavelength. The phase velocity of the wave is always less than the electron drift velocity exciting it. As the aspect angle departs from 90° the velocity of the wave decreases somewhat.

Thus waves propagating at the local acoustic velocity:
Figure 4.2 (After Farley 1963)

The dependence of the phase velocity of the ion-acoustic waves for several wavelengths is given as a function of the aspect angle. As the ion-acoustic wave propagates at angles away from orthogonality the phase velocity decreases.
$T = 230^\circ K$

$v_e = 2.6 \times 10^4 \text{ sec}^{-1}$

$v_t = 1.5 \times 10^3 \text{ sec}^{-1}$
\[ V = \left( \frac{2kT}{m_i} \right)^{\frac{1}{2}} \]

\( k = \text{Boltzmann's constant} \)

\( T = \text{temperature,} \ ^\circ\text{Kelvin} \)

\( m_i = \text{ion mass} \)

are most easily excited when that propagation is at right angles to the magnetic field. As the streaming (electron drift) velocity increases, waves can be generated that propagate at increasing angles to the magnetic field. The phase velocity of the ion-acoustic waves is a function of electron temperature as well as ion temperature. The velocity of the wave is expected to be somewhat larger than the acoustic velocity. This latter velocity for auroral conditions is not well known nor is it likely to be constant, but is expected to lie in the range of 320 to 480 m/sec. These velocities were calculated using observed auroral (N\(_2\) rotational) temperatures (Brandy, 1965; Hunten et al, 1963).
CHAPTER 5

EXPERIMENTAL RESULTS

During the period of the experiment auroral activity was very sparse. Indeed months passed during the latter part of 1969 and the earlier part of 1970 without significant activity. However auroral activity was observed from 20:45 to 21:45 Local Time March 6, 1969 (1:45 to 2:45 UT March 7, 1969). Figure 5.1 shows the amplitude (40, 350, 000 Hz) record for that period. Data in the form of continuous wave audio frequency signals were recorded on magnetic tape from 1:55 to 2:06:30 UT; from 2:10 to 2:16:20 UT; from 2:35:20 to 2:44:30 UT. No data was recorded between 2:16 and 2:35 UT because of the low level of the signals for most of that period. The tapes were taken back to the laboratory for analysis. Altogether about 150 spectra were obtained; at least one every 15 seconds, more often during periods of particular interest. As well, spectra of meteor signals during the period of activity were taken to check on the zero shift position on the spectra. These meteor signals are shown superimposed in Figure 5.2. The single dotted spectrum is from the early part of the scatter event. The two "narrow line component" concentrations of signal strength at ± 100 Hz are
Figure 5.1 Amplitude Record

The amplitude of the signal at 40.350000 MHz received on the SE antenna is shown for the period of the auroral event. The break in the signal at 9 PM EST (0100 UT) is caused by a regularly scheduled break in transmission for identification purposes.
Figure 5.2 Meteors

The superimposed spectra are those for which there is, in addition to any other signals, a meteor signal present. The concentration of meteoric signal strength near the zero frequency shift position serves as a frequent check on the stability of the oscillators and the magnitude of the auroral frequency shifts since the meteor signals occur frequently throughout the auroral event. The earliest meteor signal occurred a few minutes after the auroral event began and the last after the auroral event ended. The meteor Doppler shift is an order of magnitude less than the auroral Doppler shifts. The auroral signals are present at the same time (within the 2 second sample used for spectral analysis). The single dotted spectrum is a broad spectrum auroral signal which serves to show the relative widths of the spread auroral spectrum, the meteor spectrum and the auroral ion-acoustic spectrum.
Figure 5.3 All Spectra

All the 150 spectra that were obtained are superimposed to show the concentration of signal strength at ± 100 Hz. The broad spectral concentration of signal which is shifted to the negative side of the transmitter frequency consists of spectra which occurred early in the auroral scatter event.
Figure 5.4 to 5.8  Time History

Selected spectra are used to show the changes with time of the spectrum of the scattered signal. The left hand spectrum in each case is for the 40.3500 MHz signal and the right for the 40.3505 MHz signal. In each case the ± 100 Hz points are indicated.
Figure 5.4 Time History
Figure 5.5
Figure 5.8
noticeable in both Figure 5.2 and 5.3. These concentrations are of the line type as opposed to the broad type which are largely negatively shifted. As seen in Figures 5.5 through 5.8 these broad spectra occur in the early part of the event. The signal strength has reached a peak and is decreasing until 2:13:07 the line spectrum has developed. Only selected spectra are shown. During the initial part of the event all the spectra are broad, although shifted toward the negative side. Once the line spectrum develops spectra are shown for every 15 seconds until 2:19 UT. The first line spectrum is negatively shifted and persists only a short time. The signal strength decreases rapidly and at 2:14 the signal level is very low. Negatively shifted echoes are observed at low signal strengths with almost no signal occurring at \( \sim 2:15:45 \) UT. A positively shifted echo is observed from 2:16 UT but is very weak. From 2:17 to 2:18 a positively shifted line component persists at very low signal levels. By 2:19 UT the signal has faded out almost entirely. At 2:35 UT the signal abruptly begins to increase and all the spectra are the positively shifted line type until the end of the event.

The magnetometer records from Sudbury show the magnetic field to be disturbed. Figures 5.9 and 5.10 are respectively the Z and H components (the D component was not available). In both figures the time of the scatter event is denoted. Figures 5.11 and 5.12 (respectively Z and H) show the period
Figure 5.9 Magnetometer Z Component (Sudbury)

The magnetic field variations (Z component only) are shown for the period 1900 UT March 6, 1970 to 0600 UT March 7, 1970. The period corresponding to the auroral event is indicated. A one hour period is marked off to show the time scale.
Figure 5.10 Magnetometer H Component (Sudbury)

The magnetic field variations (H Component only) are shown for the period 1900 UT March 6, 1970 to 0600 UT March 7, 1970. The period corresponding to the auroral event is indicated. A one hour period is marked to show the time scale.
Figure 5.11  Z Component Magnetic Field (Sudbury)

The Z Component variations are shown on a larger scale for the period \( \sim 0145 \) to 0245 UT during which auroral scatter occurred.

Figure 5.12  H Component Magnetic Field (Sudbury)

The H Component variations are shown on a larger scale for the period \( \sim 0145 \) to 0245 UT during which auroral scatter occurred.
of the scatter event on a larger scale. The zero level is indicated for both components. The $Z$ component changes sign at approximately 2:16 UT. The $H$ component is positive (before ~ 2:16) before it changes sign and a negative disturbance develops. Magnetograms were also obtained for Ottawa ($45^\circ 24'$ N. Lat.; $75^\circ 33'$ W. Long.), Churchill $58^\circ 45'$ N. Lat.; $94^\circ 00'$ W. Long.) and Great Whale ($55.3^\circ$ N. Lat.; $77.75^\circ$ W. Long.). As seen in Figure 5.13, 5.14, 5.15 and 5.16 magnetic disturbances were recorded at all three locations during the time of the auroral scatter event. The sensitive magnetometer at Churchill recorded such fluctuations that the magnetogram is nearly unreadable.
Figure 5.13 Ottawa Magnetogram March 7, 1970

The variations in the three components of the magnetic field recorded at Ottawa are shown for the period 0100 to 0400 UT March 7, 1970. A disturbance occurred during the period for which auroral scatter was observed.
Figure 5.13 Magnetogram
Figure 5.14 Magnetogram Fort Churchill, March 7, 1970

The three components of the magnetic field variations recorded on a sensitive magnetometer located at Fort Churchill show that the magnetic field was strongly disturbed at the time the auroral scatter was observed.
Figure 5.14  Magnetogram
Figure 5.15 Magnetogram Fort Churchill, March 7, 1970

A less sensitive magnetometer also located at Fort Churchill shows the variations in the geomagnetic field on a reduced scale eliminating the overlap of the traces evident in the previous figure.
FORT CHURCHILL U.T.→
MARCH 7TH 1970.

Figure 5.15  Magnetogram
Figure 5.16 Magnetogram Great Whale, March 7, 1970

The magnetic field was disturbed during the period of the auroral event as is evident from the variations recorded by the magnetometer located at Great Whale River in the province of Quebec.
Figure 5.16  Magnetogram
CHAPTER 6

DISCUSSION AND CONCLUSIONS

Although the aspect angle approximates 90° nowhere within the scattering volume, indeed an aspect angle of 96° is appropriate, it is, nevertheless, evident from Figure 5.3 that ion-acoustic waves are responsible for part of the scatter. On the basis of Farley's theory the generation of ion-acoustic waves under these conditions requires electron streaming velocities in the order of kilometers/sec! The Doppler shift of ± 100 Hz corresponds to an approximate propagation (ion-acoustic or ion thermal) velocity of 450 m/sec or a temperature of 350° K. This velocity and corresponding temperature fall within the range expected based on measured auroral temperatures (Hunten et al, 1963; Brandy, 1965).

The change of sign in the z component of the magnetic field can be taken as indication that either a line current, which is a reasonable approximation, passed over the magnetometer location at Sudbury, or that the direction of current flow reversed. The time at which the change in sign occurred corresponds to the time at which the negatively shifted ion-acoustic echoes have died away and before the positively shifted ion-acoustic echoes have begun. From the
H component (Sudbury) it can be deduced that there was a
reversal of the direction of current flow. The H Component
is positive until approximately 2:16 UT. In the period
(about 4 minutes) preceding that time negatively shifted
ion-acoustic echoes are observed.

Once the H Component changes sign and the negative
disturbance develops, positively shifted ion-acoustic waves
are observed. The currents deduced from the magnetic field
variations flow first eastward (electron motion is in the
opposite sense i.e. westward) as required for negatively
shifted ion-acoustic waves; then the current reverses and a
westward current (eastward electron motion) flows as required
for positively shifted ion-acoustic echoes. Magnetic dis-
turbances appear to have been in progress at the other stations
as well. The beginning of the disturbance recorded at
Sudbury cannot be precisely indicated because the Z component
was driven off scale, but from the b component a positive
going variation began at about 10 minutes before 2 hours UT,
which corresponds well with the beginning of the auroral
scatter event.

Considering the H (or X) component recorded at Ottawa,
Great Whale and Fort Churchill (see Figure 6.1 for location
of these relative to the scattering volume) the disturbance
was negative in sign. If a line current is used as a model,
this indicates a westward flow. Similarly from the sign of
Figure 6.1 Map of the various sites

The sites of the various magnetometers are shown along with the location of the scatter circuit.
Figure 6.1
Map showing magnetometer sites
relative to scatter circuit
the Z component, the current is located to the north of Ottawa but south of Fort Churchill. At Great Whale the Z component at 0200 begins to swing positive placing the current to the south of Great Whale. At about 0230 the Z component swings sharply negative before reversing and becoming once more positive. The magnetometer is an integrative device, i.e. the magnetic field variations measured are the result of the total effect of all existing currents. However if local currents are present (microstructure of the polar electrojet) these would explain the differences observed at Sudbury and the other observation points which place the current to the north. The intensity of the current can be deduced by constructing from the field components the total disturbance vector and then taking a distance along a line perpendicular to that vector so that the current is positioned at an appropriate height. (If records from two stations are used the current can be located using co-ordinate geometry.) Induced earth currents, however, act so as to reduce the Z component and increase the H component with the result that the apparent height of the current is greater than the true height (Chapman and Bartels, 1940). Corrections can be made, usually a factor of 2 for the Z component and a factor of 0.9 for the H component (e.g. Barcus and Brown, 1962; Brown and Campbell, 1962). On the basis of an infinite line current above a flat earth without applying any correction, the current intensity using the Great Whale records, is approximately
90 thousand Amperes. If the correction factors mentioned above are used, the current is increased to about 356 thousand Amperes. For comparison, line currents deduced by Scrase (1961) lie in the range 43 to 1,180 thousand Amperes. If electron drift velocities are taken to be of the same order of magnitude as the ion thermal velocity deduced from the observed Doppler frequency shift for the ion-acoustic echoes, and using electron densities for auroral plasma of the order observed by McNamara (1969), the calculated current flows across an area of the order $10^3$ square kilometers. If on the other hand, the much higher velocities required by the linear Farley theory are used the area would be correspondingly reduced. However there seems little justification for the existence of such high velocities.

McDiarmid and McNamara (1969) proposed a physical model based on Farley's two-stream instability theory and used it to explain radio-auroral data. As one check of their model they tried to determine if it were consistent with the observed magnetic field variations. The area required is comparable with the above result.

The positively shifted ion-acoustic echoes occur at the time when the magnetic disturbance is well developed. The ratio of the power present at each of the frequencies indicates that these echoes come from the northern part of the scattering volume. The negative ion-acoustic echoes are
located more to the south. The broad spectral echoes which are mostly negatively shifted initially are located to the north but as the event develops these echoes come from the same southerly region in which the negatively shifted ion-acoustic wave echoes develop.

When the time history of the scatter event is examined, it is very similar to that of the event described in Chapter 2. The event starts with the scattered energy being both Doppler spread and shifted for the early part of the event. This energy is shifted to the negative side (motion away from the receiver) where the first ion-acoustic type echoes appear. Then the scattered signal virtually disappears before a weak positively shifted ion-acoustic echo appears. This minimum in the scattered signal is coincident with the change in sign of H and Z components of the magnetic field variation recorded at Sudbury. Later in the event strong positively shifted ion-acoustic spectra are prominent. The strength of these slowly decays until the scatter event ends. The pattern is indeed similar to that of the earlier event, broad shifted spectra are observed before the narrow ion-acoustic spectra develop which then dominate the rest of the event.

Although not explained, it is clear that ion-acoustic echoes are observed under non-specular conditions. Therefore the many echoes observed at more northern stations under conditions where specularity cannot be attained, may contain significant numbers of ion-acoustic echoes, a point previously
in doubt. This difficulty was pointed out by McDiarmid (1970) who further develops the model proposed by McDiarmid and McNamara (1969) and uses it as basis for the explanation of the data obtained by Hofste and Forsyth (1969). The model is found to be adequate for the explanation of radio-auroral backscatter under conditions where the aspect angle is close to 90°; however for angles greater than 4 or 5° from orthogonality high streaming velocities are required (large magnitude electric fields). Refraction of the ion-acoustic waves could be responsible for radio-scatter at small angles off orthogonality. The evidence from the present experiment indicates that ion-acoustic waves are responsible for scatter under conditions where the aspect angle is approximately 6° from orthogonality. The positively and negatively shifted ion-acoustic echoes come from separated parts of the scattering volume. Simultaneous magnetograms suggest that an electrojet was present. While not proving the existence of the auroral electrojet the "threshold" behaviour of the ion-acoustic waves relative to the magnetic fluctuations gives strong support for models of auroral phenomena which include strong localized currents in the lower parts of auroral displays. Such currents are of course required for the generation of ion-acoustic waves especially under conditions of non-specularity. However rather than inordinately high streaming velocities it may be that (a) non-linear effects, (b) lower boundary effects, give rise to the propagation of
ion-acoustic waves at significant angles to the orthogonal plane.

The system is now back in operation in the intended condition and although very few echoes can be expected in the next few years, a single occurrence of echoes for the 90° scattering angle would add greatly to our knowledge of the scattering phenomenon. Even more information would be available about the scattering phenomenon and the associated currents if a network of magnetometers were located below the scattering volume. The scarcity of echoes is due to the decreasing solar activity, the relatively low latitudes at which the scattering volume is located and the aspect angle being significantly different from orthogonality. Nevertheless it is only at these latitudes that the sequence of the experiments could have been carried out. Now that the present evidence has been obtained it would be worthwhile doing the same experiment at higher latitudes where more echoes could be obtained, making the experiment much easier (and more statistically reliable for those studies in which statistical results are desired).
APPENDIX I

The phase difference $\Delta \phi$ between a transmitted signal and a scattered signal depends upon the wavelength ($\lambda$) of the transmitter and the distance ($R$) to the scatterer

i.e. $\Delta \phi = \frac{2\pi}{\lambda} (2R)$ for the radar case. \hspace{1cm} \text{Eqn. Al.1}$

However for the case of a separated receiver and transmitter (bistatic) Eqn. Al.1 becomes

$$\Delta \phi = \frac{2\pi}{\lambda} (r_1 + r_2)$$ \hspace{1cm} \text{Eqn. Al.2}$

where $r_1$ = distance between scatterer and transmitter

$r_2$ = distance from scatterer to receiver.

As the range changes $\Delta \phi$ changes. The rate of change of the phase difference is a frequency $f$

i.e. $f = \frac{1}{2\pi} \frac{d}{dt} (\Delta \phi)$ \hspace{1cm} \text{Eqn. Al.3}$

substituting $f = \frac{1}{2\pi} \frac{d}{dt} \frac{2\pi}{\lambda} (r_1 + r_2)$

$$= \frac{1}{\lambda} \frac{d}{dt} (r_1 + r_2)$$

$$= \frac{1}{\lambda} (\mathbf{v} \cdot \hat{r}_1 + \mathbf{v} \cdot \hat{r}_2)$$ \hspace{1cm} \text{Eqn. Al.4}$

where $\mathbf{v}$ is velocity of a scatterer

and $\hat{r}_1$ and $\hat{r}_2$ are unit vectors along $r_1$ and $r_2$ respectively

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\[ \frac{1}{\lambda} \mathbf{v} \cdot (\hat{\mathbf{f}}_1 + \hat{\mathbf{f}}_2) \]

\[ = \frac{1}{\lambda} \mathbf{v} \cdot (\hat{k} \ 2 \ \cos \frac{\theta}{2}) \quad \text{Eqn. Al.5} \]

where \( \hat{k} \) is a unit vector along the bisector of the scatter angle \( \theta \)

\[ f = \frac{2}{\lambda} \mathbf{v} \cdot \hat{k} \ \cos \frac{\theta}{2} \ \text{Hz} \quad \text{Eqn. Al.6} \]
APPENDIX IIA

In an effort to further examine the scattering of radio-waves by auroral ionization it was decided to set up an experiment which would not only allow examination of the scattered frequency spectrum but also by using two closely spaced frequencies radiated from directive arrays oriented in slightly divergent directions and viewing these as nearly as possible at right angles would allow location (range) of the scattering body with respect to the receiving site. At the receiving site two receiving arrays also oriented so that slightly different volumes were under observation, were erected to permit limits to be put on the east-west location of the scattering body. To do this of course is easiest when a 90° scatter geometry is used. Section B of this appendix gives a calculation for the scatter angle using the locations and bearings of the fixed directional arrays. These arrays as pointed out in Chapter 3 consisted of four five-element Yagi antennas, which were spaced λ/2 apart, vertically polarized and fed in phase. As such the scatter geometry and beamwidths (half-power, based on the two arrays) were given in Figure A2.1.

The next figure (A2.2) shows the contours of the aspect angles for that geometry. However during the period
Figure A2.1 Ottawa–London Scatter Circuit

The scatter circuit is shown for the originally intended configuration. The receiving antenna beam is at right angles to the transmitting antenna beam i.e. the scatter angle is 90°. The contour of the aspect angle shown is 104°.
Figure A2.2 Aspect Angles

The contours of the aspect angles are given for the 90° scatter geometry. The contours that would have been applicable are those which fall within the volume delineated by the half power points of the radiation patterns of the receiving and transmitting antenna arrays.
of the experiments the arrays suffered severe storm damage. When the antennas were repaired phasing errors were introduced in the feeding of the antennas. This was not discovered until after the data had already been recorded. It then became necessary to determine the effective radiation patterns. If the original in phase feeding of the antennas is represented by ↑↑↑↑ (one vector for each Yagi), then the following were found:

At Ottawa -
The north array (fed by 40,350,000 MHz Tx) ↑↑↑↑
The south array (fed by 40,350,500 MHz Tx) ↑↑↑↑

At London -
The NE array ↓↓↓↓
The SE array ↓↓↓↓
The SW array ↑↑↑↑

As a result there are only two problems to be solved. One consisting of four elements spaced \( \lambda/2 \), of which one of the end elements is fed 180° out of phase with respect to the other three elements. The second problem consists of one pair of elements (i.e. one half or side of the array) fed 180° out of phase with respect to the second pair (or other half of the array).

The case of three in phase and one out of phase, can be simplified by using an origin at the centre of the array and with the elements comprising the pair symmetrically spaced about that origin. The first case then consists of (a)
two elements $\lambda/2$ apart, fed in phase; (b) two elements $3\lambda/2$
apart and fed $180^\circ$ out of phase.

The radiation intensity is given by:

$$S^* = \frac{30}{2\pi} \frac{I_0}{R^2} \left( F_0 F_1 F_2 F_3 \right)^2 \text{ Stratton}$$

where

$$F_S = \begin{bmatrix}
\cos \left( \frac{\pi}{2} \cos \theta \right) \\
\frac{n S Y_S}{\sin \theta} \\
\frac{\sin \left( \frac{\gamma S}{2} \right)}{\sin \left( \frac{\gamma S}{2} \right)}
\end{bmatrix} \quad \text{S = 1, 2, 3}$$

(spatial coordinates)

$n$ = number of elements

$\gamma_S = k a_S \sin \theta \cos \phi + \alpha_S$

$\alpha$ = phase difference (angle) between adjacent elements

$a$ = inter-element spacing

If the $X$ axis is taken as the axis along which the elements are spaced, then $F_2 = F_3 = 1$. Since it is the horizontal pattern which is of interest, then $\theta = \frac{\pi}{2}$ and $F_0 (\theta) = 1$. The expression for $S^*$ will have two terms. The first term will have $a_1 = \lambda/2$ and $\alpha_1 = 0$. The second term will have $a_1 = \frac{3\lambda}{2}$ and $\alpha_1 = \pi$. However $n = 2$ for both.
\[ i.e. \ S^* = \chi \left( \begin{bmatrix} \sin \left( \frac{k \lambda \cos \phi}{2} \right) \\ \sin \left( \frac{k \lambda \cos \phi}{2} \right) \end{bmatrix} \right) + \left( \begin{bmatrix} \sin \left( \frac{3k \lambda \cos \phi + \pi}{2} \right) \\ \sin \left( \frac{3k \lambda \cos \phi + \pi}{2} \right) \end{bmatrix} \right)^2 \]

where \ \( \chi = \frac{30 I_0^2}{2 \pi R^2} \)

Evaluating the first term:

\[
\left[ \begin{array}{c} \sin \left( \frac{\lambda}{2} \cos \phi \right) \\ \sin \left( \frac{\lambda}{2} \cos \phi \right) \end{array} \right].
\]

\[
= \left[ \begin{array}{c} \sin \left( \frac{\pi \cos \phi}{2} \right) \\ \sin \left( \frac{\pi \cos \phi}{2} \right) \end{array} \right]
\]

The second term:

\[
\left[ \begin{array}{c} \sin \left( \frac{\lambda}{2} \cos \phi + \pi \right) \\ \sin \left( \frac{\lambda}{2} \cos \phi + \pi \right) \end{array} \right].
\]

\[
= \left[ \begin{array}{c} \sin \left( \frac{3\pi \cos \phi + \pi}{2} \right) \\ \sin \left( \frac{3\pi \cos \phi + \pi}{2} \right) \end{array} \right]
\]

but \ \sin (3\pi \cos \phi + \pi) = \sin (3\pi \cos \phi) \cos \pi + \cos (3\pi \cos \phi) \sin \pi

\[
= -\sin (3\pi \cos \phi)
\]

and \ \sin \left( \frac{3\pi \cos \phi + \pi}{2} \right) = \sin \left( \frac{3\pi \cos \phi}{2} \right) \cos \frac{\pi}{2} + \cos \left( \frac{3\pi \cos \phi}{2} \right) \sin \frac{\pi}{2}

\[
= \cos \left( \frac{3\pi}{2} \cos \phi \right)
\]
Therefore, the second term becomes:

\[- \left[ \frac{\sin (3\pi \cos \phi)}{\cos (\frac{3\pi \cos \phi}{2})} \right] \]

Therefore:

\[ S^* = \chi \left\{ \left[ \frac{\sin (\pi \cos \phi)}{\sin (\frac{\pi \cos \phi}{2})} \right]_1 - \left[ \frac{\sin (3\pi \cos \phi)}{\cos (\frac{3\pi \cos \phi}{2})} \right]_2 \right\}^2 \]

The second case, again taking symmetric pairs about a central origin has one term for which \( a = \lambda/2 \) and \( \alpha = \pi \) and a second term for which \( a = \frac{3\lambda}{2} \) and \( \alpha = \pi \). This second term has already been evaluated for the first case.

Hence:

\[ S^* = \chi \left\{ \left[ \frac{2(k\lambda \cos \phi + \pi)}{\sin (\frac{2}{2})} \right] \left[ \frac{2}{(k\lambda \cos \phi + \pi)} \right]_1 - \left[ \frac{\sin (3\pi \cos \phi)}{\cos (\frac{3\pi \cos \phi}{2})} \right]_2 \right\}^2 \]

The first term:

\[ [ ]_1 = \left[ \frac{\sin (\pi \cos \phi + \pi)}{\sin (\frac{\pi \cos \phi + \pi}{2})} \right] \]

but \( \sin (\pi \cos \phi + \pi) \)

\[ = \sin (\pi \cos \phi) \cos \pi + \cos (\pi \cos \phi) \sin \pi \]

\[ = -\sin (\pi \cos \phi) \]

and \( \sin (\frac{\pi \cos \phi + \pi}{2}) \)

\[ = \sin (\frac{\pi \cos \phi}{2}) \cos \frac{\pi}{2} + \cos (\pi \cos \phi) \sin \frac{\pi}{2} \]

\[ = \cos (\frac{\pi \cos \phi}{2}) \]
Therefore:

$$S* = \chi \left\{ -\frac{\sin (\pi \cos \phi)}{\cos (\frac{\pi}{2} \cos \phi)} - \frac{\sin (3\pi \cos \phi)}{\cos (\frac{3\pi}{2} \cos \phi)} \right\}^2$$

So far all the patterns have been treated as if the antennas were not Yagis. Since however they are, then $S*$ must be multiplied by the radiation pattern of a single Yagi to give the overall pattern of an array of Yagi antennas.

If a 10 dB free space gain (wrt. an isotropic radiator; Crysdale and Olive, 1956) and $G = \frac{4\pi}{\lambda^2} A_e$.

where $G =$ numerical gain

$\lambda =$ wavelength

$A_e =$ effective aperture,

then $A_e = \frac{\lambda^2}{4\pi} G = \frac{10 \lambda^2}{4\pi} \sim 0.8\lambda^2$

If the aperture is assumed to be rectangular with the dimension in the direction of the Yagi's elements to be $\sim \lambda$ then the other dimension will be $\sim x = \frac{A_e}{\lambda} = 0.8\lambda$. The radiation pattern of a single Yagi is that of the intensity pattern for a single slit diffraction pattern.

i.e. $I = A (\frac{\sin \beta}{\beta})^2$

where $A$ is a constant

$$\beta = \frac{\pi x}{\lambda} \sin \theta$$

$x =$ slit width

$\theta =$ angle between field point and line along Yagi boom.
Figure A2.3 Antenna Pattern

The antenna pattern effective at the time the data were recorded was calculated on the basis of the phasing in effect for the antenna array. The radiation pattern shown is that of the North antenna at the Ottawa transmitter site.

Figure A2.4 Antenna Pattern

This is the effective radiation pattern for the South antenna at the Ottawa transmitter site.
Figure A2.3  Antenna Pattern
Figure A2.4  Antenna Pattern
Then $I = A \left( \frac{\sin (0.8 \pi \sin \theta)}{0.8 \pi \sin \theta} \right)^2$

To obtain the final pattern for the array of Yagi antennas the pattern obtained for the four elements was multiplied by the pattern for the individual Yagi. (Note $\phi = 0$ is shifted by $90^\circ$ from $\theta = 0$). The resultant patterns (normalized) are shown in Figures A2.3 and A2.4 for the first and second cases respectively.

The radiation pattern in the second case is twice as wide as that in case one, i.e. the gain (directivity) of the South array at Ottawa is half that of the North array. However if one allows for the $\sim 8^\circ$ difference in direction of the two arrays then the pattern of the North array only partially overlaps the pattern of the South array. Allowing for the difference in the gains, the ratio of the received amplitudes for the two frequencies can still serve as an indication of the location of a scatterer.

The side lobes are down by 12 dB from the maximum of the central lobe in the first case ($\uparrow\uparrow\uparrow\uparrow\downarrow\uparrow$). While in the second case, the side lobes are down by more than 20 dB. Because of their position and lower sensitivity the side lobes on the North array ($\uparrow\uparrow\uparrow\downarrow\uparrow\uparrow\uparrow\downarrow\uparrow$) should not contribute significantly to any scattered signal.

Because the major lobes were shifted the effective scatter geometry is as described in Chapter 3. Since the patterns were shifted the receiving arrays were looking at essentially the same volume.
Appendix IIB

Determination of the Scatter Angle

The scatter angle calculated on the following pages is for the right angle scatter circuit which was originally intended.
APPENDIX IIB

DETERMINATION OF THE SCATTER ANGLE

Co-ordinates for Ottawa transmitter array:

45.195° North Latitude
75.992° West Longitude

Bearing 286.9° (each array is 4° either above or below this).

Co-ordinates for Delaware Radio Observatory receiving array:

42.85° North Latitude
81.40° West Longitude

Bearing 14.6°

The required angle is LPO. (Fig. A2.5) (This is the scatter angle θ)

The known relationship from spherical geometry is:

\[
\cos LPO = - \cos PLO \cos POL + \sin PLO \sin POL \cos LO
\]

To determine LPO, the angles POL, PLO, LO are required.

LO is the angle between London and Ottawa at the centre
of the earth. (Fig. A2.6)

Now:

\[
\cos LO = \cos LN \cos ON + \sin LN \sin ON \cos LNO
\]

where \( LN = 90° - (\text{Latitude of receiving array}) = 47.1° \)

\( ON = 90° - (\text{Latitude of transmitting array}) = 44.8° \)

\( LNO = (\text{Difference in Longitude}) = 5.41° \)

Therefore:

\[
\cos LO = (0.681)(0.710) + (0.733)(0.705)(0.996)
\]

\[= (0.996)\]
Figure A2.5 Spherical Geometry

The spherical geometry showing the angle (LPO) to be determined is given where L is the location of the receiver, O the location of the transmitter.

Figure A2.6 Spherical Geometry

This figure gives the set of spherical triangles indicating the value of the angles required for the evaluation of the LPO in Figure A2.5.
Therefore: $LO = 5.10^\circ$

Now: $POL = NOL - NOP$

But $\sin NOL = \frac{\sin LN \sin LNO}{\sin LO}$

$= 0.772$

Therefore $NOL = 50.5^\circ$

Since $NOP = (360 - 286.9) = 73.1$

$= 90 - 16.9$

Therefore $POL = 56.4^\circ$

But $\sin NLO = \sin NO \frac{\sin NLO}{\sin LO}$

$= 0.742$

Therefore $NLO = 48.0^\circ$

$NLP = 14.6^\circ = 90 - 75.4^\circ$

However $PLO = NLO - NLP$

$PLO = NLO - 14.6 = 33.4^\circ$

i.e. $POL = 56.4^\circ$

$PLO = 33.4^\circ$

$LO = 5.1^\circ$

Therefore:

$\cos LPO = -(0.834)(0.553) + (0.55)(0.833)(0.996)$

$= -(0.461) + (0.457)$

$= -(0.004)$

Therefore: $LPO = 90.2^\circ$

The scatter angle for the circuit is then $90.2^\circ$
APPENDIX III
ION-ACOUSTIC WAVES

To explain the constant Doppler shift that was observed for scatter associated with the equatorial electrojet Bowles et al (1960) suggested that the scatterers were a family of longitudinal plane waves similar to sound waves. Doppler shift measurements showed that the waves tended to travel at the acoustic velocity of the medium. Farley (1963) worked out the conditions for a two-stream or streaming instability to occur when an ionospheric electrojet is present. Farley found that growing-wave solutions leading to the generation of longitudinal acoustic waves can occur in the E region (100 km height region) when the streaming or average drift velocity of the electron relative to the ions only slightly exceeds the local acoustic velocity.

At the equator and in the auroral zone an electrojet flows across the geomagnetic field at right angles. The ion-acoustic waves are most easily excited when their wave vector is orthogonal to the magnetic field and close to direction of the electron streaming velocity. As the electron streaming velocity increases the ion-acoustic waves can propagate at increasing angles to the electron streaming velocity. Similarly
as the streaming velocity increases the ion-acoustic waves can be excited which propagate at increasing angles from the plane orthogonal to the geomagnetic field.

As the departure from orthogonality increases the phase velocity of the ion-acoustic waves decreases somewhat. The scattering structure generated by ion-acoustic waves is a coherent one in that the radio frequency employed selects from the complex wave structure present a series of irregularities whose spacing is half the transmitted frequency in the radar case or half the component of the transmitted wavelength along bisector of the scatter angle in the bistatic case. Since all these irregularities are propagating at the same velocity (approximately the local acoustic velocity) the frequency shift observed should correspond to that velocity. The spectrum is broadened by various processes but is much narrower than the Gaussian type spectrum associated with a random array of irregularities. For the case of a bistatic circuit operating in the neighbourhood of 40 MHz Doppler frequency shifts of the order of 100 Hz are to be expected.
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