IONOSPHERIC RADIO WAVE PROPAGATION AT
OBLIQUE INCIDENCE

by

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A List of Symbols and Abbreviations used in the Text

\( B \)  
Strength of earth's magnetic induction

\( B \)  
Subsolar absorption

\( c \)  
Velocity of light

\( C \)  
\( \cos i \)

CIRA  
COSPAR International Reference Atmosphere 1965

\( D, E, F_1, F_2, F \)  
Regions of the ionosphere

\( e \)  
Electronic charge

EUV  
Extreme ultra-violet

\( f_\mu \)  
Gyrofrequency

\( f \)  
Frequency

\( f_L \)  
Longitudinal gyrofrequency

\( h \)  
Height

\( h \)  
Group height

HF  
High frequency

\( H \)  
Scale height

\( i \)  
Angle of incidence

kHz  
Kilohertz

\( k \)  
\( 2\pi/\lambda \) or \( 2\pi f/c \)

L  
Absorption

LF  
Low frequency

MF  
Medium frequency

MHz  
Megahertz

\( l, m, n \)  
Direction cosines of the incident wave

\( m \)  
Electron mass
N Electron density
n Phase refractive index, sometimes $\mu$
$N(h)$ Electron density/height distribution
P Phase path
$p'$ Group path
q Root of Booker quartic equation. Vertical component of $\mu$
R Zurich sunspot number
S Sin $i$
T Temperature
U $1 - iz$
VLF Very low frequency
X $8.061 \times 10^7 N/r^2$
$Y$ $e^{B/2\pi} \text{fm}$
Z $2/2 \pi f$
$z$ Vertical Cartesian co-ordinate
$\alpha, \beta, \gamma, \delta, \epsilon$ Coefficients of Booker quartic
$\alpha, \beta$ Relate the absorption to Zurich sunspot number
$\Theta$ Angle between wave normal and earth's magnetic field
$\lambda$ Wavelength
$\omega$ Collisional frequency for electrons
$\omega_m$ Monoenergetic frequency for electrons
$\omega_{\text{eff}}$ Effective frequency for electrons
$\chi$ Solar zenith angle
$\omega$ Angular wave gyrofrequency $2\pi f$

$\omega_L$ Angular longitudinal gyrofrequency

$\omega_\mu$ Angular gyrofrequency
Summary

The absorption of a radio wave propagated through the ionosphere at oblique incidence, depends fundamentally, on the height distributions of electron density and the collisional frequency of the electrons with the neutral gas atoms. The variation of the electron density with height will also determine the paths along which the radio energy flows.

Experimental observations have been made of the absorption losses and of the various modes of propagation over four oblique incidence paths, of lengths between 500 and 1000 km. The seasonal, diurnal and anomalous variations in these data have been discussed. The experimental observations have also been used to test the validity of the theoretical results of predictions and ray tracing analyses.

The prediction of path parameters, such as mode structure and absorption, is important in the design of broadcasting circuits and the basic equations and assumptions of these methods are discussed in detail in an attempt to determine the accuracy of these procedures. The predicted conditions for the four test circuits have been compared with experimentally observed values.

At oblique incidence, the absorption can be calculated by use of ray tracing methods. A computer program, based on the Booker equations, was written so that the absorption on the oblique
paths could be evaluated for a range of electron density models. This program was compared with other standard ray tracing methods for both experimental and analytical models of the ionosphere and the results were found to be in excellent agreement. The ray tracing results were also compared with the experimental data in order to establish the validity of the ionospheric models. Composite models consisting of published D region distributions and experimentally derived E and F regions were found to give results in good agreement with experiment.

Absorption data for several oblique and vertical incidence paths was available for 1966 and a correlation analysis of these results has been carried out. Marked similarities were evident; a result which is important when predicting path parameters for one oblique circuit from measurements made on another.

Absorption variations during ionospheric disturbances have also been studied and compared with steep incidence VLF results. The enhanced electron density during these periods appears, in most cases, to be located at heights above 75-80 km.

This study has revealed that ray tracing and prediction methods, when applied to oblique incidence circuits of up to 1000 km. in length, can yield results which are consistent with experimental observations of absorption and angle of arrival for such circuits.
Chapter 1

Introduction

1.1 The Ionosphere

In 1878 Balfour Stewart suggested the existence of an ionised region in the earth's upper atmosphere to account for the diurnal variations in the earth's magnetic field. There is evidence, however that Faraday (1832), Gauss (in 1839) and Lord Kelvin (in 1860) independently advanced similar proposals. Such an ionised region would act as a reflector for radio waves within a certain frequency band and prevent their escape into free space (Kaiser 1962 and Chalmers 1962).

The propagation of radio waves to large distances was first proved possible by Marconi in 1901 who successfully received in Newfoundland, signals from a transmitter in Cornwall, U.K. Clearly some mechanism was at work which deviated the rays from their normal rectilinear path and Kennelly and Heaviside in 1902 independently suggested that the deviation could be caused by a conducting layer which was situated at a height of 110 km above the earth's surface. This concept of a conducting layer was rejected by some of the physicists of the time who favoured a theory based on diffraction (Watson 1919) to account for the long distance propagation of radio waves.

Eccles (1912) when investigating the refractive properties of an ionised gas, found that rays were deviated away from the normal to the incident plane, (i.e. a refractive index of the medium of less than unity), thus waves incident upon the ionosphere from below would be deviated away from the vertical and reflection would be possible. Larmor (1924) later extended the analysis of Eccles by considering the
effects of collisions of free electrons with the neutral gas molecules. It was also shown that no signals could be received via the ionosphere within a certain range of the transmitter, this being the so called "skip distance". The extension of the Larmor-Eccles theory to allow for the effect of the earth's magnetic field was undertaken by Appleton (1925) and Hartree (1929).

The height of the reflecting layer was first determined experimentally by Appleton and Barnett (1925) using a wave interference method. Later Breit and Tuve (1926) using a pulse technique, in which the time delay between the transmission of the pulse and the receipt of a returned echo gave a measure of the height of the reflecting layer, confirmed the results of Appleton and Barnett and also demonstrated the existence of more than one such region.

From these investigations Appleton suggested the now accepted nomenclature for the ionospheric layers, designating the region he investigated, the E (or electric) layer. Subsequently discovered layers have been termed the D, F1 and F2 regions.

The initial study of the physical and chemical processes in the upper atmosphere was performed by Chapman (1931) to account for the formation of ionisation within the upper atmosphere and it was shown that for a particular atmospheric constituent, the ionisation rate was a maximum at a specific altitude. Further advances in this field of aeronomy have extended the Chapman theory to take into account a larger number of atmospheric constituents and a broader spectrum of ionising radiation.
1.2 The Ionospheric Regions

The term ionosphere was first used by Sir Robert Watson-Watt to describe that part of the earth's atmosphere in which free electrons exist in sufficient numbers to affect the propagation of radio waves. The ionosphere is normally assumed to extend from 50 or 60 km up to 1000 km but the main ground based radio propagation techniques have been extensively used for investigating the region up to a height of about 400 km.

The major atmospheric constituents at ionospheric levels are oxygen and nitrogen. Below 100 km the molecular species of nitrogen and oxygen are dominant but above this level the oxygen molecules dissociate, the oxygen existing in the atomic state. The formation of the ionospheric layers is controlled by the production of electron-ion pairs by incoming solar ionising radiation and the subsequent interaction of these charged particles with the neutral gas atmosphere. The complexity of these reactions, and ambiguities in the reaction rates, together with uncertainties regarding the energy-wavelength distribution of the solar spectrum make accurate calculations of the resulting electron density height distributions exceedingly difficult. The ionising processes result in the formation of electrons and ions such that charge neutrality is maintained, it can be shown however that the electrons alone influence the propagation of radio waves through the medium.

The subdivision of the ionosphere into layers or regions is a convenient method of describing the general features at various levels but the designation of specific regions is not indicative of distinct
and independent layers with pronounced troughs or valleys between them. (Figure 1.1).

The characteristics of the individual regions will now be described.

1.2.1 The Ionospheric D Region

Ionisation occurs below the E layer in the height range 55-95 km and this has been referred to as the D region and although this region is the closest to the earth's surface relatively little information has been obtained regarding its physical characteristics.

The D region ionisation is thought to be produced both by cosmic rays and solar ionising radiation. The Galactic Cosmic Rays (G.C.R.) are considered to be the main cause of ionisation below 75 km at solar minimum and below 65 km at solar maximum. The variation in intensity of the G.C.R. with solar activity is small, the flux increasing by a factor of about 2 from solar maximum to minimum. Both solar Lyman-alpha and X radiation below $10^{10}$ can ionise the atmosphere in the height range 70-90 km. X-rays of this wavelength are able to ionise the major atmospheric constituents whereas Lyman-alpha radiation is incapable of ionising these gases. The minor constituent nitric oxide however is readily ionised by Lyman-alpha and such a process can account for a considerable proportion of the D region electron density especially during quiet solar conditions when the X-ray flux is comparatively small.

During solar flares the intensity of short wavelength
X-rays is greatly enhanced thus producing large increases in the number of free electrons in the D region and this excess ionisation greatly modifies the propagation characteristics of radio waves transmitted through the D region.

Due to the relatively low electron densities in this region, conventional H.F. radio sounding techniques can not be used to determine the electron density height distribution and most experimental investigations utilize low or very low frequency radio waves which can be reflected from the D region. It is possible however using very high power transmitters and extremely sensitive receivers to obtain weak partial reflections from the D region heights for frequencies between 1 and 3 MHz.

Rocket measurements of the D region electron density distribution have been made and confirm the general shape of the profile deduced from ground based experiments. The value of the electron density in the D region is of the order of $5 \times 10^3 \text{el/cm}^3$ at 90 km with a sub peak of the order of $10^2 \text{el/cm}^3$ at about 65-70 km (Figure 1.2).

1.2.2 The E Region

This region of the ionosphere lies in the height range 100–140 km and has been extensively studied by radio methods. The electron density distribution closely resembles that of a Chapman layer and exhibits the marked solar control characteristic of such a layer. At temperate latitudes the peak electron densities are of the order of $10^5 \text{el/cm}^3$ at noon. During the night time the normal E layer completely recombines as a consequence of
Figure 1.2  The Ionospheric D Region Electron Density Profile
the rapid recombination processes at these heights and thus no radio reflections can be obtained during this time.

Frequently reflections are obtained from the E region at frequencies far greater than the normal E layer critical frequencies. These comprise reflections from patches or clouds of intense ionisation which are sometimes present at E layer heights. This anomalous ionisation is known as "Sporadic E" and can occur at any time of day or night but is most prevalent in the summer months.

Ionisation at these heights can be produced by Lyman\(\alpha\) and Lyman\(\beta\) continuum and also by soft X-rays of wavelength greater than 20\(\AA\). There is some doubt however, regarding the relative contributions of the X-rays and EUV processes to the total ionisation distribution. In contrast to the D region, the marked solar control of the normal E region indicates that there is little or no influence on the electron density from sources other than the sun, although small perturbations are produced by the action of meteor activity and during periods of geomagnetic disturbances.

1.2.3 The F Region

The ionisation at heights in excess of 150 km is referred to as the F region. A maximum \(10^6\ \text{el/cm}^3\) occurs in the electron density height distribution at about 400 km. The upper limit of the layer is ill defined as small values of electron density persist to greater heights (greater than 1000 km).

Ionisation in this region is due mainly to the solar
Lyman continuum in the wavelength range 200 to 350Å.

Stratification frequently occurs separating the F region into two layers, the F1 (lower) and F2 (upper) respectively although this division is not always noticeable in winter but can easily be discerned in summer at temperate latitudes. The F2 region does not exhibit the dependence on solar zenith angle evident in the E and F1 regions, although it is particularly sensitive to solar activity. One anomalous feature of the F2 region is the decrease in critical frequency noticed from winter to summer. The variation with sunspot cycle of the F2 critical frequency is similar to that of the lower layers but for values of sunspot number in excess of 150 there appears to be a saturation effect.

Due to the slow rates of recombination in the F region the ionisation can persist through the night-time period, although the number density will be considerably less than the daytime values.

There is an ambiguity regarding the shape of the electron density profile between the E and F regions and the existence of a valley has been suggested. In recent years considerable attention has been paid to the ionosphere above the F region maximum using satellite borne experiments such as the topside sounders of the Allouette satellite.

1.3 Methods of Investigation

The basic radio method for investigating the ionosphere is the pulse technique of Breit and Tuve. In this method a series of
short pulses of radio frequency is transmitted vertically into the ionosphere and the time delay between the transmission of the pulse and the reception of the echo allows an estimate of the height of reflection to be determined, assuming the wave is propagated with the free space velocity $c$

The energy of the wave packet travels with the group velocity $u$, which in the ionosphere will vary with height and will be less than the free space velocity (group retardation). Thus the reflection height $h'$ determined by the pulse method is not the true height of reflection but the so-called "equivalent height" of reflection.

By continuously increasing the transmitter frequency the variation of equivalent height with frequency can be obtained, and from this information the electron density - true height profile may be calculated. Records of $h'$ against frequency, the so-called ionogram are produced by most ionospheric observatories.

It has now become possible, using rocket borne experiments, to measure parameters such as electron densities and temperatures, gas densities and collisional frequencies in situ. The large increase in the number of rocket firings since the International Geophysical Year has enabled detailed comparison to be made between direct and ground based measurements. The usefulness of a rocket experiment is limited by the short duration of the flight although with the advent of satellites this difficulty has largely been overcome. Stable orbits can only be obtained for satellites at heights in excess of 100 km and consequently they are of limited use in studying the lowest ionosphere. Recently it has been possible to place satellites in
orbits such that they remain stationary with respect to the earth (geostationary), thus continuous measurements of the total electron content, between the satellite and an observing station on earth, and its changes with flares or magnetic storms can be obtained.

In view of the continuous coverage available with respect to both time and geographical position, ground based methods are still a major tool for ionospheric investigation.

1.4 The Influence of the Ionosphere on Radiowave Propagation

The ionosphere behaves as an anisotropic dispersive plasma and the principal effects on a radio wave propagated into this medium are absorption of the energy of the wave by processes other than spatial attenuation, changes in the polarisation of the wave, separation of the wave into two components due to the influence of the magnetic field present, dispersion and fading. Although all these factors will influence the received signal strength, it is thought that the controlling feature is the ionospheric absorption and a special study has therefore been made of this phenomenon.

Ionospheric absorption was first studied by measuring the amplitude of the first returned echo using the pulse technique of Breit and Tuve. Measurements of the echo amplitude of radio wave pulses propagated vertically into the ionosphere enable the absorption and the effective reflection coefficient to be determined. This method also allows the height of reflection, an important factor in the determination of absorption, to be obtained. In general the absorption effects in the lower ionosphere have been studied using frequencies in the range 1.8 to 2.8 MHz, the exact frequency is chosen such that it is not
close to the critical frequency of the layer in order to simplify the analysis of the results.

Impinging on the earth's atmosphere from external sources is a large amount of radio frequency noise and measurements of the variation of its signal strength enable the electron density in the ionosphere to be determined using a Riometer (Relative Ionospheric Opacity). It is obvious that for these signals to reach the receiving site, the frequency must be such that it is in excess of the penetration or critical frequency of the ionosphere and typical frequencies used are in the 25 to 40 MHz range. With frequencies of this order the total ionospheric absorption is low and it is necessary to have equipment which will accurately measure changes in absorption of 0.2dB or less.

Simple theoretical formulae for the evaluation of ionospheric absorption depend on the inverse square of the frequency and when a sweep frequency ionospheric recorder (ionosonde) is used, the minimum frequency from which an echo is received (fmin) is a measure of the absorption of the lower ionosphere. This assumption is only justifiable if the absorption changes to which fmin is correlated are large compared with the other variable characteristics of the ionosphere e.g. during large solar flares or solar eclipses. Very little use is made of this method as the reliability of the information in most cases is not all that could be desired.

Simple pulse sounding techniques have been extended to allow absorption measurements at oblique incidence, but difficulties arise in finding suitable sites for transmitter and receiver and the most convenient method for obtaining oblique incidence absorption is to
monitor the signal strength of a distant C.W. transmitter. This technique is more complicated than the pulse method as there is no indication of the reflection height of the received signal or of its complexity (i.e. whether signals are arriving by more than one path), but by suitable choice of frequency and distance only one mode of propagation will be possible. The importance of these oblique incidence experiments is immeasurable in terms of the aid which they give to the practical communications aspect of radio propagation.

1.5 The Calculation of Ionospheric Absorption

The variation of field strength of a radio wave received after propagation via the ionosphere at daytime and night-time enables a measure of the ionospheric absorption to be obtained. The absorption is a direct ratio of these field strengths assuming that there is no absorption present at night and that the day and night-time propagation paths are identical otherwise the difference in path length has to be considered. Ionospheric absorption is given by

\[ L = 20 \log_{10} \frac{E_d}{E_n} \text{ dBs in the case of identical reflections} \]

or

\[ L = 20 \log_{10} \frac{E_d l_d}{E_n l_n} \text{ in the case of different reflection levels} \]

where \( E_d \) and \( E_n \) are the day and night-time signal strengths respectively and \( l_d \) and \( l_n \) are the corresponding half-path lengths. Further corrections have to be added to these general equations to allow for the variation of transmitting and receiving antennae gain if the modes of propagation change. In general the maximum signal strength received will occur on nights when Sporadic E ionisation is present and these values are taken to be the calibration values \( E_n \).
1.6 The Proposed Experiment

The object of this investigation was to study the radio wave absorption for a number of oblique incidence paths. Experimental measurements of the received signal strength and angle of arrival have been made for these paths and the results reduced to absorption coefficients.

In order to test the experimental results a theoretical study of oblique incidence absorption has been made and a computer program developed to calculate the ionospheric absorption from a given set of ionospheric parameters. It is of considerable practical importance to be able to predict the expected signal level (absorption) for a given communication circuit. In view of this, two of the most widely used prediction techniques have been studied to provide estimates of the likely path characteristics for various times of day and season.

The results of the comparison between prediction and experiment are presented and suggestions made for possible improvements of the present method.
Chapter 2

Previous Experimental and Theoretical Studies of Absorption

2.1 The propagation of electromagnetic waves within a weakly ionised plasma can be represented in terms of Maxwell's equations together with the equations of motion of the free electrons. In general the motion of heavy ions can be neglected for wave frequencies in excess of $1$ kHz. From the general equations a number of methods for calculating radio wave absorption have been developed which differ from one another only in the degree of simplification assumed. Among the most widely used of these analyses are those based on

1) Appleton-Hartree theory
2) Ray Theory
3) Full Wave Theory

The Appleton-Hartree theory has been extensively used for the study of absorption at vertical incidence, but at oblique incidence its use has been limited due to the availability of more suitable techniques. The ray theory approach is particularly useful at oblique incidence as calculation of the mode structure of the received signal can be carried out with great rapidity. However the approximations used break down near the level of reflection and consequently special treatment of this region is necessary. In the full wave theory no assumption other than that of a horizontally stratified ionosphere is made and thus greater accuracy is attainable by this technique. However the amount of computation is considerably greater than in the other methods. This technique is of immense value at low frequencies where the medium varies rapidly within the space of one wavelength.
The method of analysis selected depends on the speed and accuracy at which the results are required and the availability of a suitable computer. In general the simpler methods are used for rapid routine calculations whereas the more sophisticated techniques are only applied to a problem when exact analysis is required.

A detailed account of the evaluation of absorption is presented in Chapter 5.

Theoretical calculations of the type described require a detailed knowledge of the ionospheric structure in order to determine the received signal strength, but this information is normally only available in retrospect. For communications engineering purposes an advanced knowledge of the likely propagation modes for a range of frequencies on a particular radio circuit is required and consequently some method of predicting propagation characteristics is needed. Prediction methods, such as those of Piggott (1959) and Lucas and Haydon (1967) have been developed from experimental data obtained from a wide network of stations.

The problem of evaluating absorption can be considered from two standpoints, that of the communications engineer and that of the ionospheric physicist. The former requires an advanced knowledge of the absorption for a given communications link while the latter is concerned with the calculation of the absorption suffered by a radio wave propagated through a given ionospheric model.

When the free electrons, vibrating under the influence of the radio frequency field, make collisions with the surrounding medium, energy is lost and consequently the radio wave is attenuated. The total...
loss of energy by collisions is proportional to the average energy of vibration of the electrons which depends on the wave frequency, the electron density and the collisional frequency of the electrons with neutral gas molecules. The fractional losses of a wave passing through an ionised medium can be expressed in terms of an absorption coefficient k. The amplitude A of a wave after travelling a distance s through an absorbing region can be related to its unabsorbed amplitude Ao by the expression

\[ A = A_0 \exp(-ks) \]  \hspace{1cm} 2.1

If the absorption coefficient varies along the path then this relation can be written:

\[ A = A_0 \exp(-\int kds) \]  \hspace{1cm} 2.1a

2.2 Theoretical Vertical Incidence Studies of Absorption

Appleton (1927 and 1932) and Hartree (1929) developed a method whereby the complex refractive index of the ionosphere can be expressed in terms of the electron density, the collisional frequency, wave frequency and direction of propagation with respect of the earth's magnetic field. The refractive index of the medium is given by

\[ n^2 = 1 - \frac{X}{1 - iz - \frac{1}{2}y_T^2/(1 - X - iz) \pm \left( \frac{1}{4}y_T^4/(1 - X - iz)^2 + y_L^2 \right)^{1/2}} \]  \hspace{1cm} 2.2

where \( n \) can be replaced by \( (\mu - i\chi) \).

Two simplifications of this expression can be obtained for the special cases of \( \mu \to 1 \) and \( \mu \to 0 \).

For \( \mu \to 1 \) the direction of propagation of the radio wave is unchanged during transmission through the ionised medium and the
absorption for this condition is termed "non-deviative". When $\mu \to 0$, there is considerable refraction of the wave and the absorption is referred to as "deviative".

These two cases have important applications in the calculation of vertical incidence absorption and it can be shown from the magneto-ionic theory that the absorption coefficients for the two cases are as follows:

(i) non-deviative absorption

$$k = \frac{1}{2c\mu} \cdot \frac{4\pi N e^2}{m} \cdot \frac{2}{(w \pm |w_L|^2 + \gamma^2)} \tag{2.3}$$

It is usual however to assume that $\gamma^2 \ll (w \pm |w_L|^2$ and that $\mu = 1$ then

$$k = \frac{e^2}{2m n c} \cdot \frac{N \gamma}{(f \pm f_L)^2} \tag{2.3a}$$

and

(ii) deviative absorption

$$k = \frac{3}{2c} \cdot \frac{1}{(1 \pm |Y_L|} \left( \frac{1}{\mu} - \gamma \right) \tag{2.4}$$

for magnetic field.

These formulae have been extensively used in the analysis of vertical incidence absorption, notably by Appleton and Piggott (1954). However the calculation of the deviative portion of the absorption is rather complicated due to the infinity which occurs in the value of $k$ when $\mu = 0$, but Whitehead (1954) and Titheridge (1966) have evaluated
the total absorption without recourse to the deviative and non deviative approximations and have shown that the singularity in the value of $k$ can be overcome.

Ray theory is of use at vertical incidence as these calculations can be carried out rapidly, but even in this case the approximation of a slowly varying medium will break down near reflection. The Ray theory treatment can either be based on the Appleton-Hartree expression or can involve the solution of the so called "Phase Integral" which expresses the complex refractive index in terms of the W.K.B. solutions. The Phase Integral method has not been used to any great extent, although Budden (1961) and Budden and Cooper (1962) have carried out numerical calculations with this technique.

The full wave theory of Budden makes no approximation concerning the variation of the medium within one free space wavelength and can be used for all calculations at vertical incidence, although the time taken for one calculation is extremely long.

The determination of absorption by any of the above methods requires a knowledge of the electron density and collisional frequency-height distributions in the ionosphere. Experimental profiles are not always available or suitable and approximations have to be made regarding the shape of the electron density profile in order to simplify the calculations. The most widely used analytical profiles are those represented by parabolic and Chapman distributions.

2.2.1 Chapman Region

The formation of an ionised region in the earth's atmosphere was first studied by Chapman (1931) and the height
distribution of electron density was calculated for the following assumptions:

(i) Ionisation of the ionospheric constituents is by monochromatic solar radiation.

(ii) Flat earth and flat ionosphere

(iii) Constant temperature and an exponential decrease in molecular density with increase in height i.e. the scale height is constant

(iv) No magnetic field

Subject to these conditions, the rate of electron production is given by

\[ q = q_o \exp (1 - z - \text{Sec} \chi \exp(-z)) \]

where \( z = \frac{h-h_o}{H} \) is the height above the level of maximum electron density \( (h_o) \) in terms of the scale height \( H \) of the atmosphere

and this leads to the following expression for the electron density:

\[ N = N_{\text{max}} (\text{Sec} \chi)^{\frac{1}{2}} \exp \left( \frac{1}{2} \left( 1 - z - \text{Sec} \chi \exp(-z) \right) \right) \]

The derivation of the deviative absorption in a Chapman region neglecting the earth's magnetic field was first undertaken by Appleton (1927) and later by Jaeger (1947). The extension of the Chapman theory to include the earth's magnetic field has been performed by Davies (1957).

2.2.2 The Parabolic Layer

If the assumption that \( \chi \) has only small values,
i.e. Sec $\chi \simeq 1$, then the expansion of equation 2.6 to first order terms shows that the electron density distribution can be represented in terms of a parabolic model:

$$N = N_{\text{max}} \left(1 - \frac{y^2}{4H^2}\right) \text{ where } y = h - h_o$$

2.7

The deviative absorption of a wave of frequency $f$ can be expressed in terms of the ratio $f/f_c$ ($f_c$ is the layer critical frequency) for both the E and F regions when they are represented by semi and truncated parabolae respectively.

Analytical solutions to the integrals involved can only be obtained on the assumption that there is no magnetic field and that the collisional frequency is constant throughout the region. Results using this type of ionospheric profile do not agree too well with observation, but modifications by Whitehead (1956) and others to include the magnetic field have improved the agreement with experimental values.

Experimental results have shown that for quiet solar conditions analytical profiles of the type described above provide information regarding propagation characteristics which is in fair agreement with experiment. This is especially valid for the E region whose behaviour approximates closely that of a Chapman region.

2.3 Experimental Vertical Incidence Absorption Studies

The study of vertical incidence absorption has been in progress since the inception of ionospheric physics and immense efforts have been made to study and explain its diurnal, seasonal and solar
variations together with the anomalies which have been noticed. These vertical incidence studies have been of great value in determining the physical characteristics of the ionosphere and have also been of importance in predicting absorption at oblique incidence.

2.3.1 **Regular Variations of Absorption**

The electron densities in the ionosphere exhibit a marked solar control and it is therefore expected that the absorption will also be dependent on solar activity. Appleton and Piggott (1954) have related the measured absorption values $L$ to the sunspot number $R$ by an expression of the form:

$$L = a (1 + bR)^2.8$$

This expression applies for both the D and E regions but the values of the constants $a$ and $b$ will be different for the two layers. Further, the values of $a$ and $b$ will vary with month and the seasonal changes in $b$ differ for the two layers, the D region value having a maximum in summer whereas the E region value has a minimum in the same season.

For E region reflections Appleton and Ratcliffe (1927) have indicated that the major part of the attenuation occurred at heights below the reflection level and that the absorption in the D region contributes significantly to the attenuation of radio waves propagated via the ionosphere.

The first attempt to investigate the diurnal solar control of the D region absorption was undertaken by White (1934) and Best and Ratcliffe (1938) who reported that the variation of absorption with solar zenith angle was approximately that predicted by the Chapman theory. This theory indicates that the absorption
should be proportional to the cosine of the solar zenith angle to
the power 3/2 i.e.

\[ L = B \cos^n \chi \quad \text{where } n = 3/2 \]

The values given by White, and Best and Ratcliffe were
in the range 1.0 to 2.0 with a mean value of 1.5, for frequencies
between 3.0 and 4.2 MHz.

Numerous studies of the type performed by the above
workers have been carried out for both the diurnal and seasonal
variations of absorption with zenith angle and are summarised in
Table 2.1.

These experiments were generally performed for quiet
days only i.e. days on which there was little or no solar or geo­
magnetic activity, since during these conditions the E region
electron density distribution approximates closely to an analytical
function.

The large variation in the reported values of \( n \) suggests
that Chapman theory Equation 2.9 cannot be applied to vertical
incidence absorption results. The basic theory of a Chapman layer
neglects the magnetic field although even with its inclusion the
experimental and theoretical results are not in good agreement.
Better agreement with the experimental results is obtained if the
electron density in the absorbing region is not as critically
dependent on the solar zenith angle as required by the Chapman
theory. It is well known that the D region does not exhibit marked
solar zenith angle control, thus supporting the conclusion of
Appleton and Ratcliffe that a major part of the total absorption

21.
<table>
<thead>
<tr>
<th>Author</th>
<th>Value of n</th>
<th>Frequency MHz</th>
<th>Type of Measurement</th>
<th>Diurnal or Seasonal</th>
</tr>
</thead>
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<tr>
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<td>0.8</td>
<td>4.0</td>
<td>Pulse</td>
<td>Seasonal</td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>5.6-7.5</td>
<td>Pulse</td>
<td>Seasonal</td>
</tr>
<tr>
<td></td>
<td>1.8</td>
<td>5.6-7.5</td>
<td>Pulse</td>
<td>Winter</td>
</tr>
<tr>
<td></td>
<td>1.7</td>
<td>5.6-7.5</td>
<td>Pulse</td>
<td>Summer</td>
</tr>
<tr>
<td>Taylor (1947)</td>
<td>0.67</td>
<td>2.0</td>
<td>CW</td>
<td>Seasonal</td>
</tr>
<tr>
<td></td>
<td>1.07</td>
<td>4.7</td>
<td>CW</td>
<td>Seasonal</td>
</tr>
<tr>
<td>N.B.S.</td>
<td>1.0</td>
<td></td>
<td>Pulse</td>
<td>Seasonal</td>
</tr>
<tr>
<td>White</td>
<td>1.3</td>
<td>5.6-7.5</td>
<td>Pulse</td>
<td>Seasonal</td>
</tr>
<tr>
<td>Best &amp; Ratcliffe</td>
<td>1.0-2.0</td>
<td>3.2-4.2</td>
<td>Pulse</td>
<td>Diurnal</td>
</tr>
</tbody>
</table>
occurs in this region.

The variation of non deviative absorption with frequency as deduced from the magneto-ionic theory for the ordinary wave is of the form

\[ L = \frac{A}{(f^2 - f_L^2)^2} \]  \hspace{1cm} 2.10

The validity of this expression has been established by Appleton and Piggott (1954) and others, for all frequencies except those near the critical frequency of the layer where deviative absorption becomes dominant.

The variation of absorption at different geographic locations has received special attention, particularly the anomalous absorption events at high latitudes. These polar cap phenomena however lie outside the scope of this thesis and reference will be made only to the spatial variations at temperate latitudes. A comparison of the vertical incidence absorption measured at different stations has been made by Rawer (1951) using data from Slough and Freiburg, a separation of 525 km, and also by Beynon and Davies (1954b), for a separation of 250 km using Slough and Swansea data. These authors concluded that although a certain degree of similarity existed between the absorption measurements at different stations there are unaccountable discrepancies. The correlation coefficient obtained by Beynon and Davies was 0.75 and that of Rawer was 0.5, thus showing a decrease in correlation coefficient with increase in distance. Further studies of two oblique paths by Beynon and Davies showed that there was little similarity between the two paths and

22.
also that the degree of correlation varied with season being better in summer than in winter.

In a review of these results Piggott (1955) reports that with identical measuring systems and by applying corrections for the various factors influencing the measurements a very high correlation can be obtained, except for a few discrepancies in winter.

2.3.2 Anomalous behaviour of Vertical Incidence Absorption in Winter

During the winter months, November to February, anomalously high values of absorption are sometimes observed. This phenomenon, referred to as the "Winter Anomaly", has been the object of many detailed investigations. The anomaly in absorption has two aspects: one, it can be considered to be confined to a number of anomalous days; or two, as a departure of the seasonal variation of absorption from that suggested by a seasonal extrapolation of the dependence of absorption on solar zenith angle, observed from the diurnal variation on the average day. This distinction has been well brought out by Thomas (1962), Dieminger et al (1967) and Lauter (1966).

One complication in the measurement of absorption, which could mask the winter anomaly, is the possibility that part of the attenuation may occur near the reflection level in addition to that in the lower part of the ionosphere. This effect is particularly serious when the frequencies used are close to the E region critical frequency making the interpretation of fixed frequency absorption measurements different. This has been overcome by
using a number of frequencies simultaneously (Bibl and Rawer 1951) or by use of frequencies low enough to be reflected at D region heights (Schwentek 1966).

Dieminger (1952) first drew attention to the association between periods of anomalous absorption and the occurrence of partially reflected echoes from low heights (80 km) in the ionosphere. A detailed analysis of similar reflections on a frequency of 1.42 MHz by Gnanalingam and Weekes (1955), led to the suggestion of a layer of ionisation with a maximum electron density of more than $10^4$ el/cm$^3$ at a height of 85 km. These weak echoes have formed the basis of the partial reflection technique for the measurement of the electron density profiles of the lower ionosphere originated by Gardner and Pawsey (1953), and later developed by Gregory (1961) and Belrose and Burke (1964). The appearance of weak echoes was found not to be restricted to days of anomalous absorption alone and it is not clear if the same scattering mechanism prevails for both normal and anomalous days.

Umlauft (1965) has suggested that the solar zenith dependence of absorption on winter anomaly days is not of the usual form, the absorption remaining constant throughout the day while abrupt changes occur around sunrise and sunset. This conclusion is not supported by Schwentek (1966) and Shirke and Narayana Rao (1967) who found that the diurnal variation with zenith angle was very similar to that for a normal day and this is substantiated by Belrose (1967) and Lauter and Sprenger (1967) from measurements of the diurnal variations of phase heights at low and very low
frequencies.

The geographical distribution of the winter anomaly can be divided into two categories: firstly the latitude dependence: and secondly the spatial extent of the anomalous features. The existence of the anomaly at latitudes about $45^\circ N$ has been reported by Thomas (1962), but at high latitudes it is partially masked by auroral effects. Dieminger et al (1967) suggest the appearance of the winter anomaly at $45^\circ N$, although there is no indication of its presence at $1^\circ N$ and $19^\circ S$, thus it would appear that it is mainly confined to the European zone at $41-51^\circ N$ which also coincides with the greatest occurrence of observing stations, but anomalous effects have been observed at Wallops Island $38^\circ N$ by Shirke and Narayana Rao (1967).

The spatial extent of this behaviour has been investigated by Thomas (1962) who suggested it could cover distances of over 1000 km but there appeared to be association between occurrences in the eastern and western zones. Dieminger et al, however, have found that good correlation existed between electron densities measured at Ottawa and absorption at Lindau, although great caution has to be exercised in relating these two parameters as it is possible that a different mechanism may be involved in the two cases.

Little or no short term correlation between the anomalous behaviour and magnetic activity appears to exist (Thomas 1962) but the same author has noticed a certain degree of association when the data was averaged over long periods.
The correlation between winter anomaly and increases in the temperature at the 10 mb level was first observed by Bossolasco and Elena (1963) and the striking resemblance of these phenomena is readily visible. Shapley and Beynon (1965) using a superposed epoch technique for the years 1959–64 later confirmed this conclusion and from measurements of electron density by the partial reflection technique found an identical behaviour pattern. Both Lauter and Sprenger (1967) and Belrose (1967) have noticed decreases in the phase height of low and very low frequencies, reflected from the D region, which are associated with sudden stratospheric warming events.

Measurement of electron density during winter anomaly periods tends to support the hypothesis that this is controlled by increase in the electron density rather than the collisional frequency although changes in this parameter can occur and should not be overlooked.

The association of certain days of high absorption with increases in stratospheric temperature is irrefutable but as yet there is no evidence to suggest that all warmings produce anomalous behaviour or that all anomalous absorption events occur at times at which there are temperature increases in the stratosphere.

The increase in D region electron density due to changes in the photochemical processes occurring at times of winter anomaly has not been successfully explained. Sechrist (1967) has advanced an explanation involving the effects of variations in the ionospheric temperature on the rate coefficient for the formation
of nitric oxide which is ionised to form the D region. However, acceptance of this theory would involve the assumption that warmings are always associated with increases in D region electron density and require proof that the additional ionisation consisted of the positive ions of nitric oxide.

It would therefore appear that extensive use of rocket techniques to measure the relevant aeronomical quantities, combined with the appropriate simultaneous ground based measurements on days of high absorption are necessary before any exact explanation of this phenomena can be deduced.

2.4 Oblique Incidence Absorption Studies - Theoretical

The Appleton-Hartree equation can be used to calculate absorption at oblique incidence provided the path of the radio wave in the ionosphere can be determined. At oblique incidence, the refractive index generally does not tend to zero and thus the deviative contribution to the total absorption is small and in most cases can be neglected.

A knowledge of the oblique path absorption losses is required in the design of a radio communications link but most of the absorption measurements have been made at vertical incidence and consequently the majority of the early work in this field was devoted to the evaluation of oblique incidence absorption from vertical incidence data. Martyn (1935) and later Appleton and Beynon (1955) related the absorption of a wave of frequency $f$ incident on the ionosphere at an angle $i$ to the absorption on a frequency $f \cos i$ incident vertically upon the ionosphere by an expression of the form

$$L(f,i) = \cos i \cdot L(f \cos i, 0)$$  \hspace{1cm} 2.10
This method, referred to as Martyn's theorem, is only valid in the case in which the earth's magnetic field is neglected.

Booker (1935, 1936, 1949) has applied the magneto-ionic theory to propagation at oblique incidence in a horizontally stratified anisotropic dispersive medium. This analysis is based on the properties of a parameter $q$, the vertical component of the refractive index, and the derivation of $q$ from a quartic equation in $q$, the so called Booker quartic equation. This method has been used in a simple form by both Booker and Millington (1951) to calculate both ray paths and absorption.

Several ray-theory methods have been developed which vary in complexity from simple no field Snell's law approximations to complicated analyses of the type described by Haselgrove (1954) in which the ray path characteristics can be determined by numerical integration of six differential equations.

Calculations based on Snell's law are relatively simple as the effects of electron collisions and the earth's magnetic field are neglected. The simplicity of this type of analysis enables the computation to be carried out very rapidly and for low computer costs. These advantages make this technique particularly suitable for the routine tracing of ray paths through the ionosphere. The evaluation of absorption may be included by assuming the non-deviative approximation of the Appleton-Hartree theory or alternatively in terms of a cubic equation in distance of the ray from the transmitter as used by Croft (1965).

Full wave techniques have not yet been applied to the problem of high frequency propagation at oblique incidence as the amount of computing is prohibitive and the bulk of theoretical calculations at
oblique incidence are performed using ray tracing techniques.

A more detailed discussion of the various ray tracing techniques is given in Chapter 5.

2.5 Oblique Incidence Absorption Studies - Experimental

Experimental studies of oblique incidence propagation have been mainly concerned with the development of communication links, such as an analysis of the limiting propagation frequencies for specific paths rather than a detailed study of ionospheric absorption.

The comparison of oblique and vertical incidence absorption to determine the validity of Martyn's theorem for absorption formed a major part of the early experimental work.

Beynon (1954) has compared the absorption measured over the oblique incidence path from Burghead to Slough, with vertical incidence absorption at the equivalent vertical frequency for the path and has shown that better agreement was obtained if the Cos i multiplying factor was omitted from equation 2.10 for first order reflections, but the second and higher order reflections gave reasonable agreement with Martyn's theorem. The first order reflections just penetrate the E region and consequently are heavily attenuated. Although Martyn's theorem should still be valid for these conditions small errors in the evaluation of the angle of incidence will cause large errors in the Cos i factor and could account for the discrepancies in the first order reflections. Further analysis by Beynon of data obtained on a transatlantic path, where low angle rays just penetrate the E region, supported his hypothesis of neglecting the Cos i factor, although the abnormally high absorption observed on F region modes was thought to
result from partial reflections or scattering from the E region.

The influence of these partial reflections from the E region on F region absorption had been pointed out earlier by Appleton, Piggott and Beynon (1948) who reported a high inverse correlation between 1 x E mode received at Harwich and the 1 x F mode received at Swansea from a transmitter at Frazerburgh.

Allcock (1954) arrived at the same conclusion as Beynon regarding the omission of the Cos i factor, but the magnitude of the difference between theory and experiment varied with time of day and it was thought that this variation could be ascribed to the differing conditions of the absorbing region of the ionosphere for upgoing and down-going waves.

For frequencies reflected from the lower E region Meadows (1958) has shown that the measured absorption was approximately 10 db lower than that predicted by Martyn's theorem (Equation 2.10) and, as suggested by Beynon, better agreement was obtained by omitting the Cos i factor. In view of this discrepancy, equation 2.10 should only be used as a rough guide for evaluating oblique path absorption from vertical incidence data. It has been suggested by Meadows that a more accurate estimate of oblique absorption can be made from measurements over a similar oblique incidence path rather than from data at vertical incidence on the equivalent vertical frequency. However, from a study of the absorption at oblique and normal incidence for frequencies in the low end of the H.F. band (2.61 and 1.73 MHz) by Schwentek and Umlauft (1961) it has been shown that Martyn's theorem is valid for paths of a few hundred kilometers.
The solar zenith dependence of oblique incidence absorption is of the same form as at vertical incidence

\[ L = B \cos^n \chi \]

and Schwentek (1963) amongst others, has quoted a value of \( n \) of 0.75 for seasonal variations on a frequency of 2.61 MHz propagated over a 300 km path.

The introduction of sweep frequency techniques at oblique incidence i.e. the so called oblique sounder, has greatly facilitated the investigation of the propagation characteristics over long paths. The ionograms obtained are particularly useful for determining parameters such as the maximum usable frequency (MUF), lowest usable frequency (LUF) and the mode structure of the received signals for oblique propagation.

Little use has been made of this technique for studying absorption losses due to the experimental difficulties involved. Recently American workers have developed a system for recording the amplitude as well as time of flight of the echoes recorded in an oblique incidence sounding link. A detailed discussion of these techniques lies outside the scope of this thesis and results obtained with this type of experiment are to be found in the literature.

2.6 Prediction of Ionospheric Absorption at Oblique Incidence

In order to predict the frequency band which can be propagated over any specific oblique path at any particular time, an estimate of the signal strength on all frequencies is required. The signal level is deduced from the consideration of factors such as spatial attenuation,
equipment characteristics and ionospheric absorption. These estimates of the absorption are made from empirical formulae derived from the basic magneto-ionic theory and the analysis of large amounts of experimental data for both vertical and oblique paths.

The experimental results indicate that the absorption of radio waves in the ionosphere is adequately explained in terms of the ionisation produced by solar ionising radiation and therefore exhibits a marked dependence on the solar zenith angle. The variation of absorption with zenith angle for a Chapman type region is of the form

\[ L = \cos^n \chi \]

2.12

According to this equation the absorption would be zero when \( \chi = 90^\circ \), but the experimental results show that this is not true and the value of \( \chi \) at which the absorption reaches its steady minimum value is approximately \( 102^\circ \). In view of this, equation 2.12 has been modified to

\[ L = \cos \left( \frac{\chi}{2} \right) \]

2.13

The variation of absorption over the solar cycle can be represented in a similar manner to that suggested by Appleton and Piggott for vertical incidence absorption i.e.

\[ L_R = L_0 (1 + bR) \]

where \( L_R \) is the absorption at sunspot number = \( R \)

\( L_0 \) is the absorption at sunspot number = 0

\( R = \) Wolf sunspot number

The deviative contribution to the total absorption is small for an oblique incidence path and hence the absorption can be adequately represented by the non-deviative approximation alone.
Based on these considerations a semi-empirical expression of the form

\[ L = \frac{615.5 \sigma_n S \cos \phi \left[ 1 + 0.0278 \right] \left[ \cos 0.881 \gamma \right]^{1/2}}{(f - f_m)^{1/4}} \]

\( \phi \) is the angle of incidence, \( S \) is the Zurich Sunspot number has been developed by Laitenen and Haydon (1962) for the prediction of oblique incidence absorption and similar expressions have been used by Piggott (1959) and Rawer (1952).

In order to evaluate the signal level at the receiver input further consideration must be given to such factors as the antennae gain, power gain and spatial attenuation. These effects are however constant for a particular mode and do not enter into the evaluation of absorption. It is however important to ascertain the propagation modes and several methods such as that described by Newbern Smith (1939) have been developed for this purpose.

2.7 D Region Experimental Results

The low electron density in the D region is insufficient to reflect vertical incidence high frequency radio waves, but due to the high collisional frequency considerable absorption can arise in this region. It is therefore imperative that an estimate of the D region electron density and collisional frequency is obtained to enable the absorption of radio waves propagated through this layer to be calculated. The techniques used for the study of this region fall into three main categories:

a) low frequency, long wavelength CW methods
b) medium and low HF partial reflection techniques
c) direct rocket and satellite borne experiments
2.7.1 **Long Wave Measurements**

For frequencies in the range 8-50 kHz the earth and lowest ionosphere act as the walls of a wave-guide and the propagation of these frequencies can be explained in terms of wave-guide modes. The electron density in the D region will control the propagation in the earth-ionospheric wave-guide and variations in the measured phase and amplitude of the received sky wave can be related to changes in the D region electron density.

The early work of Best, Ratcliffe and Wilkes (1936) showed that the level of reflection for these frequencies was around 70 km during the day and 90 km at night. Further studies by Bain and Bracewell (1952) using path lengths of 90 and 535 km on a frequency of 16 kHz revealed that it was necessary to postulate the existence of two D layers at heights of 70 and 90 km, these layers being designated the $D_\beta$ and $D_\omega$ respectively. Rocket measurements of electron densities in the D region have since confirmed the existence of these layers during the day and that only the $D_\omega$ or normal D layer is present during the night.

The E layer conforms well to the Chapman theory and it would appear as though the D region is part of the tail of this layer, but Bracewell (1952) has shown that it is not the "tail" of the Chapman like E region but a completely distinct layer.

Recently Deeks (1966) has applied a full wave method of analysis to many of the earlier VLF experimental measurements and has deduced a series of D region $N(h)$ profiles for various times of day and season and a selection of these electron density...
2.7.2 Medium and Low HF Measurements

It is possible, using high power transmitters and sensitive receiving equipment on a noise free site, to obtain weak echoes by partial reflections from heights around 90 km (Gardner and Pawsey (1953), Weeks and Gnanalingam (1952), Dieminger (1952), Awe (1961a and b) and more recently Belrose and Hewitt (1964), Belrose and Burke (1964) and Thrane et al (1968)). Gardner and Pawsey indicated that the ionisation below the E layer consisted of two layers during the day and only one, the upper layer, was present at night, thus confirming the results of Bain and Bracewell. The work of Thrane et al using both the partial reflection and cross modulation techniques has produced D region electron density distributions at solar minimum conditions for latitudes between $70^\circ$N and $19^\circ$S. Profiles measured at the same zenith angle for the various latitudes showed close similarities but there was no indication of any strong latitudinal dependence of the electron density.

The extensive use of the partial reflection and cross modulation techniques has increased the availability of D region electron density profiles and work such as that of Belrose and Burke where the electron densities have been used to determine the collisional frequencies, has greatly enhanced the knowledge of the structure of the D region.

2.8 Conclusions

From the published work it would appear that only a small
Figure 2.1. D Region Electron Densities.
amount of effort has been devoted to a synoptic study of oblique incidence absorption, although special emphasis has been placed on the analyses of the limiting frequencies for any propagation path, but here again the majority of the work has been directed towards the upper rather than the lower limit of the frequency spectrum.

The results available show that the features observed at vertical incidence do manifest themselves at oblique incidence. The use of Martyn's theorem to obtain oblique incidence absorption from that measured at vertical incidence can only be used as a rough guide and not for accurate calculations.

According to the applications required, the theoretical calculations can be carried out using the standard non-deviative formula, ray theory or full wave methods. Difficulties arise with the first two methods due to the breakdown of the underlying assumptions near the reflection level, but as no suitable full wave method has been devised for oblique calculations ray theory is a reasonable compromise.

The need for further studies of oblique incidence radio wave propagation is evident from the scarcity of literature available on the topic and special emphasis is placed on the physical rather than the engineering aspect of oblique propagation.
3.1 Introduction

Techniques similar to those used for radio wave investigations of the ionosphere at vertical incidence have also been developed for use over oblique propagation paths. These oblique incidence sounders can conveniently be used to determine the limiting frequencies of propagation and the mode structure of the received signals, however it is not always possible to determine the equivalent path at distances greater than those for which ground wave signals can be received. Measurements of absorption, polarisation fading and magneto-ionic splitting can be performed at oblique incidence but considerable experimental difficulties are encountered in some of these measurements. Due to the availability of suitable equipment only studies of angle of arrival and absorption have been undertaken in the present work.

3.2 Measurement of Oblique Incidence Absorption

Both pulse and continuous wave techniques are employed at oblique incidence but difficulties arise in the CW method of recognising the mode structure of the received signals. The results obtained using this technique are however, comparable in accuracy with those measured at vertical incidence using pulse methods. The oblique incidence results have the advantage of being directly applicable to communications problems.

Time of flight measurements can be obtained with a single pulse transmitter and receiver provided there is a ground pulse (i.e. the path length less than 150 km) although even when no ground pulse is present
the propagation modes can be accurately identified. Group path can be measured over great distances where a more elaborate sounding system, in which both ends of the circuit are equipped with a synchronized transmitter and receiver, is used. The CW measurements provide no information concerning the mode structure of the received signals, but it is possible by suitable choice of frequency and path to make one particular mode of propagation dominant for considerable periods of time. The receiving antennae can be chosen so that the maximum lobe of its polar diagram is at the angle of elevation corresponding to the dominant mode and therefore give some degree of mode selection.

The absorption coefficient of the daytime ionosphere can be calculated from a knowledge of the received signal strengths at night and during the day provided the signal level at night-time is measured when the residual ionospheric absorption is negligible. If the daytime and night-time field strengths are $E_d$ and $E_n$ and the respective half paths are $l_d$ and $l_n$ then the absorption is given by

$$L = 20 \log \frac{E_d}{E_n} \frac{l_d}{l_n}$$

3.1

The value of $E_n l_n$ is the calibration constant and assumes that at night the reflection coefficient $\rho$ is unity. If the night-time propagation mode is the same as that during the day then equation 3.1 reduces to

$$L = 20 \log \frac{E_d}{E_n}$$

3.2

since the ratio $l_d/l_n$ is unity. When the modes are not the same then it is necessary to include a further correction term to allow for the differences in antennae gain at the various angles of arrival.

38.
For simplicity the propagation mode is chosen to be $1 \times E$ so that the calibration constant is obtained using propagation via Sporadic $E$ at night.

Although it is possible to keep one mode dominant for long periods it is necessary to calculate the maximum variation in the received signal which is likely to be produced by other interfering modes, particularly during the calibration periods. If $2l_1$ and $2l_2$ are the oblique path lengths for two modes, $G_{r1}$ and $G_{r2}$, $G_{t1}$ and $G_{t2}$ the relative gains of the receiving and transmitting antennae at the corresponding angles then the relative signals due to the two modes will be

$$\frac{E_1}{E_2} = \frac{G_{r1} G_{t1}}{G_{r2} G_{t2}} \frac{l_2}{l_1}$$

when no absorption is present the total signal $E$ is given by

$$E = \sqrt{E_1^2 + E_2^2} = E_1 \sqrt{1 + E_2^2/E_1^2}$$

If the transmitting antenna is a vertical monopole and the receiver antenna a horizontal dipole then $G_t \propto \delta \propto \alpha$, $G_r \propto C \propto \alpha$ then

$$\frac{E_1}{E_2} = \frac{h_1'}{h_2} \left(\frac{l_2}{l_1}\right)^3$$

and the ratios of the signal strength can easily be determined from this equation.

The presence of Sporadic $E$ during the night-time calibration period can be determined from ionosonde records obtained at one end of the oblique path, although care must be taken to ensure that the
The blanketing frequency of the Sporadic E is in excess of the equivalent vertical frequency, thus ensuring complete reflection from this layer. The Sporadic E observed on the end point ionograms may not necessarily extend over the complete path but with reasonable care and statistical analysis of the night-time records the signal level due to Sporadic E can be ascertained.

The experimental arrangements for the measurement of signal strength at oblique incidence are similar to those developed for vertical incidence studies. The constant amplitude method, although widely used at vertical incidence, is not ideal for oblique incidence work and the constant gain technique, which is better suited to automatic recording, is invariably used for oblique incidence measurements.

Schwentek (1964) has developed a technique which determines the distribution of signal strengths at 30 sec or 1 min intervals for sampling periods of 30 or 60 min. This technique is of particular importance in analysing the night-time records when an estimate of the signal strength from Sporadic E is required and clear identification of the mode in required. The distribution of signal strength obtained by this analysis is similar to that shown in Figure 3.1. The mode structure of the signals can also be established from ionograms taken during the sampling period and the transmission curve for the particular frequency. The peaks in the signal strength histogram clearly correspond to the individual modes present.

3.3 Non Dissipative Phenomena

The signal strength of a radio wave reflected from the ionosphere is governed by factors in addition to the absorption losses.
Figure 3.1  Night-time signal strength histogram
These non-dissipative losses, which are dependent on the ionospheric structure can be divided into five categories as follows:

i) Polarisation

ii) Spatial attenuation

iii) Dispersion

iv) Ionospheric irregularities

v) Partial reflections or scattering

Dispersion is an important factor when using pulse techniques because significant errors can arise from the distortion by the ionosphere of the returned echo. These errors can however be neglected when using CW methods.

The amplitude of a radio wave radiated from a point source is dependent on the divergence of the wave front and varies inversely as the square of the distance from the source. In practice the spatial attenuation is inversely proportional to the apparent path length \( P' \), (by Breit and Tuve's theorem) but this does not adequately represent the propagation when the earth's magnetic field is present. In general the spatial attenuation will be dependent on the electron density distribution and is not uniquely determined by \( P' \), but this error is normally small except at frequencies near the critical frequency of the layer. For long distance propagation the curvature of the earth and ionosphere will alter the divergence of the wave, and focusing results, thus the simple spatial attenuation laws can become invalid. It is extremely difficult to make accurate measurements of the laws governing this phenomenon as the observed amplitudes are modified by other factors.

From the magneto-ionic theory it can be seen that there are
two characteristic waves, the ordinary and extraordinary, which can be excited when a radio wave is incident on the lower boundary of the ionosphere. Once excited, the amplitudes and paths of propagation of the two waves are generally independent and the differential absorption between these two can cause the suppression of one of them. At temperate latitudes during the day, the extraordinary mode is more severely absorbed than the ordinary mode and is usually neglected, although during the night their amplitudes may become of comparable magnitude. The suppression during night-time of the extraordinary component can be achieved by choice of a suitable aerial array.

Ionospheric irregularities cause the signal amplitude to fluctuate in a random fashion and it is convenient to classify these fluctuations into three categories:

   i) Scattered or partial reflections
   ii) Long term fading
   iii) Short term fading

Radio waves can be scattered by clouds of dense ionisation embedded in the surrounding medium. These clouds vary in shape and size thus when a wave reflected in the ionosphere encounters these clouds, irregular scattering of the energy occurs, resulting in large and variable attenuation losses. This is particularly true if there is partial reflection from a Sporadic E layer as well as reflections from the E region and great care must be taken in interpreting measurements when scattering occurs because the modes of propagation are not accurately known and a great deal of energy may be reflected from the laterally displaced clouds of ionisation.
Both long and short term fading occur when radio waves are reflected from a "rough" ionosphere. The electron density contours are seldom "slab-like" and are usually distorted into convex and concave surfaces, the radii of curvature of these irregularities varying with time and being superimposed on each other. Reflections from these irregularities thus result in continual focussing and defocussing of the reflected signals, giving rise to the observed amplitude fluctuations.

Short term fading, which is caused by irregularities of small radius of curvature, corresponds to variations in the amplitude of the received signals which have a quasi-period of a few seconds. Ratcliffe (1948) has shown that these short term fluctuations indicate that the amplitude varies as if it were controlled by a large number of perturbations, the resultant amplitude being represented by a Rayleigh distribution

$$p(x)dx = \frac{\pi}{2} x \exp\left(-\frac{\pi x^2}{4}\right)dx$$

where \(p(x)dx\) is the probability that the fluctuation lies in the range \(x \rightarrow x + dx\) and \(x\) is the ratio of the instantaneous amplitude to its mean value.

The mean amplitude \(I\) of a wave fading according to the above equation differs from the mean amplitude of a steady signal having the same power by

$$I = \sqrt{\pi/2} \cdot I_0$$

thus the presence of the irregularities increases the mean amplitude by a factor of about 1.3.

The long period fading, with a quasi-period of approximately
10 min, is associated with the presence in the ionosphere of levels of constant electron density which are slightly curved, that is the radius of curvature of the irregularities is large, and therefore the mean amplitude of the reflected wave is affected due to the changing divergence of the wave fronts. The fluctuations of the amplitude will be dependent on the radius of curvature but as long as measurements over one complete fading cycle are available it is possible to obtain accurate estimates of the mean signal.

As the quasi-period for short term fading is of the order of a few seconds, the variations due to it can be smoothed out by integrating the amplitude over periods of 45-50 seconds. These integrated values will not be independent of long term fading but it is possible, using a block of integrated values, to determine the percentage of the time for which the signal level will be between two given limits. It is not convenient to use the integration techniques to overcome long term fading as this would require an integration period of greater than 30 min during which time the variation in the ionospheric structure would mask the fluctuations caused by the irregularities alone.

3.4 **Sampling Techniques**

The accuracy of the absorption coefficient calculated from the signal strength data depends on the number of individual measurements in a sample and also on the length of the sample, thus if the sampling period is of the same order as the fading period, only a limited number of independent observations may be obtained from a continuous record. Beynon and Davies (1954) have given a detailed analysis of the statistics of fading for vertical incidence.
pulse absorption and have showed that if the samples are taken every ten seconds then the standard errors for various lengths of sample are

- 29% for 20 samples in 190 secs
- 17% for 80 samples in 790 secs
- 1% for 200 samples in 1990 secs

If the samples are taken at equal intervals in a fixed period of time then the errors for the number of samples are reduced to

- 15% for 20 samples in t minutes
- 5% for 80 samples in t minutes
- 1% for 200 samples in t minutes

Meadows and Moorat (1958) have obtained greater accuracy by comparing the instantaneous signal level with the root mean signal level for various ratios of standard deviation to mean signal level. The likely accuracy of any given reading is then estimated by defining a range of values in which the instantaneous reading has a 99% chance of occurring. These authors have also studied short term fading effects at both vertical and oblique incidence and have shown that the confidence limits which can be placed on absorption values are $+4$ to $-12$ and $+4$ to $-11$ dB respectively with an accuracy of 99%

3.5 **Oblique Sounding Techniques**

As mentioned previously, oblique sweep frequency pulse measurements have played an important role in the study of oblique propagation characteristics and particularly in determining the frequency ranges which can be propagated on any given circuit. Extensive work has been carried out using this type of experiment to determine the accuracy of the predicted values of the limiting frequencies and of mode structure.
The results obtained for the maximum usable frequency show excellent agreement between theory and experiment but the lower frequency limit has not been studied in such detail due to the many complicating factors that can influence the parameters.

3.6 Angle of Arrival

The difficulty in determining the mode structure of CW signals reflected from the ionosphere has severely restricted the measurement of oblique incidence absorption. Measurement of the amplitude at different angles of elevation can overcome some of the difficulties in the analysis but the effect of fading on the strength of the different modes can lead to complications. Due to the complexity of the experimental arrangement required for these measurements only a limited use has been made of this technique. Comparison of the angle of arrival and pulse sounding techniques over the same path has shown that both methods are capable of resolving the mode structure to the same degree of accuracy. In principle it is possible to determine the field strength on each of the modes but no attempt has been made in this direction.

The angle of arrival method has the advantage that the measurements can be performed on any existing CW broadcasting stations and unlike the oblique sounding techniques it does not require the setting up of special transmitting sites.

Two different methods of measuring the angle of arrival of downcoming radio waves exist. The first and less frequently used method involves measuring the relative phases of the received signal on two or more parallel horizontally separated dipoles. The second technique depends on producing either maxima or minima at various
angles of elevation in the polar diagram at an antenna array consisting of vertically stacked horizontal loops.

This latter method is preferable in that it is possible by changing the combination of loops used, to produce maxima or nulls in the polar diagram at small intervals of angle from 0° to 90°.

3.7 Conclusions

Absorption losses over oblique incidence paths can be accurately determined using CW techniques provided the following conditions are fulfilled.

i) There is no ground wave contamination of the sky wave signals

ii) The angular separation between the first E and first F modes is large

iii) The angle of elevation of the maximum in the receiving antenna gain pattern is such that one particular mode is dominant for as long as possible

iv) That sufficient observations are made at a time when there is little or no residual ionospheric absorption to enable an accurate value of the calibration constant to be determined

In general path lengths of less than 200 km are not suitable for this type of experiment as large ground wave signals will be received together with the wanted sky waves. At distances greater
than 1200 km the angular separation of the various propagation modes becomes very small and consequently difficulties arise in isolating the dominant mode in the received signals. Consequently the path lengths employed for this investigation all lie between 350 and 980 km.

Simultaneous measurements of the angle of arrival and signal strength of each of the propagation modes can greatly increase the value of oblique incidence absorption studies; however, this technique is restricted by the large aerial arrays and the complexity of the equipment required to make this type of observation. During the present study such an apparatus was available to the author on four separate occasions and these observations are intended to supplement the more conventional type of experimental measurements already referred to.
Chapter 4

Experimental Techniques

4.1 Introduction

In the present series of experiments the field strength and angles of arrival of the ionospherically propagated signals from a number of commercial C.W. transmitters have been monitored. The received signal strengths have been recorded continuously at Leicester using a new data-logging system and the angles of arrival measured using equipment made available by courtesy of G.C.H.Q., Cheltenham.

4.2 Experimental Measurements of Signal Strength

During the last 4 years the signal strength of the 2.61 MHz frequency transmitted from Norddeich, West Germany, a distance of 550 km from Leicester, has been continuously recorded. Three other frequencies of approximately 6 MHz were added to the monitoring programme in 1965. The path lengths of all these circuits are between 610 and 980 km. A list of the frequencies monitored together with the relevant path and equipment parameters is given in Table 4.1.

4.3 The C.W. Experiment

A Marconi CR 150 receiver was used to measure the signal strength of the 2.61 MHz transmissions and Racal RA 17 receivers for the other frequencies. Experimental measurements have been made using both manual and automatic techniques and these will now be discussed in detail.

4.3.1 Manual Equipment

The automatic volume control (A.V.C.) line of a receiver varies as a known function of the input signal level and
<table>
<thead>
<tr>
<th>Transmitter</th>
<th>Location</th>
<th>Frequency MHz</th>
<th>Distance from Leicester km</th>
<th>Transmitter power kW</th>
<th>Transmitting Antenna</th>
<th>Receiving Antenna</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norddeich</td>
<td>53°37' N, 7°10' E</td>
<td>2.014</td>
<td>550</td>
<td>2.5</td>
<td>Vertical $\frac{\lambda}{2}$ monopole</td>
<td>Horizontal $\frac{\lambda}{2}$ single dipole</td>
</tr>
<tr>
<td>Junglistern</td>
<td>47°20' N, 6°10' E</td>
<td>0.000</td>
<td>010 .</td>
<td>50.0</td>
<td>2 element $\frac{\lambda}{2}$ Yagi separation and height above ground $\frac{\lambda}{4}$</td>
<td>Horizontal $\frac{\lambda}{2}$ folded dipole</td>
</tr>
<tr>
<td>Radio Bremen</td>
<td>53°7' N, 8°53' E</td>
<td>0.100</td>
<td>030</td>
<td>5.0</td>
<td>Horizontal Rhombic Antenna $\frac{\lambda}{2}$ high</td>
<td>Horizontal $\frac{\lambda}{2}$ folded dipole</td>
</tr>
<tr>
<td>Riss Berlin</td>
<td>50°32' N, 13°24' E</td>
<td>0.005</td>
<td>050</td>
<td>25.0</td>
<td>Horizontal Rhombic Antenna $\frac{\lambda}{2}$ high</td>
<td>Horizontal $\frac{\lambda}{2}$ folded dipole</td>
</tr>
</tbody>
</table>
thus by monitoring this voltage, its variation with time enables the input signal strength to be determined from suitable calibration curves.

Originally the A.V.C. voltage was monitored using a pen recorder with a chart speed of 3 inches per hour. A time constant in the form of a resistor-capacitor integrating circuit, was inserted on the input to the pen recorder to prevent rapid fluctuations.

The continuously variable gain control of the receiver was removed and replaced by a stepped control of six ranges, with a total dynamic range in excess of 80 dB which are switched in as required. A block diagram of the manual system is shown in Figure 4.1. The records require hand scaling and this is made difficult by the frequent changes in attenuator setting. The constant output technique mentioned previously could not be used in this experiment due to the large fluctuations in signal strength from night to day.

4.3.2 Automatic Equipment

To alleviate the necessity of scaling records manually, a system was developed whereby the A.V.C. voltage of a number of receivers could be monitored and the readings automatically punched on paper tape in a form compatible with a digital computer.

The A.V.C. lines of the receivers were connected to the scanning unit of a digital voltmeter which could be programmed to read each channel consecutively at preselected time
Figure 4.1. Block Diagram of Manual Receiving System
intervals by means of a digital clock incorporated in the system. The voltages as measured by the voltmeter were converted from an analogue to digital form by a punch encoder which also served as the output unit to the paper tape punch. The digital clock also punched the time at which each scan was initiated on to the paper tape, before any readings in that particular scan. A block diagram is shown in Figure 4.3. The time between scans was variable in steps from 1 per 10 sec to 1 per 5 min and the speed at which the channels could be sampled in the scan was either 1 or 2 per sec.

Two methods of measuring the A.V.C. voltages were possible with this technique

i) Spot readings of the A.V.C. voltage every 30, 60, 90 or 120 sec

ii) Integration of the A.V.C. voltage for periods between 30 sec and 5 min

The integrator consisted of an operational amplifier with a large condenser providing the necessary feedback. The integrators (Figure 4.4) were reset using the pulses derived from the scanner unit before each channel was sampled i.e. the pulse used to trigger the reading of channel two was used to reset the integrator on channel one.

4.3.3 The Resetting System (Figure 4.5)

The negative 12 volt pulse from the scanner is used to trigger a monostable Tr1 and Tr2. The length of the output pulse is controlled by the RC network C2 and R4. This pulse is
Figure 4.3 Block diagram of automatic signal strength measuring system
Figure 4.4 The Integrating Circuit.

R1 2.2 k.ohm.
R2 100k ohm.
C 16 μF.
R1  22k ohm.  
R2  6.8k ohm.  
R3  10k ohm.  
R4  10k ohm.  
R5  4.7k ohm.  
R6  1k ohm.  
R7  100k ohm.  
C1  0.01 µf.  
C2  25 µf.  
C3  2 µf.  
Tr1  OC 75  
Tr2  OC 75  
Tr3  OC 25  

Figure 4.5  The Integrator Resetting System
then passed through the power amplifier Tr3 and the output activates a relay which closes the contacts across the integrating condenser thus discharging it completely.

4.3.4 **Comparison of Manual and Automatic Systems**

Using identical receiving systems on the same frequency but with one receiver linked to a pen recorder and the other to the digital voltmeter taking spot readings of the voltage at varying intervals of time, a comparison was made over a period of several days of the results obtained by these two methods. The Automatic system was set for a scanning period of 60 sec and a time constant of the order of 10 sec and an identical time constant was used for the pen recorder system. Typical results of these comparisons are shown in Figure 4.6. A correlation analysis of the two methods yields a value for the correlation coefficient \( r = 0.96 \) and a test of significance shows \( r \) to be highly significant. Similar values were obtained when using scanning periods of up to 2 min, the correlation coefficients being 0.94 and 0.93 for periods of 90 and 120 sec respectively. However, when the scanning period was greater than 2 min the correlation deteriorated and with a period of 5 min between readings the correlation coefficient fell to about 0.65.

Although there is a high correlation between the continuous and spot sampling techniques, errors can arise in the latter if there are large bursts of noise occurring at the time.
Figure 4.6 Correlation of signal strength from the automatic and manual systems.
the voltages are sampled. To reduce the errors from this cause the A.V.C. voltage of the receiver was integrated before sampling. A correlation analysis similar to that described above was performed for the integrated and continuous pen recorder values for integration periods between 30 sec and 5 min. Figures 4.7 and 4.8 again show excellent correlation for integration periods of 1 and 2 min, the correlation coefficients being 0.96 and 0.92 respectively, but for the 5 min period r was reduced to 0.80. A comparison of the two automatic techniques for sampling separations of 1 and 2 min yields correlation coefficients of 0.96 and 0.94 respectively.

The above analyses show that the manual and automatic techniques are of equal accuracy and the reduction in the amount of manual labour required by the automatic method makes it much more suitable for a long series of signal strength measurements.

4.4 Calibration of the Signal Strength Measuring System

The reflection coefficient of the ionosphere is determined from the ratio of daytime value of signal strength to the night-time calibration constant (see Chapter 3) and it is not necessary to know the absolute value of the received signal strength. It is essential, however, that the equipment and sensitivity remains constant over long periods and frequent calibrations of the receiving system are thus required.

Calibration was carried out using a conventional R.F. signal generator connected to the aerial input of the receiver. In this way a measured deflection on the pen recorder or a given binary coded
Figure 4.7 Correlation of manual and integration techniques for sampling period of 1 min.
Figure 4.8 Correlation of manual and integration techniques for sampling period of 2 min.
decimal pattern on paper tape can be interpreted in terms of a known signal amplitude. Care was taken to ensure that the output impedance of the signal generator was correctly matched to the receiver input.

4.5 Antenna Design

For accurate measurements of signal strength and absorption all signals received by ground wave and high angle paths must be removed so that the wanted propagation modes only are recorded.

On the oblique paths monitored, the angular separation between the first E and first F modes is of the order of 20–30°. To isolate one of these modes completely it is necessary to arrange an aerial array with a large narrow lobe at the angle of elevation corresponding to the wanted mode. This is usually achieved with complex arrays, such as log-periodics, which are too large and expensive for general use. Some measure of selectivity can be obtained using simple aerial systems and in this work dipole antennae, at carefully chosen heights above the ground have been utilised.

The antennae used at the Leicester receiving site were horizontal half wavelength folded dipoles for the three higher frequencies and a single half wavelength dipole for the lowest frequency of 2.614 MHz. The impedance of the folded dipoles is 300 ohms balanced and the receiver input impedance of 75 ohms unbalanced thus necessitating the use of 300 ohms balanced to 75 ohms unbalanced impedance matching transformers between the aerials and the receivers.

The polar diagram of the receiving antennae used are shown in Figure 4.9.
1. 2.61 MHz \( \frac{1}{2} \) wavelength dipole.
2. 6.00 MHz \( \frac{1}{4} \) wavelength dipole.

Figure 4.9 Angle of elevation vs receiving antennae gain
4.6 **Discussion of Experimental Techniques**

The accuracy of the signal strength measurements is dependent on the accuracy and reliability of the receiving equipment. To ensure the validity of the experimental results great care was taken to make sure that all the variable factors which could affect the readings were frequently checked.

The receivers were calibrated over the whole of their dynamic range once per month and spot checks at selected levels of input signal were made every week. The frequency drift of the receivers, the zero drift of the integrators and the data logger were continually checked and when any variations in these parameters was found the complete receiving system was recalibrated immediately.

Night-time calibrations to determine the maximum unabsorbed field strength were made twice or three times a week to ensure that any variations in transmitter power were taken into account when calculating absorption values.

4.7 **Angle of Arrival Measurements**

Total field strength recordings give little indication of the mode content of the received signals. If vertical incidence ionograms are available an estimate of the propagation modes for any oblique path can be made using the method outlined by Newbern Smith (1939). This technique can only provide an indication of the mode structure and gives no information concerning the relative amplitudes of the modes.

Experimental techniques have been developed for directly measuring the mode content of a C.W. signal and a system of this type has been built and developed by G.C.H.Q. Cheltenham. From time to time
the mode content of the signals used for the oblique incidence study have been determined by means of this equipment.

The aerial array for the angle of arrival equipment is supported on a 250 ft wooden tower with platforms at intervals of 40 ft. These platforms, the lowest being at a height of 44.5 ft above ground level support the horizontal metre square loops. The early measurement of angle of arrival by Wilkins and Minnis (1956) used single turn loops which were rotated to eliminate the errors due to the electrical dipole moment of the aerial. This difficulty can be overcome by using square twin loops which are in effect two simple loops connected such that their dipole moments cancel (Ross (1947) and Horner (1948)). By selecting different combinations of the loops the position of maximum gain can be moved through various angles of elevation. Unfortunately, all the lobes do not have the same gain but a compensator unit has recently been introduced which ensures that the antenna gain is constant at all angles of elevation. This allows the dominant mode to be identified although no absolute measure of the signal strength of each mode is possible.

The accuracy of the system has been assessed by calibrating using an airborne transmitter. The results of extensive tests show that the errors in elevation angle were always less than 2° for frequencies greater than 5.0 MHz. A further check on the accuracy of the system was performed by comparing the results obtained using a series of European transmitters, with those calculated from a ray tracing analysis and the results obtained show errors of less than 1° for all paths.
Two procedures for measuring the elevation angles of the received signals are available with the equipment,

a) Null Selection
b) Elevation Scanning

4.7.1 **Null Selection Method**

The number of combinations that can be formed from up to six aerials added in phase or anti-phase is \( \frac{1}{2} \times (2^6 - 1) \) i.e. 364. These combinations have different vertical lobe patterns with nulls at one particular angle of elevation and maxima at other angles. The voltage induced in an aerial at a height \( h \) can be expressed as

\[
V \propto f \sin \Delta \cdot F(h)
\]

where \( f \) is the frequency in megacycles and \( h \) is the height of the aerial in metres. Thus for any given height the amplitude of \( V \) can be calculated in terms of \( f \cdot \sin \Delta \). The amplitudes of the signals in each of the six aerials were calculated by a computer for values of \( f \cdot \sin \Delta \) between 0.0 and 20.00 at intervals of 0.05 and these amplitudes used to evaluate all the possible combinations. For each value of \( f \cdot \sin \Delta \) the distribution of nulls in the various combinations was examined and two of these combinations which produced a null at a particular \( f \cdot \sin \Delta \), but widely different polar diagrams at other values of \( f \cdot \sin \Delta \) were selected.

The two aerial combinations for various \( f \cdot \sin \Delta \) were fed into the two channels of a twin channel receiver and the aerial combinations switched manually until a straight line at 45° was produced on an X-Y display. At positions where the
aerials do not produce a null at the angle of arrival of the particular mode, a complex pattern is seen on the X-Y display.

In a further development of this technique the phases of the 100 kHz outputs from the twin channel receiver are compared in such a way that the two wave forms are only in phase if the aerials selected produce a null at the angle of arrival. One of the 100 kHz outputs was full wave rectified and fed into an oscilloscope. The other output was squared and differentiated to produce positive and negative spikes. This waveform was clipped so that there were only positive spikes and then fed into the same oscilloscope amplifier in such a way that it acts as the tube bright-up. Thus when the bright-up lies in the trough of the rectified waveform, the outputs are in phase and the aerial combinations provide a null at the angle of arrival of the mode being investigated. A block diagram of the null selection method is shown in Figure 4.10.

4.7.2 Elevation Scanning

The computed signal amplitudes indicated that there were sufficient aerial combinations having maxima in the range of $f \cdot \sin \Delta$ from 1.50 to 7.00 to allow an elevation scanning technique to be carried out.

Combinations of aerials producing maxima in the polar diagram at equal intervals of $f \cdot \sin \Delta$ were programmed. An oscillator of approximately 300 Hz drives a 32 bit counter, the output of which operates an R.F. switch to select the correct set of aerials for each value of $f \cdot \sin \Delta$. A staircase waveform
Figure 4.11
Block diagram of null selection technique for measuring angles of arrival.

400 Hz Oscillator

32 bit Counter

RF Switch

Adder

Compensator Unit

Y Amplifier

X Amplifier

Oscilloscope
derived from the counter is applied to the X amplifier of an oscilloscope. The combined aerial signal is fed to a receiver, the I.F. output of which is displayed as a Y deflection.

A block diagram of this technique is shown in Figure 4.11 and typical displays in Figures 4.12.

This method of selecting the angle of arrival has the advantage that the number of modes is easily seen and their relative amplitudes known, as a compensator has been incorporated for each combination so that the gain of each lobe is approximately the same.

A series of measurements covering summer, winter and equinox months has been made on the three 6 MHz frequencies for which signal strength data is available. These results, together with a comparison of the mode structures obtained from prediction techniques and ray tracing methods, are presented later.
Figure 4.10  Block diagram of elevation scanning technique for measuring angles of arrival.
Figure 4.12  Typical Elevation Scanning Displays
Chapter 5

Calculation of Ionospheric Absorption

The absorption losses of a radiowave propagated over an oblique incidence path can be evaluated by either of the following methods,

a) Prediction techniques

b) Tracing the ray paths through the ionosphere.

Prediction techniques depend on empirical formulae based on experimental evidence and their main feature is the ability to show the likely propagation modes at any particular time of day and season. Smith (1939), Appleton and Beynon (1940 and 1947) and Høller (1963) have developed such methods, the modes being determined from vertical incidence ionograms taken at the mid-point of the oblique path. These methods have been extended by Piggott (1959), Haydon (1966) and Lucas and Haydon (1966) to incorporate calculations of field strength, and a full discussion of these methods will be given later.

The trajectory of a radiowave in its travel through the ionosphere can be determined from magneto-ionic theory and these mathematical techniques are referred to as ray tracing procedures. This type of analysis enables the mode structure and the relative amplitude of the active modes to be determined with considerable accuracy for any ionospheric model.

5.1 Theoretical Investigation of Radiowave Propagation Characteristics

The propagation of electromagnetic waves in a slowly varying horizontally stratified ionosphere is governed by a series of so called wave equations. If the medium is assumed to be slowly varying then
the wave equations can be solved analytically in an exponential form known as the W.K.B. Solutions (Budden 1961, Ch. 9) and this procedure is still valid even when the effect of the earth's magnetic field is included (Budden 1961, Ch. 18). The stipulation that the medium is slowly varying is important as at points in the medium at which this criteria does not hold the W.K.B. solutions fail and this will normally occur in two main regions, a) near reflection and b) in regions where coupling occurs.

Under these conditions a more detailed investigation is necessary and generally a full-wave technique is required in which the four first order equations governing the propagation are integrated down through the ionosphere using a step by step method, (Budden (1955 a and b)). Similar calculations have been performed by Barron and Budden (1959), Barron (1961) and Pitteway (1965). The application of full wave theory is especially valuable at low and very low frequencies where rapid changes in the ionospheric constitution take place within the space of one wavelength.

Another important analytical technique is the phase integral method developed by Budden (1961), Cooper (1961), Budden and Cooper (1962) and Altman (1965). In this analysis, which was first suggested by Eckersley (1931), the complex refractive index \( n \), (given by the Appleton-Hartree equation) is integrated from ground level up to the height (usually a complex quantity) where \( n \) becomes zero. Generally there are two or three "reflection" levels depending on whether the frequency is above or below the gyrofrequency which can be identified with the reflection levels of the so called ordinary, extraordinary
& Z magneto-ionic components.

This type of analysis is essentially ray theory and thus the W.K.B. solution will fail in those regions where ray theory breaks down. For high frequencies (above 1 MHz) most of the radiowave propagation characteristics can be calculated using ray theory and approximations can be made even at levels where this is not strictly applicable.

In general more accurate results can be obtained using the full-wave method, but the amount of computing time required for one calculation, even at vertical incidence, is excessive and for a long series of calculations a simpler and faster method is required. It is for this purpose that ray tracing techniques have been devised as a means of establishing the propagation conditions for an oblique incidence path through a model ionosphere.

5.2 Ray Tracing Techniques

A ray tracing procedure may involve the solution of a single equation or it can involve millions of calculations on a digital computer. The geomagnetic field may or may not be included, the ionosphere can be described in either one, two or three dimensions and the ray path calculated in two or three dimensions. The analysis may be carried out on a digital or analogue computer or by graphical or other analytical techniques. The degree of complexity is determined by a knowledge of the ionospheric conditions and the intended application of the program. The various ray tracing methods differ in the basic equations employed and approximations which are utilised at each step along the ray path to determine the incremental parts of the trajectory.
Digital computer methods fall into three main categories

a) **Rapid Methods**

These techniques use models which are based on analytical models of the ionospheric layers. Assumptions are made which enable the ray path through the layers to be evaluated from a few simple expressions.

One of these methods, known as the Kift–Fooks method after its originators at Slough (Kift (1960) and Fooks (1962)), assumes that the ionosphere can be represented by three concentric parabolic layers corresponding to the E, F_1 and F_2 regions and the ray path is computed by evaluating seven linear equations (Westover and Roben (1963)). No account is taken of the magnetic field and only two dimensional traces can be made. The rapidity with which the calculations are performed is offset by the severity of the approximations involved and the consequent probability of large errors.

b) **Semi-analytical Methods**

If the magnetic field is neglected then the refractive index can be treated as a scalar and Snell's law can be applied in either the trigonometric or differential form (Davies and Finney (1962)). The ionospheric structure can be represented in various ways, the simplest being that due to de Voogt (1963) in which the electron density profiles are synthesised by means of a number of straight line segments of a form which allows an
analytical solution to be obtained for the differential form of Snell's law. This method has been used for field strength calculations by Maliphant (1966), and also by Croft (1965) in an attempt to synthesise ground backscatter records. An advantage of this procedure over the techniques previously mentioned is that both analytical and experimental profiles can be analysed. It does however, contain the limitation that no account is taken of the earth's magnetic field.

c) Generalised Methods

When account is taken of the geomagnetic field, the refractive index becomes a function of the field direction and the wave direction and thus more sophisticated mathematical techniques are required. Most frequently used is the analysis due to Haselgrove (1954 and 1957) which is based on Hamilton's classical work in optics and mechanics. A thorough treatment of the physical foundations of the method has been described by Brandstatter (1959).

The Haselgrove technique involves the numerical integration of six simultaneous differential equations at short intervals along the ray path to determine the successive ray direction changes. Various workers, Finney (NBS Report), Dudziak (1961), Grossi (1966), Wilts (1965) and Jones (1966) have written computer programs based on the Haselgrove equations, all the programs being developed
for specific but different applications.

Other methods of ray tracing such as those of Poeverlain (1949) and Booker (1949) also include the effects of the earth's magnetic field. However these procedures contain assumptions which restrict their usefulness to particular applications.

The ray tracing technique to be applied for a particular circuit depends on the accuracy of the results required and the reliability of the ionospheric parameters used in the calculation since it is unnecessary to employ a sophisticated program if the electron density model is only an approximation to the real ionosphere.

5.3 A Ray-tracing method based on the Booker quartic

A ray-tracing procedure based on the work of Booker (1949) has been developed for use on a high speed digital computer. The program requires considerably less computer time than similar calculations based on the Haslegrove equations and since the effects of the earth's magnetic field are included it gives more accurate results than the semi-analytical methods. Experimental observations have been made only for propagation paths of less than 1000 km and therefore the ray-tracing calculations can be simplified by assuming a flat earth and a horizontally stratified ionosphere.

Details of the method of analysis are now presented. Booker has shown that the vertical component of the complex refractive index $q$ at any height in the ionosphere can be expressed as

$$ q = n \cos \Theta $$  \hspace{1cm} 5.1
where

\[ n = \text{complex refractive index} \]
\[ \theta = \text{angle between the wave normal and the vertical within the ionosphere} \]

The quartic equation is of the form

\[ \alpha q^4 + \beta q^3 + \gamma q^2 + \delta q + \varepsilon = 0 \quad 5.2 \]

where

\[ \alpha = U(U^2 - Y^2) + X(n^2 Y^2 - U^2) \quad 5.3a \]
\[ \beta = 2n X Y^2 (S_1 1 + S_2 m) \quad 5.3b \]
\[ \gamma = -2U(U - X) (C^2 U - X) + 2Y^2 (C^2 U - X) \]
\[ + X Y^2 (1 - C^2 n^2 + (S_1 1 + S_2 m)^2) \quad 5.3c \]
\[ \delta = -2C^2 n X Y^2 (S_1 1 + S_2 m) \quad 5.3d \]
\[ \varepsilon = (U - X) (C^2 U - X)^2 - C^2 X^2 (C^2 U - X) \]
\[ - C^2 X Y^2 (S_1 1 + S_2 m)^2 \quad 5.3e \]

In general \( S_2 \) is put equal to zero, i.e. the ray path is restricted to the plane of incidence. The equations can be further simplified by neglecting the collisional frequency term as this does not have any great effect on the ray path, however, for absorption calculations the collisional frequency term must be included.

A transmitter may be regarded as a point source emitting waves whose wave fronts are spherical and which can be represented in terms of a series of incremental plane waves. Each field quantity of a component plane wave in free space is proportional to

\[ \exp \left( ik (ct - S_1 x - S_2 y) - \int_0^z q dz \right) \quad 5.4 \]
Thus the whole wave field is given by

\[ \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} A(S_1 S_2) \exp \left\{ ik(ct - S_1x - S_2y - \int z \, dq) \right\} \quad 5.5 \]

where \( A(S_1 S_2) \) is a function of the transmitting aerial and the field component used. This integral expresses the addition of many harmonically varying quantities, the contribution of this integral to the total field only being appreciable near the values of \( S_1 \) and \( S_2 \) for which the phase is stationary. The phase is given by

\[ \phi = k(ct - S_1x - S_2y - \int z \, dq) \quad 5.6 \]

and for this to be stationary both the following conditions must hold

\[ - \frac{\partial \phi}{\partial S_1} \frac{z}{S_1} + \int \frac{\partial q}{\partial S_1} \, dz = 0 \]

\[ \text{and} \quad - \frac{\partial \phi}{\partial S_2} \equiv y + \int \frac{\partial q}{\partial S_2} \, dz = 0 \quad 5.7 \]

Thus the equations for an element of ray path are

\[ \frac{dx}{dz} = - \left( \frac{\partial q}{\partial S_1} \right)_{S_1 = S} \quad \frac{dy}{dz} = - \left( \frac{\partial q}{\partial S_2} \right)_{S_2 = 0} \quad 5.8 \]

now

\[ \frac{\partial q}{\partial S} = \frac{2}{\partial q} F(q) \left/ \frac{\partial F(q)}{\partial q} \right. \quad 5.9 \]

and

\[ F(q) = \alpha q^4 + \beta q^3 + \gamma q^2 + \delta q + e = 0 \]
Thus

\[
\frac{dx}{dz} = \frac{\partial \phi}{\partial S_1} q^3 + \frac{\partial \gamma}{\partial S_1} q^2 + \frac{\partial \zeta}{\partial S_1} q + \frac{\partial \varepsilon}{\partial S_1} / \frac{\partial F(q)}{\partial q} \tag{5.10}
\]

\[
\frac{dy}{dz} = \frac{\partial \phi}{\partial S_2} q^3 + \frac{\partial \gamma}{\partial S_2} q^2 + \frac{\partial \zeta}{\partial S_2} q + \frac{\partial \varepsilon}{\partial S_2} / \frac{\partial F(q)}{\partial q} \tag{5.11}
\]

At the reflection level the ray path is horizontal thus both \(\frac{dy}{dz}\) and \(\frac{dx}{dz}\) must be infinite at this point. Equation 5.3 shows that the numerators in 5.10 and 5.11 cannot reach an infinite value unless \(q\) is infinite, hence the denominators must be zero and thus for reflection to take place

\[
\frac{\partial F(q)}{\partial q} = 0 \tag{5.12}
\]

provided that neither numerator is zero at the same level. Furthermore, at reflection two roots of the Booker quartic are equal and thus equation 5.12 is also the condition for equal roots.

The ray path is calculated from equations 5.10 and 5.11 although in the case where deviations out of the plane of incidence are not required the propagation can be expressed solely by equation 5.10. The effect of collisions is usually neglected when calculating the ray path and equations 5.3 then reduce to

\[
\alpha = 1 - X - Y^2 - Xn^2Y^2 \tag{5.13a}
\]

\[
\beta = 2S_1 nXY^2 \tag{5.13b}
\]

\[
\gamma = -2(1 - X)(c^2 - X) + 2Y^2 (c^2 - X) + XY^2 (1 - c^2 n^2 + S^2 l^2) \tag{5.13c}
\]

68.
\[ \delta = -2S C \ln XY^2 \]
\[ e = (1 - X)(C^2 - X)^2 - C^2 Y^2 (C^2 - X) - C^2 X Y^2 \]

For these conditions all four roots of the quartic are real in those parts of the ionosphere in which the waves are non-evanescent.

If the absorption of the radiowaves is to be calculated the collisional frequency term must be included. The quantity \( q \) depends on \( v \) through \( U = 1 - iZ \) only. If \( q_0 \) is the value of \( q \) at \( Z = 0 \) then using Taylor's expansion for small values of \( Z \)

\[ q(U = 1 - iZ) = q(U = 1) - iZ \frac{dq}{dU} - \frac{1}{2} Z^2 \frac{d^2 q}{dU^2} \]

where the derivatives are obtained for \( Z = 0 \). With small values of \( Z \) only the first two terms in equation 5.14 need be used and it is the second term which gives the attenuation of the wave; thus the amplitude is reduced by a factor

\[ \exp \left\{ -k \int \frac{2q}{U} \ dz \right\} \]

where the range of integration extends over the whole path of the wave packet. The quantity \( \frac{2q}{U} \) can be obtained from 5.2 using the form of the coefficients shown in 5.3

thus \[ \frac{2q}{U} = \frac{dF(q)}{dU} \int \frac{dF}{dq} \]

giving

\[ \frac{2q}{U} = \frac{4 \frac{2x}{2u} + u^2 \frac{2x}{2u} - \frac{2e}{2u}}{\lambda C^2 + \lambda e^2 + \lambda U} \]

69.
The ground distance and absorption of any oblique incident radiowave can therefore be described by equations 5.2, 5.3, 5.10, 5.11, 5.13, 5.15 and 5.17 and a computer program has been written to evaluate these equations. In this method the roots of the quartic equation at given values of $X$ were found using an iterative method due to Bairstow.

Depending on the values of $X$, $Y$ and $I$ the quartic equation can have three distinct types of solution viz:

a) all four roots real consisting of two pairs with opposite signs
b) Two real roots and one complex pair
c) Two complex pairs of roots.

At heights below the reflection level the pair of roots corresponding to a particular magneto-ionic component will be real but not equal. Thus at a level in the ionosphere below the reflection height of both ordinary and extraordinary components two pairs of real roots are obtained corresponding to case a) above. At a reflection level a particular pair of roots become equal although still real. Above the reflection level the roots form a complex pair and the wave is of an evanescent character. Thus case b) represents one propagating and one evanescent wave and in case c) both magneto-ionic components are non-propagating.

The program first determines the reflection height, and the upgoing ray corresponding to one magneto-ionic component is traced up to this level, the down going ray is then followed from the reflection height to the ground. For this procedure the ionosphere calculated in each slab before proceeding to the next one. The width of these strata
depend on the position of the ray with respect to the height of reflection. In general a slab thickness of 1 km is assumed although it is possible for the last 2 or 3 km before reflection to reduce this to a value between 0.5 and 0.1 km. The results show good agreement with those obtained from other ray-tracing methods and a full account of these comparisons is given in Chapter 7.

5.4 Prediction Methods

For any radio circuit propagation parameters such as received signal strength and angle of arrival can be predicted using a number of empirical relationships based on a long series of observations at vertical and oblique incidence. The predicted value of the received field strength of any propagation mode will depend on other factors in addition to the absorption losses. Thus the evaluation of absorption forms only one part of the analysis required to determine the field strength and allowance must be made for factors such as spatial attenuation, focussing and equipment characteristics.

a) Determination of the unabsorbed field strength

This is defined as the median incident field intensity that would be observed using an antenna of fixed linear polarisation if no ionospheric absorption was present. This definition does not take into account factors such as a) focussing caused by the curvature of the reflecting layers, b) interference and polarisation fading and c) loss of energy on reflection at the ground between hops.
Focusing effects usually produce signal strength fluctuations which are small compared with those due to irregularities in the reflecting layer. They can however be important for very oblique paths i.e. at angles of incidence of less than 5°.

Interference and polarisation fading can reduce the median field intensity by factors of 0.832 (-1.6 dB) and 0.707 (-3.0 dB) respectively (CRPL Report 462).

The ground reflection losses between hops is dependent on the frequency, angle of incidence on the ground and the electrical properties of the earth and it is usual to assume a loss factor of 0.63 (-6 dB) for this effect.

The losses due to spatial attenuation follow the inverse square law of distance and prediction methods normally assume a fixed height of 105 km and 320 km for the reflection heights of E and F modes respectively.

The transmitting and receiving antennae do not generally have a uniform gain at all angles and therefore corrections have to be applied to the unabsorbed field intensity for each mode to take this into account.

Thus
\[
FS_T = FS_1 + P + G_T + G_R + IF + PF + GD
\]

\[FS_T = \text{Total unabsorbed field strength}\]

\[FS_1 = \text{Unabsorbed field strength for a 1 kw transmitter}\]

\[P = \text{Power gain of transmitter in dB above 1 kw}\]
$G_T G_R = \text{Transmitting and receiving antenna gains}$

$\text{IF, PF} = \text{Interference and polarisation fading losses}$

$\text{GD} = \text{Ground Reflection losses}$

b) Active and dominant modes

It is usual to define the active and dominant modes as follows:

A mode is "active" on frequencies between the lowest usable frequency (L.U.F.) and maximum usable frequency (M.U.F.) of that mode.

A mode is "dominant" for the frequency band in which the field strength or power delivered to a receiving antenna exceeds that of any other modes.

E region modes will be active provided the E region MUF is greater than the operating frequency. This MUF can be found by combining the absorption index for the particular geographical location with the relevant sun-spot number to give the E region critical frequency. The E region MUF is then determined from this critical frequency and the path length.

For F region modes account must be taken of the screening effects of the E region below a certain frequency. Thus for E layer screening the first F reflection cut-off frequency, $f_s (1F)$ is the lowest frequency which can penetrate the E layer without prohibitive losses at an angle of incidence which will give 1F transmission to the required distance. Thus the 1F mode will be active between $f_s (1F)$ to the MUF for 1F propagation and the 2F mode from $f_s (2F)$
to the MUF for 2F propagation i.e. the IF MUF for a distance of D/2.
The field strength of an F1 reflection is appreciably less than that
of the F2 reflection and its cut-off frequency is much higher than
for the F2 mode. Due to its limited occurrence the F1 mode of
propagation is usually omitted from most prediction methods.

c) Absorption Loss

All prediction methods use the same general formula
to calculate absorption and differ only in the way in
which diurnal, seasonal, solar cycle and frequency
variations are implemented. Differences also occur
due to the updating of some of the methods in the
light of recent work.

The absorption coefficient $\alpha$ is given by an expres­
sion of the form

$$\alpha = \sum_{i} n \beta (1 + aR) \sec i F(f, f_L)$$

5.19

$n$ is the number of hops

$k$ is the non deviative absorption coefficient for the
time and season

$R$ Zurich sun-spot number

$\beta$ and $a$ show the variation of $\alpha$ with $R$

$i$ is the angle of incidence on the absorbing layer

$f$ the working frequency

$f_L$ longitudinal frequency

The complexity of the equation used is dependent on the
method by which the predictions are to be obtained. In the case of graphical solutions it is normal to keep the calculations as simple as possible (Piggott 1959) but a more sophisticated analysis is possible with the aid of high speed computers (Lucas and Haydon (1960)).

The Piggott method enables the signal strength on each mode to be determined but does not take into account the possibility of interfering noise being of greater amplitude than the signal required. Other methods such as that of Lucas and Haydon do allow for the noise present and calculate the signal to noise ratio for each mode rather than the absolute signal level. (In most cases greater significance should be attached to the relative values of signal strength predicted rather than the absolute magnitudes.)

Most of the prediction methods now in use are limited to frequencies greater than 3.0 MHz. The use of simple ray-tracing methods may in future enable predictions to be made with greater accuracy.

Recently prediction techniques have been developed which utilize real time ionospheric data rather than the retrospective use of data collected over long periods. This method is a forecasting of ionospheric conditions rather than a true prediction technique. Oblique sounders have been linked to a central control unit and the information relayed to the control has been analysed by an on-line computer programmed to determine the ionospheric characteristics likely to be found in the immediate future from this information.

Such a system allows the operating frequency for any particular circuit to be changed to suit the prevailing ionospheric conditions without recourse to any long term prediction method.
5.5 Conclusions

The calculation of the dominant and active modes and absorption for any oblique path, using prediction methods, yields no information regarding the structure of the ionosphere and therefore the major application of these techniques in the design and running of long distance broadcasting links. The ray-tracing techniques however fulfilled an important role in the analysis of experimental observations in terms of detailed ionospheric models, although the simpler methods using analytical profiles can be used in the field of predictions.
Chapter 6

Experimental Results

The techniques for measuring the signal strength and angle of arrival of ionospherically propagated C.W. radiowaves have already been discussed in Chapters 3 and 4. In this chapter measurements of these parameters are presented and their inter-relations with various geophysical phenomena are described.

6.1 Signal Strength Measurements

From an analysis of the diurnal variations of the signal strength of obliquely propagated radiowaves it is possible to determine the ionospheric absorption of these waves, provided the propagation modes during the day and at night are known and that the ionospheric absorption at night is negligible.

6.1.1 The Norddeich-Leicester Circuit

The signal strength of the 2.61 MHz transmissions from the German Post Office transmitter at Norddeich (53°37'N, 7°10'E) received at Leicester has been monitored for the past three years during the daylight hours and also at regular intervals during the night-time for calibration purposes. The transmitter power is 2.5 kw and is situated at a distance of 550 km from the receiving site.

For this circuit a 1 x E mode of propagation will be present whenever the E region critical frequency (foE) or the blanketing frequency of sporadic E (fbEs) is greater than 1 MHz and the 1 x F mode will be screened if foE or fbEs is above 1.85 MHz. Calibration values of signal strength can therefore
be obtained provided the night-time value of \( fb\)Es is in excess of 2.0 MHz.

For the Norddeich to Leicester circuit during daytime, propagation is always by the 1 x E mode and in order to ensure the same path geometry, use has been made of sporadic E reflection for night-time calibration purposes. F layer reflections can be used to determine the calibration constant provided the signal strength change due to the different angles of arrival can be estimated.

It is possible to identify the signal strengths corresponding to the different modes of propagation at night by studying the distribution of signal levels obtained during the calibration periods. Provided these distributions are based on sufficient hours observations, they may be obtained from one or two nights or from a whole month. The shape of these histograms will vary with the propagation conditions present during the recording periods, but exhibit certain regular features which identify the main modes of propagation.

A convenient sample may be obtained by measuring the signal level every minute from three hours after sunset to two hours before sunrise and an example of this is shown in Figure 6.1 for the period 1st to 9th June 1965.

The interpretations of the histograms is simplified with the aid of ionograms taken at the mid-point of the circuit together with the Newbern Smith transmission curves for the appropriate distance. Ionograms for the path mid-point
Figure 6.1  Night-time signal strength histogram for the Norddeich-Leicester path (1st to 9th June, 1965).
are not available for the Norddeich to Leicester circuit consequently end-point ionograms taken at Leicester have been used. Figure 6.2 illustrates an ionogram together with the appropriate transmission curve for the circuit. The virtual heights of reflection, which must be known in order to evaluate the angles of incidence from the oblique path lengths, may be obtained directly from the heights of interception of the transmission curve, and the traces on the ionogram. Clearly some errors are introduced by this procedure but provided care is taken in examining both the histograms and the ionograms spurious results can easily be recognised.

The geometry of the Norddeich to Leicester path is shown in Figure 6.3 which, together with the propagation modes determined from the ionograms, enable the peaks of the histogram to be identified. Similar distributions have been obtained for each month although some differences occur due to the varying propagation conditions throughout the year. The absorption at different times of the day for any particular month can be calculated from these calibration values.

6.1.1.a **Variation of Ionospheric Absorption**

i) **Diurnal Changes**

Typical diurnal variations of signal strength for winter, equinox and summer conditions are presented in Figure 6.4. In all cases the signal amplitude decreases during the morning, with a minimum around local noon, and increases during the afternoon to a flat maximum at night. The ionospheric
Figure 6.2 Leicester Ionogram together with the transmission curve for the Norddeich-Leicester path.
Figure 6.4  Diurnal variations of signal strength for the Norddeich-Leicester path.
absorption values deduced from these signal strength records is shown in Figure 6.5.

The absorption in an idealized Chapman layer is related to the solar zenith angle by an equation of the form

\[ L = B \cos^n \chi \]

where \( n = 1.5 \)

This expression should be valid for both diurnal and seasonal variations in absorption. The dependence of the absorption on \( \cos \chi \) for the Norddeich-Leicester circuit is illustrated in Figure 6.6. The exponent \( n \) for winter, equinox and summer months in 1965 being 0.70, 0.70 and 0.67 respectively. Monthly values of \( n \) for the whole observing period (April 1964–March 1967) are presented in Table 6.1. The exponent \( n \) does not approach 1.5 as would be expected for a Chapman region however the log of the absorption is directly proportional to log \( \cos \chi \) indicating that the absorbing region is "Chapman-like". Although marked seasonal differences occur in absorption, \( n \) is approximately constant, thus the dependence of the diurnal absorption change on zenith angle shows little variation throughout the year.

ii) Seasonal Changes

The monthly mean noon values of absorption for the period April 1964 to March 1967 are shown in Figure 6.7 and although there is a marked seasonal variation with high values in summer, anomalous behaviour during the winter months is
Figure 6.5 Diurnal variations of absorption for the Norddeich-Leicester path.
Figure 6.6  Diurnal variations of absorption with \( \cos \chi \) for the Nordeich-Leicester path.
TABLE 6.1 The values of the exponent \( n \) determined from the diurnal variation of absorption for different months over the Norddiech to Leicester path.

<table>
<thead>
<tr>
<th>Month</th>
<th>1964 Value of ( n )</th>
<th>1965 Value of ( n )</th>
<th>1966 Value of ( n )</th>
<th>1967 Value of ( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan.</td>
<td>-</td>
<td>.70</td>
<td>.76</td>
<td>.73</td>
</tr>
<tr>
<td>Feb.</td>
<td>-</td>
<td>.75</td>
<td>.70</td>
<td>.76</td>
</tr>
<tr>
<td>March</td>
<td>-</td>
<td>.70</td>
<td>.73</td>
<td>.70</td>
</tr>
<tr>
<td>Apr.</td>
<td>.75</td>
<td>.71</td>
<td>.68</td>
<td></td>
</tr>
<tr>
<td>May</td>
<td>.75</td>
<td>.50</td>
<td>.65</td>
<td></td>
</tr>
<tr>
<td>June</td>
<td>.8</td>
<td>.67</td>
<td>.68</td>
<td></td>
</tr>
<tr>
<td>July</td>
<td>.71</td>
<td>.65</td>
<td>.71</td>
<td></td>
</tr>
<tr>
<td>Aug.</td>
<td>.70</td>
<td>.66</td>
<td>.62</td>
<td></td>
</tr>
<tr>
<td>Sep.</td>
<td>.71</td>
<td>.56</td>
<td>.73</td>
<td></td>
</tr>
<tr>
<td>Oct.</td>
<td>.69</td>
<td>.60</td>
<td>.68</td>
<td></td>
</tr>
<tr>
<td>Nov.</td>
<td>.82</td>
<td>.50</td>
<td>.68</td>
<td></td>
</tr>
<tr>
<td>Dec.</td>
<td>.71</td>
<td>.77</td>
<td>.82</td>
<td></td>
</tr>
</tbody>
</table>
Figure 6.7 Monthly mean noon values of absorption for the Norddeich-Leicester circuit.
evident. The dependence of the monthly mean noon absorption on solar zenith angle again follows the simple "Chapman-like" law of equation 6.1 as illustrated by Figure 6.8. The winter values are however higher than predicted by the Chapman expression and some additional ionisation processes must be postulated to account for this excess absorption. The exponents \( n \) for the summer and equinox periods of 1964, 1965 and 1966 are 0.71, 0.68 and 0.69 respectively. The values deduced from measurements at other stations are very similar to the above (Table 6.2). The good agreement in the values of \( n \) for both diurnal and seasonal variations of absorption indicates that the absorbing region is the same in all cases.

Other workers, Schwentek (1966) and Lauter and Nitzsche (1967), have published values of \( n \) which are in good agreement with these determined from the present study.

\textbf{iii) The Winter Anomaly}

Anomally high values of absorption during the winter months have been reported by many workers, Appleton and Piggott (1954), Thomas (1962), Lauter (1966) and Dieminger (1967). The increased monthly mean winter absorption could arise from the presence of either groups of a few days of very high absorption or alternatively from a general rise in the absorption level for most days during this period with possibly only a small number of days of very high absorption. The seasonal variation of absorption follows an equation of the
Figure 6.8   Variation of noon absorption with $\cos\chi$ for the Norddeich-Leicester circuit.
<table>
<thead>
<tr>
<th>Station</th>
<th>Year</th>
<th>Frequency</th>
<th>Value of n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freiburg</td>
<td>1964</td>
<td>1.725</td>
<td>.72</td>
</tr>
<tr>
<td></td>
<td>1965</td>
<td>1.725</td>
<td>.74</td>
</tr>
<tr>
<td></td>
<td>1966</td>
<td>1.725</td>
<td>.60</td>
</tr>
<tr>
<td>Freiburg</td>
<td>1964</td>
<td>2.05</td>
<td>.73</td>
</tr>
<tr>
<td></td>
<td>1965</td>
<td>2.05</td>
<td>.74</td>
</tr>
<tr>
<td></td>
<td>1966</td>
<td>2.05</td>
<td>.69</td>
</tr>
<tr>
<td>Freiburg</td>
<td>1964</td>
<td>2.44</td>
<td>.73</td>
</tr>
<tr>
<td></td>
<td>1965</td>
<td>2.44</td>
<td>.73</td>
</tr>
<tr>
<td></td>
<td>1966</td>
<td>2.44</td>
<td>.70</td>
</tr>
<tr>
<td>Lindau</td>
<td>1964</td>
<td>2.61</td>
<td>.66</td>
</tr>
<tr>
<td></td>
<td>1965</td>
<td>2.61</td>
<td>.62</td>
</tr>
<tr>
<td></td>
<td>1966</td>
<td>2.61</td>
<td>.72</td>
</tr>
<tr>
<td></td>
<td>1967</td>
<td>2.61</td>
<td>.72</td>
</tr>
<tr>
<td>Neustrelitz</td>
<td>1965</td>
<td>2.61</td>
<td>.63</td>
</tr>
<tr>
<td></td>
<td>1966</td>
<td>2.61</td>
<td>.75</td>
</tr>
<tr>
<td>Neustrelitz</td>
<td>1965</td>
<td>2.775</td>
<td>.72</td>
</tr>
<tr>
<td></td>
<td>1966</td>
<td>2.775</td>
<td>.69</td>
</tr>
<tr>
<td>Leicester</td>
<td>1964</td>
<td>2.61</td>
<td>.71</td>
</tr>
<tr>
<td></td>
<td>1965</td>
<td>2.61</td>
<td>.68</td>
</tr>
<tr>
<td></td>
<td>1966</td>
<td>2.61</td>
<td>.69</td>
</tr>
</tbody>
</table>
form

\[ L = B \cos 0.75\lambda \]  

and therefore it is possible using this expression to determine the absorption which would have been measured if the winter anomaly was absent. The difference between the daily noon values of absorption measured during the period October 1964 to February 1965 and that determined from equation 6.2 is illustrated in Figure 6.9. Apart from a few days the absorption is at least 20% above the theoretically expected values, although at certain times the absorption increases markedly above the general high level and percentage increases of 100–125% are not uncommon. It would therefore appear that the anomalous behaviour of absorption in winter is not restricted to a few days alone, but that the general level of absorption is higher than predicted although there are groups of days which show significant increases even above this level.

iv) Dependence on Solar Activity

It is well known that the absorption of radio waves propagated by the lower ionosphere is dependent on solar activity. The present measurements (1964–1966) were made during a minimum in the solar cycle and the sun spot number remained at a very low level throughout this period. There was therefore little opportunity to confirm any dependence on solar activity although the slight increase in sun spot number in the latter part of 1966 and early 1967 has produced some evidence of a correlation between these parameters. The occasions on which any association was
Figure 6.9 The difference between the measured and calculated absorption for the period November/December 1965.
established occurred during the winter months and it is uncertain whether the enhanced absorption is due to solar activity alone or whether other phenomena such as winter anomaly days also control the absorption (Figure 6.10).

6.1.2 Luxembourg - Leicester Circuit

The signal strength of the 6.09 MHz transmissions from a commercial radio station at Junglister, Luxembourg (49°40' N, 6°19' E), a distance of 610 km from Leicester, have been monitored for two years from January 1965 to December 1966. The dominant modes for the circuit have been identified for each month using monthly mean vertical incidence ionograms and the transmission curve for the path. The signal strength histograms for the Luxembourg to Leicester path are similar to those obtained for the Norddeich to Leicester circuit and sample distribution given in Figure 6.11 for a summer night. The night-time calibration values are determined by a similar procedure to that adopted for the Norddeich-Leicester path.

i) Diurnal Variations

The diurnal changes of the monthly mean absorption for summer, winter and equinox periods are reproduced in Figure 6.12 and the dependence of the absorption on \( \cos \theta \) in Figure 6.13. The values of \( n \) for winter equinox and summer are 0.65, 0.91 and 1.07 respectively.

The diurnal variations of absorption for the winter and equinox months show no evidence of mode changes and it would appear that propagation at these times is always by the 1 x F
Zurich Sun-Spot number

Figure 6.10 Comparison of noon absorption and solar activity
Figure 6.11  Signal strength histogram for the Luxembourg-Leicester path.
Figure 6.12 Diurnal variations of absorption for the Luxembourg-Leicester path.
Figure 6.15 Diurnal variation of absorption with $\cos X$ for the Luxembourg-Leicester path.
mode. In the summer months irregular features are present between 0900–1000 and 1400–1500 U.T. in the diurnal absorption pattern, which are probably due to changes in the dominant mode of propagation. Between 1000 and 1400 U.T. the E region critical frequency is such that the 1 x F mode cannot penetrate the E region and the only modes propagated at this time are the 1 x E (shown) and 2 x F. The signal strength histograms indicate that the absorption on the 2 x F mode is in excess of that for 1 x E propagation which is therefore the dominant mode. At all other times the 1 x F mode is dominant.

ii) Seasonal Variations

The seasonal changes of the monthly mean values of noon absorption are shown in Figure 6.14 and their dependence on solar zenith angle in Figure 6.15. Apart from the months of November, December and January, the absorption varies according to equation 6.1 with \( n = 0.94 \) and 1.00 for 1965 and 1966 respectively. Although the winter months exhibit characteristic increases in absorption the magnitude of the enhancement is considerably less than for the Norddeich-Leicester circuit. The equivalent vertical frequency for the path is 4.1 MHz and a marked similarity is found between winter values and the 4.0 MHz vertical incidence measurements of Appleton and Piggott (1954).

As explained in the previous section the dominant mode at noon is dependent on season thus 1 x E propagation dominates from April to August and 1 x F during the other months. This change in the reflecting layer further complicates the
Figure 6.15  Solar zenith dependence of noon absorption.
(Luxembourg-Leicester)
seasonal variations of absorption.

The seasonal change in the diurnal variation of absorption is also of some interest. The data points in Figure 6.13 for both the winter and equinox months, where only one propagation mode is present during the day-light hours show considerably less scatter than in summer when mode changes occur during the day.

6.1.3 The Bremen–Leicester Circuit

The radio circuit from Bremen to Leicester is similar in both path length and operating frequency to that between Luxembourg and Leicester. The transmitter, located at Bremen (53°7' N, 8°53' E) radiates a frequency of 6.19 MHz, the distance from Leicester being 650 km.

The mode structure of the received signal has been resolved in an identical manner to that previously described for the Luxembourg to Leicester circuit.

Typical examples of the diurnal variation of absorption for various seasons are shown in Figure 6.16. Slight irregularities are evident in summer at times when changes occur in the mode structure. The dependence of the absorption on the diurnal change in the solar zenith angle approximates to the expression 6.1, the exponent n being .91, 1.0 and 1.17 for winter, equinox and summer respectively. This dependence is illustrated in Figure 6.17.

The seasonal variation of noon absorption during the period 1965 to 1966 (Figure 6.18) has a pronounced
Figure 6.16  Diurnal variation of absorption.
(Bremea-Leicester)
Figure 6.17 Solar zenith dependence of the diurnal absorption variation (Bremen-Leicester).
Figure 6.18
Monthly mean noon absorption
(Braun-Longest)
maximum during the summer months and a subsidiary peak in winter. The change in dominant mode at the equinoxes does not give rise to any discontinuities in the shape of the monthly variations.

The dependence of the noon absorption on the solar zenith angle is apparent from Figure 6.19 and corresponds to equation 6.1 with values of the exponent $n=1.22$ and $1.13$ for 1965 and 1966 respectively. The absorption values for the winter months lie above the straight line approximation of Figure 6.19 for the summer and equinox periods, thus further illustrating the existence of the winter anomaly.

The marked similarity in the seasonal absorption variation for Bremen to Leicester and Luxembourg to Leicester circuits is shown in Figure 6.20 where, apart from one divergence in August 1966, the variations of the noon values follow an almost identical pattern. A comparison of the diurnal variations for a summer month for these circuits, Figure 6.21, provides further evidence of this striking resemblance and although slight discrepancies occur during the morning the general agreement is excellent. The good correlation between these two circuits suggests that it may be possible to predict propagation characteristics on one oblique path from measurements made on another.

6.1.4 The Berlin-Leicester Circuit

The Rias Berlin transmitter ($52^\circ31'N, 13^\circ24'E$) is situated at a distance of 980 km from Leicester and operates on a frequency of 6.005 MHz. The path length is longer than that
Figure 6.19 Solar zenith dependence of absorption (Bremen-Leicester)
Figure 6.10  Comparison of the monthly mean absorption for the 6 MHz path.
Figure 6.21  Comparison of the diurnal variation in summer for the Bremen and Luxembourg paths.
for the other two 6 MHz frequencies discussed above and therefore it is possible that different variations of absorption will occur.

The seasonal trend of the noon absorption for this circuit is shown in Figure 6.22 and the appearance of the winter anomaly is immediately evident. The dominant mode at noon is always 2 x F since the 1 x F mode is screened by the E layer and the signal strength of the 1 x E mode is far less than for the 2 x F mode. Figure 6.23 shows the variation of noon absorption with solar zenith angle for 1965 and 1966 and best fit straight lines with slopes n = 1.02 and 1.06 are obtained for these years respectively. Values of n = 0.92, 1.29 and 1.5 are obtained from the diurnal variation of absorption for winter, equinox and summer respectively. These n values are greater than those for the other two 6 MHz circuits and probably results from the increase in deviative absorption and the losses which occur at the ground between hops.

The diurnal variation of absorption is shown in Figure 6.25. A feature of these curves is that the diurnal rate of change of absorption decreases markedly just after sunrise and just before sunset and this probably results from the 1 x F mode dominating due to the lowering of the E region critical frequency.

A comparison of the absorption changes for this circuit and those for the Luxembourg and Bremen paths has been included in Figure 6.20.
Figure 6.22  Seasonal variation of noon absorption.
(Berlin-Leicester)
Fig. 6.24. Variation of Absorption with Zenith angle (Berlin-Leicester).
Figure 6.25  Diurnal variation of absorption.
(Berlin-Leicester)
6.1.5 Summary of the 6 MHz Observations

The diurnal and seasonal variations of absorption depend on the solar zenith angle according to the relation

\[ L = B \cos^n \chi \]

For all the 6 MHz circuits, \( n \) lies in the range 0.7 to 1.5 with an average value of 1.04 compared with 0.65 for the Norddeich to Leicester path. These results indicate that the absorption on these higher frequencies occurs in a region of the ionosphere closely resembling a Chapman layer. The E region is such a layer, and it appears that significant absorption of the 6 MHz signals for the propagation paths monitored, can occur in this region of the ionosphere. The marked similarity of the seasonal variation in absorption for all three 6 MHz paths suggests that the same region of the ionosphere controls the attenuation on these circuits.

Changes in the modes of propagation at different times during the day do not produce large or rapid fluctuations in the diurnal variations of absorption and the daily patterns show smooth variations throughout the day.

A comparison of the results for the 6 MHz circuits with predicted and calculated values of absorption will be presented in Chapter 7.

6.2 Angle of Arrival Measurements

At intervals between March 1966 and January 1967 measurements of the angles of arrival of the 6 MHz circuits were carried out at a Government laboratory (Canewdon). The observations were made
during four periods of one week covering equinox, summer and winter conditions. The lower frequency limit of the system was 5 MHz and the measurements were therefore restricted to the three 6 MHz frequencies employed for the absorption study.

Measurements were made on the three frequencies consecutively and about 40 angle values determined per hour, thus giving approximately 100 observations on each frequency during an 8 hour working day. Figures 6.26, 6.27 and 6.28 show the variation of angle of arrival with time of day for the Luxembourg-Canewdon, Bremen-Canewdon and Berlin-Canewdon paths respectively. Little systematic change of angle with time is discernible, although it is evident that the number of modes received depends on season as well as on time of day.

As a check on the validity of the angle of arrival measurements the equivalent heights of reflection from these observations were compared with vertical incidence ionograms taken simultaneously at Leicester. The equivalent heights of reflection and the equivalent vertical frequencies were calculated from the angle of arrival of the various modes, assuming a flat earth and ionosphere and that the geometry of the path was symmetrical. The vertical heights at the equivalent vertical frequency of the various modes have been superimposed on ionograms taken at Leicester as shown in Figure 6.29. In nearly all cases there is excellent agreement between the equivalent heights deduced from the angle of arrival measurements and from the ionograms.

Although it was not possible to measure the absolute
Figure 6.26 Angles of arrival for the Luxembourg-Caen radar path.
Figure 6.27  Angles of arrival for the Bremen-Canewdon path.
Figure 6.38  Angles of arrival for the Berlin-Camden path.
Figure 6.29  Leicester ionogram with the equivalent heights of reflection and equivalent vertical frequencies of the various modes of propagation superimposed on them.
amplitude of each mode, it was observed that marked decreases in
signal strength occurred when the equivalent vertical frequency of
any mode was approximately equal to the critical frequency of the E or
F1 layers. All the modes showed marked fading effects. Although no
detailed study of this was undertaken, it was noticed that in summer
a substantial increase in the F region modes was sometimes accompanied
by a decrease in the signal level of the E mode and vice versa.

A comparison of the measured and predicted mode structure
for all circuits for which angle of arrival measurements are available
is presented in Chapter 7.

6.3 D Region Characteristics deduced from Experimental
Measurements

The equivalent vertical frequency of the 2.61 MHz Norddeich-
Leicester transmissions is 935 kHz, thus reflection occurs at heights
of about 90–95 km during the day. The absorption must therefore arise
entirely within the D region and observations on this frequency can
provide useful information regarding the behaviour of this region.

The phase and amplitude of ionospherically propagated VLF
radio waves are also controlled by the D region ionisation and a com­
parison of the oblique incidence absorption data with very low
frequency observations has been included.

6.3.1 Interpretation of low H.F. Absorption Measurements

The analyses of the diurnal variation of absorption
for various months on different frequencies at oblique incidence
yield values of \( n \) between 0.65 and 0.8 (Table 6.3). These values
of \( n \) do not vary in any systematic manner with season as shown in
TABLE 6.3 The values of the exponent n determined from the monthly diurnal variation of absorption for different paths

<table>
<thead>
<tr>
<th>Month</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan.</td>
<td>0.50</td>
<td>0.73</td>
<td>0.73</td>
<td>0.77</td>
<td>0.70</td>
<td>0.76</td>
</tr>
<tr>
<td>Feb.</td>
<td>0.73</td>
<td>0.73</td>
<td>0.73</td>
<td>0.75</td>
<td>0.70</td>
<td>0.70</td>
</tr>
<tr>
<td>March</td>
<td>0.73</td>
<td>0.72</td>
<td>0.73</td>
<td>0.65</td>
<td>0.70</td>
<td>0.73</td>
</tr>
<tr>
<td>April</td>
<td>0.64</td>
<td>0.77</td>
<td>0.80</td>
<td>0.71</td>
<td>0.71</td>
<td>0.68</td>
</tr>
<tr>
<td>May</td>
<td>0.68</td>
<td>0.75</td>
<td>0.71</td>
<td>0.70</td>
<td>0.51</td>
<td>0.65</td>
</tr>
<tr>
<td>June</td>
<td>0.63</td>
<td>0.64</td>
<td>0.66</td>
<td>0.68</td>
<td>0.67</td>
<td>0.68</td>
</tr>
<tr>
<td>July</td>
<td>0.60</td>
<td>0.60</td>
<td>0.66</td>
<td>0.66</td>
<td>0.65</td>
<td>0.71</td>
</tr>
<tr>
<td>Aug.</td>
<td>0.60</td>
<td>0.60</td>
<td>0.71</td>
<td>0.71</td>
<td>0.66</td>
<td>0.62</td>
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<tr>
<td>Sept.</td>
<td>0.83</td>
<td>0.71</td>
<td>0.69</td>
<td>0.66</td>
<td>0.56</td>
<td>0.73</td>
</tr>
<tr>
<td>Oct.</td>
<td>0.73</td>
<td>0.67</td>
<td>0.57</td>
<td>0.60</td>
<td>0.60</td>
<td>0.68</td>
</tr>
<tr>
<td>Nov.</td>
<td>0.65</td>
<td>0.67</td>
<td>0.70</td>
<td>0.73</td>
<td>0.50</td>
<td>0.68</td>
</tr>
<tr>
<td>Dec.</td>
<td>0.68</td>
<td>0.61</td>
<td>0.74</td>
<td>0.75</td>
<td>0.77</td>
<td>0.82</td>
</tr>
</tbody>
</table>

1  2.775 MHz Keil to Neustrelitz 1966
2  2.61 MHz Norddeich to Neustrelitz 1966
3  2.61 MHz Norddeich to Lindau 1965
4  2.61 MHz Norddeich to Lindau 1964
5  2.61 MHz Norddeich to Leicester 1965
6  2.61 MHz Norddeich to Leicester 1966
Figure 6.30. The winter values are not significantly different from those for the other seasons indicating that the dependence of the diurnal variation of absorption on zenith angle in winter is unaffected by the presence of the winter anomaly. Thus it appears that the ionisation which produces the winter anomaly is subject to the same solar control as the quiet day ionosphere.

The ionisation at D region heights is produced by solar X-rays and Lyman radiation and Galactic Cosmic Rays. The lowest D region is formed almost exclusively by the Cosmic Rays and therefore exhibits little or no solar control. Nearly all of the ionisation density is produced at sunrise (\( \chi = 90^\circ \)), and remains constant throughout the day until sunset when recombination commences. The absorption at \( \chi = 90^\circ \) has been determined from graphs similar to Figure 6.5 and this attenuation must be due almost entirely to the cosmic ray ionisation. This part of the total absorption \( (L_{90}) \) will remain constant throughout the day and the solar dependence of the absorption in the upper D region can be examined by subtracting the value of \( \chi = 90^\circ \) from the total \( (L_T) \) measured at other times of the day. A linear relationship exists between \( \log (L_T - L_{90}) \) and \( \log \cos \chi \) which suggests that the solar control varies according to equation 6.1.

The values of the exponent \( n \) have been determined for the various propagation paths and are plotted as a function of season in Figure 6.31. For nearly all the months, the values of \( n \) are greater than obtained using the total absorption
Figure 6.30  Variation of Chapman exponent n.
Figure 6.31 Variation of Chapman exponent $n$ for the dependence of $I_2 - I_90$ on solar zenith angle.
and thus the upper D region approximates more closely to the Chapman theory.

For the winter months the magnitude of \((L_T - L_{90})\) is greater than expected from equation 6.1. It appears therefore that the ionisation responsible for the winter anomaly is located at heights above the cosmic ray D region. This conclusion is supported by VLF observations made at Leicester, which show no anomalous features during the winter. These very low frequencies are reflected from the lowest D region and provide a sensitive monitor of electron density variations at these heights. Similar conclusions have been reported by Lauter and Nitzsche (1967) from measurements of oblique incidence on frequencies between 185 and 2614 kHz.

6.3.2 Geophysical Effects

From time to time marked geophysical disturbances take place which can greatly influence the propagation of radio-waves in the ionosphere. Bourne and Hewitt (1968) have reported marked changes in the absorption during the recovery phase of certain magnetic storms and it is of some interest to examine the present observations for such effects.

A number of magnetic storms have been reported during the period October–November 1966. The noon absorption values for the Norddeich–Leicester and Norddeich–Neustrelitz paths are reproduced in Figure 6.33 and there is some evidence of enhanced absorption following storm activity. The phase of the VLF, 19.6 kHz transmissions from Criggion to Leicester were also monitored during the same period and the phase variations
Figure 6.33  Comparison of oblique incidence noon absorption with VLF phase measurements for magnetically active periods.

\[ S\text{udden COMMENCEMENT} \]
have been included in Figure 6.33. This comparison reveals that there is little effect on the phase at times of magnetic activity whereas the absorption measured at frequencies around 2.6 MHz on oblique incidence do exhibit certain associations with these disturbances. It would therefore appear that these disturbances are confined to heights above the VLF reflection level (70-75 km).

This conclusion is supported by the work of Belrose and Thomas (1968) who also report that magnetic disturbances which produce MF and HF effects need not necessarily influence VLF propagation.

6.4 Correlation of simultaneous Absorption Measurements at widely separated Stations

Absorption data from several European stations for the years 1964-1966 has been examined for similarities in ionospheric absorption. Table 6.4 lists the stations which have been correlated, together with the separation of either the stations or the appropriate path mid-points. In most cases data for 25 to 30 days per month was available but those months which contained less than 20 days were neglected, thus eliminating the possibility of good correlation arising by chance alone.

In addition to the large scale seasonal variations which occur in the noon value of ionospheric absorption marked and irregular day to day fluctuations are also observed. It is important that these two types of variations are clearly distinguished when correlating the absorption values, consequently the data has been presented for
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correlation analysis in the following forms:

a) the daily values alone

b) seven day running means of the daily values

c) the deviations of the daily values from the running means.

The correlation of the individual daily values will contain the effects of both rapid and long term variations of absorption and are therefore of limited value. In order to isolate the long term changes, 7 day running means of the daily values have been correlated. The day to day fluctuations can then be examined in terms of the difference between the daily values and the corresponding 7 day running mean.

6.4.1 The Correlation Coefficient

The degree of similarity existing between two variables can be represented algebraically in terms of the correlation coefficient $r$. This coefficient lies between $+1$ and $-1$, positive values corresponding to an in-phase relationship and negative to variations in anti-phase. The degree of correlation will depend on the size of the sample considered and in all cases a test of significance of the coefficient $r$ must be made.

Consider two sets of variables $x$ and $y$ then the correlation between these two groups is given by

$$r = \frac{\sum xy - \frac{n \overline{xy}}{n}}{\sqrt{\left(\sum x^2 - \frac{n \overline{x}^2}{n}\right)} \sqrt{\left(\sum y^2 - \frac{n \overline{y}^2}{n}\right)}}$$

6.4.1
and the significance of this value using the "Students t test" is

\[ t = \frac{r}{\sqrt{1-r^2}} \sqrt{n-4} \]

6.4.2

where: \( n \) is the number of pairs of points in the sample
\( \bar{x} \) and \( \bar{y} \) are the mean values of the two sets

The value of \( t \) calculated from a particular set of data is used in conjunction with published tables to determine the significance of the correlation obtained. For samples of 30 pairs of data points, the correlation coefficient is significant if it is greater than 0.36 and for 40 samples if \( r \) exceeds 0.31.

6.4.2 Correlation of the daily Values of noon Absorption

Table 6.5 lists the correlation coefficients of the daily noon absorption values during 1966 for the pairs of stations given in Table 6.4. The correlation coefficient shows a seasonal variation, the winter and equinox values being greater than those for the summer. The dependence of the coefficient on station separation is illustrated in Figure 6.34.

For the winter months, January-February and October-December the absorption is highly correlated for separations up to 600 km and the correlation decreases linearly with increasing distance between observing stations.

During summer, the values of the correlation coefficient are extremely low and there is no evidence of any systematic variation with separation. The correlation for the
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the equinox months of March and April is significantly higher that for all other times and the value of $r^2$ coefficient decreases linearly with increasing distance.

This analysis indicates that the daily noon values of absorption are well correlated up to distances of 600-650 km for winter and equinox periods, and the correlation coefficient is inversely proportional to distance. For the summer months little correlation is evident.

A series of more limited comparisons have been carried out by Rawer (1951) and Beynon and Davies (1954) for separations between 230 and 540 km. The correlation values obtained by Rawer for vertical incidence data from Slough and Freiburg show a distinct minimum in summer and a maximum at winter and equinox, the values in summer being negative in several cases. Beynon and Davies have reported a much better correlation for all seasons with $r = 0.85$ for winter and 0.81 for summer compared with Rawer's values of 0.67 and 0.15 for the same seasons. These latter values are in very good agreement with the present work.

The good correlation for the equinox months is probably due to the rapid changes in absorption with solar zenith angle overriding any local differences between stations. In winter the high values of $r$ could result from the widespread influence of the winter anomaly affecting all stations simultaneously. The absorption remains approximately constant throughout the summer and even small irregular day to day fluctuations caused by localised disturbances could account for the poor
6.4.3 Correlation of the seven day running means of the Daily Noon Values

By considering the 7 day running-mean values, large, short term fluctuations can be smoothed out, thus allowing a comparison of the long term variations.

The seasonal values of correlation coefficient for the running-mean data are given in Table 6.6 and are plotted as a function of station separation in Figure 6.35.

The correlation in summer is better than that obtained using the daily values, but as before, there is no significant correlation for many of the circuits considered and there is little evidence of a linear decrease with increasing distance.

The equinox values of $r$ are extremely high and are inversely proportional to distance, the values even at 750 km still being in excess of 0.65. The correlation is increased compared with that for the daily values alone, especially for station separations greater than 400-450 km, indicating that the good correlation obtained using the daily values is due, at least in part, to the large changes in solar zenith angle.

The dependence in correlation coefficient on distance for the period October-December is similar to that for the equinox months and the values of $r$ are somewhat higher than obtained using the daily values. Thus it appears that the large fluctuations are extremely well correlated for separations of up to 750 km and the decrease in correlation when using daily values
TABLE 6.6 Correlation coefficient for the seven day running means of the daily values of noon absorption during 1966

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Figure 6.35 Variation of the correlation coefficient of running mean absorption values with station separation for 1966.
is due to localised irregularities.

6.4.4 Correlations of the difference between daily and running Mean Values

The daily fluctuations in absorption can only be examined when the seasonal variation is removed. This can conveniently be done by subtracting the 7 day running mean value from the corresponding daily value.

Table 6.7 and Figure 6.36 show the variation of the correlation coefficient $r$ with distance for these differences. During the summer months little or no correlation exists even for separations of less than 150 km whereas for other seasons there is good correlation for distances up to 400 km.

One interesting feature of the dependence on distance during the winter and equinox months is the appearance of two dissimilar trends for different distances. The decrease in correlation with the distance for separations between 100 and 450 km is much less than for greater separations. It is perhaps significant that the pairs of circuits with separations between 100 and 450 km are both oblique paths whereas those pairs separated by more than 450 km consist of one oblique and one vertical path.

6.4.5 Summary and Discussion of Correlation Analysis

In winter, both daily and running-mean values give high correlation coefficients for all station separations. The deviations from the running-means are well correlated only for distances of less than 450 km and the correlation coefficient decreases rapidly with increasing station separation beyond this limit. The rate of change of correlation coefficient with
TABLE 6.7 Correlation coefficient for the deviations of the
daily values from the seven day running means during 1956

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<tr>
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<td>.05</td>
<td>.15</td>
<td>-.09</td>
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<td>.38</td>
<td>.46</td>
<td>.08</td>
<td>.11</td>
<td>.40</td>
</tr>
</tbody>
</table>
Figure 6.35: Variation of the correlation coefficient of the "difference" absorption values with station separation for 1960.
distance for daily and running mean values are approximately linear but for the "difference" values the variation is also dependent on the nature of the circuit.

During the equinox months, excellent correlation is obtained for all forms of the data, although, as in the case of the winter months, the correlation of the deviations of the running means decreased markedly for separations in excess of 450 km. The variation with station separation exhibits the same general trends as during the winter.

In summer both the daily values and the deviations from the running means show poor correlation, which is only slightly improved for the running mean values. No systematic change of correlation coefficient with distance can be detected during summer.

The high correlation for daily and running mean values in winter indicates that the disturbances which persist for several days cover large areas of the ionosphere. Similar effects are observed for the "difference" results over short paths, but a decrease in $r$ is found for separations greater than 450 km. Correlation between oblique incidence paths are generally better than that for mixed oblique and vertical incidence paths. The oblique incidence reflection heights lie within the D region and thus good correlation for such paths could result from the stable nature of this layer. Alternatively the vertical incidence absorption may contain a large deviative contribution which could be responsible for the marked fluctuations.
An analysis by Jones (1965) of the correlation of the 2 MHz absorption measured at Slough and Swansea reveals that the correlation of the non-deviative contribution to the total absorption is higher than the coefficients determined for the total absorption, again suggesting that the D region is either highly stable or that any irregularities are widespread.

For the equinox months, the correlation coefficients are, for the most part, very high for all forms of data used. Therefore the excellent agreement of the daily values is not due entirely to the large seasonal changes in the zenith angle occurring at this time. This is also evident from the striking similarities in the deviations from the running-means for the various stations. Furthermore, the small increases in correlation coefficient of the running-means compared with the daily values is less than would be expected if the variations were due entirely to the solar zenith angle changes.

During the summer months, the correlation coefficients obtained from both the daily and running mean data are extremely low. The value of r for the means are only slightly greater than for the daily values. These results, together with the poor agreement between the deviations from the means indicates that neither the day to day fluctuations nor the long term changes during the summer show any consistent behaviour. As mentioned previously the values of the summer correlation coefficients are in agreement with those of Rawer.

Piggott (1955) has however suggested that the low
correlation between absorption values measured at widely separated stations is a consequence of the different experimental techniques used. It seems unlikely that consistently low values of $r$ would be obtained only in one season if due to the experimental errors alone. The approximately linear variation of correlation coefficient with distance revealed by the present study would be unlikely to occur if the data from each station contained large and variable sampling errors.

Clearly some experimental errors will be present in the data used and could partly account for the poor correlation in summer. For the shorter paths it has been possible during the winter and equinox to reproduce similar high values of $r$ to those determined by Piggott from Slough and Swansea absorption results.

The results of this correlation analysis are of some importance in predicting propagation conditions over oblique incidence circuits. It appears that the absorption variations on any given oblique propagation path are highly correlated with those on similar but different circuits.
Chapter 7

A Comparison of Calculated Propagation Characteristics with Experimental Observations

The experimental measurements of absorption and angle of arrival have been discussed in chapter 6 and this section presents a comparison of these observations with results obtained from ray tracing and prediction calculations.

7.1 Ray Tracing Calculations

A ray tracing program based on the Booker quartic equation has been written for the Leicester computer. This program has been used in conjunction with various ionospheric models to evaluate the absorption and mode structure for circuits over which experimental results exist.

7.1.1 Ionospheric Models

In order to calculate these parameters, a knowledge of the ionospheric electron density and collisional frequency profiles is required. The electron density profiles of the lower ionosphere adopted for the present investigation are due to Deeks (1966) and Smith (1967) and vertical incidence ionograms were analysed to provide the electron density height distribution, \( N(h) \), at heights above 100 km. The height levels of these profiles necessitates an extrapolation of the \( N(h) \) curve in the range 95-105 km. A typical example of these composite profiles is given in Figure 7.1 which illustrates three possible types of extrapolation.

Ray tracing and prediction techniques are simplified
by assuming an electron density distribution which can be represented analytically by both semi-parabolic and Chapman distributions.

The mono-energetic collisional frequency profile has been deduced from the CIRA model atmosphere following the procedure of Thrane and Piggott (1966). However, it is well known that the collisional frequency of the electrons is a function of their velocity, \( v \), and \( P h_{\text{eff}} \) (1959), and a modification of the Appleton-Hartree expression to allow for this effect has been given by Sen and Wyller (1960). If the mono-energetic collisional frequency, \( \omega m \), is less than the angular wave frequency and the angular gyrofrequency, as is the case for HF propagation, the complicated expressions for \( \omega m \) given by Sen and Wyller can be replaced by an effective collisional frequency, \( \omega \text{ eff} \), where

\[
\omega \text{ eff} = \frac{\omega m}{2} \tag{7.1}
\]

This approximation is valid for HF propagation at heights above about 60 km where \( \omega m \) is of the order of \( 10^6/\text{sec} \).

The variation of \( \omega \text{ eff} \) with height has been determined using equation 7.1 up to 130 km. It is necessary to extrapolate the profile since few measurements of collisional frequency are available above this level. Although errors are introduced by this procedure, the absorption appears to be relatively insensitive to variations in \( \omega \text{ eff} \) at F region heights.

7.1.2 Accuracy of the Ray Tracing Program

The accuracy of the Booker ray tracing program.
has been checked by comparing the results with those obtained by other methods of analysis and both experimental and analytical models of the ionosphere were employed for these comparisons.

The path length and absorption for a frequency of 2.4 MHz, propagated through an experimentally determined N(h) distribution at various angles of elevation were calculated with a Haslegrove program written at ESSA/ITSA Boulder. The analysis was repeated with the Booker quartic program and the results are presented in Table 7.1. A feature of the Booker method is the ability to vary the incremental step length along the ray path. The step length can either be fixed or progressively reduced as the reflection level is approached and the results of calculations for which these two procedures were adopted are also included in Table 7.1.

Quasi-parabolic layer profiles of the type discussed by Croft and Hoogasian (1968) were employed in further tests of the program accuracy (Table 7.2). Exact analytical solutions can be calculated for the ground range of a radio wave propagated via a quasi-parabolic layer and models of this type can therefore provide an estimate of the error in the ranges derived from the Booker method. The ground ranges for frequencies (f), between 2.5 and 10 MHz at angles of elevation of 5 to 20° have been calculated for a quasi-parabolic layer with a vertical critical frequency (fc) of 5 MHz. Suitable modifications have been made to account for the effects of the earth's curvature.

The results of these comparisons can be summarised as
### Table 7.1: Synopsis of Results Obtained from Various Ray-Tracing Programs, Using the Deeks March Equinox Midday Sun-Spot Minimum Profile up to 90 km and a Leicester Ionogram for the Same Conditions Above 90 km

(Least-Earth Propagation, Ordinary Wave, Transmitter Location U.K., Frequency 2.4 MHz, Gyrofrequency 1.2 MHz)

<table>
<thead>
<tr>
<th>Method</th>
<th>Haselgrove</th>
<th>Booker Variable Step Length</th>
<th>Booker 1 km Step Length</th>
<th>Booker 2 km Step Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle of Elevation Degrees</td>
<td>Ground range km</td>
<td>Absorption km db</td>
<td>Ground range km</td>
<td>Absorption db</td>
</tr>
<tr>
<td>10</td>
<td>945</td>
<td>110</td>
<td>936</td>
<td>112</td>
</tr>
<tr>
<td>15</td>
<td>642</td>
<td>104</td>
<td>634</td>
<td>105</td>
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<td>89</td>
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<tr>
<td>40</td>
<td>227</td>
<td>90</td>
<td>223</td>
<td>91</td>
</tr>
<tr>
<td>Elevation angle degree</td>
<td>$f/f_c = 0.5$</td>
<td>1.0</td>
<td>1.5</td>
<td>2.0</td>
</tr>
<tr>
<td>------------------------</td>
<td>---------------</td>
<td>-----</td>
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</tr>
<tr>
<td></td>
<td>Ground range km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Analytical</td>
<td>Booker</td>
<td>Analytical</td>
<td>Booker</td>
</tr>
<tr>
<td>5</td>
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<td>1874</td>
<td>1932</td>
<td>1874</td>
</tr>
<tr>
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<td>1332</td>
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<td>1020</td>
</tr>
<tr>
<td>20</td>
<td>794</td>
<td>787</td>
<td>817</td>
<td>810</td>
</tr>
</tbody>
</table>
follows:

a) **Experimental Profile**

The Booker and Haslegrove results differ by less than 2% in ground range and 3% in absorption, provided the step length of the Booker program is less than 1 km.

b) **Analytical Profile**

The Croft and Booker procedures agree to better than 2% in ground range for all cases considered but no comparison of absorption was possible. Small errors are likely to occur due to the differing methods of interpolating the electron density and collisional frequencies.

7.1.3 **Ray Tracing through Semi-Analytical Ionospheres**

The E and F regions of the ionosphere can be adequately represented by Chapman like profiles, but this type of model does not apply to the D region. On this basis, models consisting of a D region represented by a Deeks profile and E and F regions by Chapman layers have been constructed and details of these model ionospheres is given in Table 7.3.

A Deeks summer noon D region has been fitted to profiles 168 and 217 of Table 7.3, and the variations of ground range with angle of elevation assuming 1 hop propagation for a frequency of 6.09 MHz propagated through this profile is shown in Figure 7.2a. The cusp for profile 168 in this Figure is probably due to the rapid increase in reflection height for small changes in
### TABLE 7.3 Analytical Models of the ionosphere

<table>
<thead>
<tr>
<th>Profile Number</th>
<th>E Layer</th>
<th>F1 Layer</th>
<th>F2 Layer</th>
<th>Method of combining the layers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>foE MHz</td>
<td>hm km</td>
<td>H km</td>
<td>foF1 MHz</td>
</tr>
<tr>
<td>168</td>
<td>3</td>
<td>120 km</td>
<td>15 km</td>
<td>6</td>
</tr>
<tr>
<td>215</td>
<td>3</td>
<td>120 km</td>
<td>15 km</td>
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</tr>
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<td></td>
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<td></td>
</tr>
<tr>
<td>216</td>
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<td>15 km</td>
<td>-</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>217</td>
<td>3</td>
<td>120 km</td>
<td>15 km</td>
<td>6</td>
</tr>
<tr>
<td>242</td>
<td>2</td>
<td>120 km</td>
<td>15 km</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 7.2 Variation of ground range and absorption with angle of elevation for profiles 168 and 217 of Table 7.3.
elevation angle when the ray just penetrates the E region and passes through the valley in this profile. The slight kinks in the curve of Figure 7.2a corresponding to profile 217 could result from the discontinuities in the profile introduced by extrapolating between the various layers, rather than any definite feature of the profile.

The approximately constant electron density around the E region maximum gives rise to rapid increases in absorption for angles of elevation between 15 and 25° (Figure 7.2b). For this range of take-off angles a more rapid increase in the absorption is obtained from profile 168 than for 217. For frequencies slightly in excess of the E region critical frequency, considerable attenuation will occur in the valley region of profile 168 whereas profile 217 has no such feature. The effect of the valley soon disappears for angles of elevation which penetrate to heights for above the E region maximum. Profiles 168 and 217 are not representative of winter conditions when no F1 region is present but are better approximations for the summer and equinox periods.

An interesting result which is apparent from Figures 7.2 and 7.3 is that the total ionospheric attenuation for propagation via the 2 hop F mode is sometimes less than for the 1 hop F. On a practical communications circuit, the ground loss would also have to be considered therefore increasing the total loss for the 2 hop F path.

Ray tracing calculations for 6.09 MHz propagated
Figure 7.3  Variation of ground range and absorption with angle of elevation for profile 215 of Table 7.3.
through a composite N(h) distribution consisting of profile 215 and a Deeks winter noon D region yields the variations of ground range and absorption given in Figure 7.3a and b respectively. To provide a more realistic winter N(h) distribution no F1 region has been included in this profile and the E and F2 regions have been joined tangentially by a straight line. This interpolation has a gradual increase in electron density with height between the layers and this results in the cusp present between elevation angles of 20 and 35° in Figure 7.3a. A similar feature is evident in Figure 7.3b in the form of a marked increase in absorption at frequencies which just penetrate the E layer.

Figure 7.2a and 7.3a indicate that for a small range of distances there are three angles of elevation at which propagation is possible for any particular path length within this range. These different modes correspond to low and high E region reflections and the low F reflection. It is clear from Figures 7.2b and 7.3b that the greatest absorption occurs for the high angle E region mode.

Profile 216 in which the height of the maximum electron density is raised to 400 km, shows similar features to profile 215 discussed above. For this profile however the cusp in the variations of ground range and absorption with angle of elevation are much more pronounced (Figures 7.4a and b).

The profiles discussed above are only representations of the type of ionospheric distributions which have been measured
Figure 7.4 Variation of ground range and absorption with angle of elevation for profile 216 of Table 7.3.
by rocket experiments and the critical frequencies and assumed layer heights are not necessarily applicable to all ionospheric conditions.

Chapman profiles for winter and summer conditions at European latitudes have been constructed from the monthly mean critical frequencies and layer heights for the months of June and December, as published in the Bulletin of the Radio and Space Research Station, Slough. Scale heights of 15, 30 and 50 km for the E, F1 and F2 regions respectively have been assumed and the lower ionosphere represented by the Deeks D region profiles for the relevant midday conditions, suitably extrapolated to fit the upper ionospheric profiles. This type of model has been justified by Croft (1965), who found that the electron density profiles in the E and F regions as measured by rockets, corresponded closely to straight line extrapolations between Chapman layers (Figure 7.5).

Figure 7.6 illustrates the variation of ground range and absorption for a typical Chapman winter profile, with and without a valley between the layers. The variations of these parameters for the corresponding summer profile are shown in Figure 7.7. The large cusps resulting from the straight line extrapolation in summer are caused by the relatively slow increase in electron density with height above the E region maximum.

7.1.4 Ray Tracing using Experimental Profiles

The ionospheric profiles determined from vertical incidence ionograms represent the actual electron density
Figure 7.5  Chapman layer electron density profile extrapolated between the different regions.
Figure 7.6 Variation of absorption and path length with elevation angle for profiles with and without valleys.
Profile with a valley between the E and F layers.

Profile without a valley between the E and F layers.

Figure 7.7 Variation of ground range and absorption with angle of elevation for a Chapman summer profile and a frequency of 6.09 MHz.
distributions at the time of the observations. The majority of ray tracing calculations have therefore been carried out using profiles of this type.

The variations of ground range and absorption with take-off angle, for a frequency of 6.09 MHz propagated through a typical summer noon electron density distribution, are illustrated in Figure 7.8. These variations are similar to those calculated for the analytical profiles, but differences occur in the absolute magnitudes. The cusps or points of inflexion in these curves arise in the same manner as previously discussed for analytical profiles with straight line tangent approximations. The magnitude of the increases in absorption near the cusps is dependent on the rate of change of electron density with height in these regions. The experimental profiles are not restricted by the linear interpolation in this height range and are therefore more suitable for accurate calculations of propagation characteristics.

7.2 Comparison of Ray Tracing and Experiment

Electron density profiles have been derived from vertical incidence ionograms for different times of day and seasons. Calculations of the absorption on the various modes propagated by these profiles, for the circuits on which experimental data is available, will now be discussed.

7.2.1 Calculations for a 2.61 MHz frequency propagated over different Paths

The 2.61 MHz transmitter at Norddeich, West Germany, has been monitored at Leicester, Lindau and Neustrelitz and
Figure 7.8 Variation of ground range and absorption with angle of elevation for an experimental summer noon profile (Frequency = 6.09 MHz).
absorption data are available for these three paths. The ionospheric absorption for these paths has been calculated for various times of day and season from the D region profiles of Deeks and Smith together with E and F region distributions deduced from ionograms.

The calculated values of absorption for the three low HF oblique paths, together with the absorption measured during typical equinox conditions are shown in Figure 7.9 and the electron density profile in Figure 7.10. The agreement between the calculated and measured results is extremely good for all these paths. For the Norddeich-Leicester and Norddeich-Neustrelitz circuits, the profile extrapolation marked (b) in Figure 7.10 produces greater absorption than profile (a). The "best-fit" for the Norddeich-Lindau data is again obtained with profile (b), but in this case the absorption is less than that due to (a). The equivalent vertical frequency of the Leicester and Neustrelitz paths are such that reflection will occur from that part of the profile (a) where a steep gradient of electron density exists, thus giving rise to "mirror-like" reflections. The decrease in the total electron content in profile (b) in this height range, is offset by the decrease in dN/dh and can therefore result in an increase in absorption for these paths. (Thomas (1968) has emphasised the dependence of the reflection coefficient on the quantity \( \gamma / \frac{dN}{dh} \). For the Norddeich-Lindau circuit, path length 296 km, the reflection level lies above the steep gradient and therefore there is no evidence
Figure 7.9 Comparison of measured and calculated absorption for the three 2.61 MHz paths.
Figure 7.10 Equinox electron density profile with three extrapolations between the D and E regions.
of the gradient effect. In all cases, extrapolation (c) provides less absorption than the other two extrapolations. Therefore during the equinox months the electron density profile for the lower ionosphere as described by model (b) of Figure 7.10 is a very good approximation to the true electron density distribution.

The diurnal variations of absorption during summer, were calculated for all the 2.61 MHz paths using the profiles of Figure 7.11 and the results of these calculations for profile (b) are in good agreement with the experimental values as shown in Figure 7.12. For the two longer paths, the dependence of absorption on the electron density gradient at the reflection level is again evident, since the absorption calculated with profile (a) is less than with profile (b) although the electron content in the former profile is greater. The shorter Norddeich-Lindau path, where the reflection level is above the sharp gradient of electron density, reveals a systematic increase in absorption with increase in electron content therefore exhibiting no effects which can be ascribed to the steep gradients below the height of reflection (Figure 7.12).

The winter electron density profile due to Deeks (1966) was evaluated for ionospherically quiet conditions and will therefore contain none of the excess ionisation associated with the winter anomaly. The calculated and measured values of the 2.61 MHz absorption in winter are presented in Figure 7.13 and it is apparent that the electron density profiles of
Figure 7.12 Comparison of the measured and calculated values of absorption for the three 2.61 MHz paths (Summer).
Figure 7.13 Comparison of measured and calculated values of absorption for the three 2.61 MHz paths (Winter).

---

Theoretical
Experimental

Norddeich/Lindau

Norddeich/Meistrelitz

Norddeich/Leicester

Absorption dBs

8  10  12  14  16
Figure 7.14 contain insufficient ionisation to account for the high winter values of absorption.

Smith et al (1967) using a wave interaction technique have measured the D region electron density distributions at a range of solar zenith angles. The D region profiles for equinox and summer noon conditions have been combined with the corresponding ionogram profiles for ray tracing analysis. The absorption calculated for these profiles and that obtained assuming a Deeks D region model are presented in the following table, together with the experimental values for the various paths.

Summer noon $\chi = 28^\circ$

<table>
<thead>
<tr>
<th>Absorption (dB)</th>
<th>Norddeich to Neustrelitz</th>
<th>Norddeich to Lindau</th>
<th>Norddeich to Leicester</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>36</td>
<td>30</td>
<td>48.5</td>
</tr>
<tr>
<td>Deeks (a)</td>
<td>32</td>
<td>36</td>
<td>43</td>
</tr>
<tr>
<td>Deeks (b)</td>
<td>37.5</td>
<td>31.5</td>
<td>47</td>
</tr>
<tr>
<td>Deeks (c)</td>
<td>26.5</td>
<td>23</td>
<td>39</td>
</tr>
<tr>
<td>Smith (a)</td>
<td>55</td>
<td>48</td>
<td>64</td>
</tr>
<tr>
<td>Smith (b)</td>
<td>49</td>
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<td>59</td>
</tr>
<tr>
<td>Smith (c)</td>
<td>43</td>
<td>38</td>
<td>54</td>
</tr>
</tbody>
</table>
Equinox noon $\chi = 54^\circ$

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>23</td>
<td>28.5</td>
<td>41.5</td>
</tr>
<tr>
<td>Deeks (a)</td>
<td>24</td>
<td>32</td>
<td>40.5</td>
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<tr>
<td>Deeks (b)</td>
<td>26.5</td>
<td>27</td>
<td>32</td>
</tr>
<tr>
<td>Deeks (c)</td>
<td>20</td>
<td>21.5</td>
<td>29</td>
</tr>
<tr>
<td>Smith (a)</td>
<td>51</td>
<td>46</td>
<td>68</td>
</tr>
<tr>
<td>Smith (b)</td>
<td>44</td>
<td>40</td>
<td>59</td>
</tr>
<tr>
<td>Smith (c)</td>
<td>40</td>
<td>31</td>
<td>50</td>
</tr>
</tbody>
</table>

The extrapolation between the Smith profiles and the corresponding E and F region distributions are similar to those already discussed for Figure 7.10.

The absorption calculated from the Smith profiles is much larger than that evaluated from the Deeks distributions and determined by experiment, and the values from these latter profiles approximate very closely to experimental observations.

7.2.2 Calculation of Absorption for the 6 MHz Paths

In this section, the angles of arrival and the absorption values for the Luxembourg-Leicester, Bremen-Leicester and Berlin-Leicester paths are compared with the calculated mode structure.

In the previous section it was established that the Deeks profiles provided the better model of the lower ionosphere for absorption calculations and these profiles have therefore been exclusively used for the analysis of the 6 MHz paths.

The absorption calculated from extrapolations of
type (a) and (b) of Figure 7.10, for the lower ionosphere, during the equinox periods, are in good agreement with experiment as shown in Figure 7.15. For the Luxembourg and Bremen paths, the absorption values plotted are those corresponding to the $1 \times F$ mode. The absorption of the alternative propagation mode, $1 \times E$, is always in excess of that for $1 \times F$ for all the profiles reproduced in Figure 7.10. The ray tracing calculations indicate 3 active modes of propagation for these circuits ($1 \times E$, $1 \times E$ and $1 \times F$), the second $1 \times E$ corresponding to the high angle or Pederson ray. However the absorption of this mode is far in excess of the other two and it is unlikely that this mode will be detected by the angle of arrival experiment.

The ray tracing program indicates that for the Berlin-Leicester circuit, the least absorbed mode is $2 \times F$ and the calculated values for this mode have been superimposed on the experimental data in Figure 7.15. The absorption for the $1 \times F$ mode is much larger than for the $1 \times E$ and $2 \times F$ modes, since the equivalent vertical frequency of this mode is approximately equal to the $E$ critical frequency. The attenuation of the $1 \times E$ mode only slightly exceeds that for $2 \times F$ propagation but the receiving antenna gain at Leicester increases with angle of elevation and therefore the dominant mode will be $2 \times F$.

In the summer months, changes in the dominant mode occur during the day for the Bremen and Luxembourg paths and these changes are detectable in the calculated absorption. Between approximately 1000 and 1400 UT, the $E$ region...
Figure 7.15  Comparison of the experimental and calculated values of absorption for the three 6 MHz paths (Equinox).
critical frequency increases to a value nearly equal to the equivalent vertical frequency of the 1 x F mode, hence marked attenuation will occur for the mode at these times. The experimental and calculated values of absorption for the dominant mode on the three 6 MHz frequencies are compared in Figure 7.16 and to account for this diurnal pattern, changes in the dominant mode for the two shorter paths must occur. The dominant mode throughout the day for the Berlin-Leicester path is 2 x F and the calculated absorption variation for this mode agree well with the experimental results.

Angle of arrival measurements during summer indicate that on all the high frequency paths, four propagation modes are present throughout the day 1 x E, 1 x E, 1 x F and 2 x F, the second 1 x E mode corresponding to the high angle ray. Most of these modes are present in the ray tracing results although in certain cases model (a) of Figure 7.11 gives only two or three active.

The calculated values of absorption for the winter months are less than these determined from experiment. It appears therefore that an increase in electron density in the ionosphere is required although the calculated structure agrees well with experiment.

7.2.3 Summary of the Comparison between Ray Tracing and Experiment

The comparison of the experimental data with the ray tracing calculations yields good agreement in both mode structure
Figure 7.16 Comparison of the experimental and calculated values of absorption for the 6 MHz paths (Summer).
and absorption for the equinox months. Furthermore the electron density extrapolation of type (b) in Figure 7.10 and 7.11 give values of absorption which are more consistent with the experimental observations than types (a) and (c).

Calculations using the D region profiles measured by Smith et al (1967) produce too much absorption on all modes of propagation for all frequencies. Considerably better agreement between calculated and measured values is obtained for the Deeks model of the D region. The profiles postulated by Deeks (1966) are consistent with a long series of experimental VLF observations on short paths within the U.K. and therefore represent the mean ionospheric electron density distribution for various seasonal conditions in these latitudes. The measurements by Smith only determine profiles relevant to a specific time on a particular day in the Southern hemisphere and are therefore not representative of the general D region distribution for temperate latitudes in this hemisphere.

No attempts have been undertaken to incorporate the day to day fluctuation of absorption observed experimentally and only average seasonal conditions have been considered.

The collisional frequency values for the winter and equinox periods have been increased by 60% for the summer to account for the seasonal variation (Thrane and Piggott (1966)).

7.3 The Prediction of Ionospheric Propagation Characteristics

Methods are available for predicting the mode structure and absorption losses on oblique propagation paths, from a knowledge of
the relevant ionospheric parameters. The results of applying various prediction techniques to the propagation paths for which experimental data are available and the comparison of calculations with experiment are discussed in this section.

Two such methods, one due to Piggott (1959) and the other to Lucas and Haydon (1966), have been used to determine the mode structures and absorption for the oblique circuits monitored at Leicester. Furthermore, wherever possible, predictions have been made assuming a range of antennae gains at the receiver, thus the predictions can be compared with experimental observations of both angle of arrival and absorption.

7.3.1 Active Modes

The accuracy of the signal strength and mode structure determined by prediction methods, depends to a large extent on their ability to provide realistic models of the ionosphere at any particular time. The Piggott method provides detailed information regarding each mode of propagation whereas only dominant mode information is available from the Haydon analysis. The monthly mean critical frequencies of the ionospheric layers, as published by Radio and Space Research Station, Slough, have been used in conjunction with the fixed reflection heights assumed in the prediction methods to determine the likely propagation modes for the four oblique circuits under consideration. A comparison of these active modes with those of the Piggott analysis will provide an indication of the accuracy of the ionospheric predictions.
The Norddeich-Leicester Circuit

The equivalent vertical frequencies of the 1 x E and 1 x F modes of propagation for this circuit are 1.0 and 1.9 MHz respectively and therefore the 1 x E mode should be propagated when the E region critical frequency, $f_0E$, or the blanketing Sporadic E frequencies $f_bEs$, exceeds 1.0 MHz. The lowest frequency of most vertical incidence ionogram is 1.5 MHz and therefore the exact times at which $f_0E$ or $f_bEs$ is below 1.0 MHz are not known and, however, it has been assumed that critical frequencies are always in excess of this value during daytime.

The 1 x F mode will not be propagated if $f_0E$ or $f_bEs$ is in excess of 1.9 MHz and the critical frequency of the F layer ($f_0F2$) must be greater than this to support IF propagation. Higher order F region modes have not been considered for this path as in most cases the absorption losses for such modes is excessive.

The times for which the 1 x E and 1 x F modes are active, calculated by the two methods discussed above, for the period 1965-1966 have been compared in Figure 7.17, illustrating the good agreement between these two types of analysis.

The Luxembourg-Leicester Circuit

The path length for this circuit is 610 km, consequently the 1 x E mode will be active if $f_0E$ or $f_bEs$ is greater than 2 MHz. The 1 and 2 hop F region modes will propagate if $f_0F2$ is greater than 4.15 or 5.3 MHz respectively provided that $f_0E$ and $f_bEs$ is not in excess of these values.
Figure 7.17 Comparison of the periods for which the 1× E and 1× F modes are active for the Norddeich-Leicester path.
A comparison of the periods for which these modes are active, using the techniques mentioned above, is presented in Figure 7.18 and it is clear that agreement for the 1 x E mode is better than for the other two modes, which can have large discrepancies in the times for which they are active.

The angle of arrival measurements discussed in Chapter 6 indicate that during the winter only the 1 x E and 1 x F propagation modes are present during the day, whereas in summer there are four active modes corresponding to 1 x E, 1 x E, 1 x F and 2 x F. Both the predictions of Piggott and the analysis of the Slough data show that in winter only the 1 x E and 1 x F modes propagate and agree with the experimental observations. In summer however, propagation by the 2 x F mode is predicted for shorter periods than are found in practice. The high angle E region mode evident in the angle of arrival measurements is not included in the prediction methods as the attenuation on this mode is large compared with the others.

The high angle E mode, Figure 6.26, is only measured for certain times at the equinox months and the propagation of this mode is dependent on the shape of the profile between the E region maximum and the F layer. The screening of the 1 x F mode by the E region around noon, as predicted by Piggott and the Slough data, is not evident from experiment and also the 2 x F mode predicted for this circuit at these times was not visible on the angle of arrival equipment.
Figure 7.15: Comparison of the periods for which the $1 \times E$, $1 \times F$, $2 \times F$, and $2 \times F$ modes are active (Luxembourg-Leicester).
The Bremen-Leicester Circuit

Figure 7.19 illustrates the periods for which the 1 x E, 1 x F and 2 x F propagation modes, as predicted by Piggott and deduced from experimental measurements of layer critical frequencies are active. Better agreement is obtained for E region propagation than for F region modes.

The similarities existing between the Luxembourg and Bremen circuits are evident from a comparison of Figures 7.18 and 7.19 and the agreement between the prediction of active modes and the angle of arrival measurements is the same as for the Luxembourg-Leicester path.

The Berlin-Leicester Circuit

Screening of the 1 x F and 2 x F modes by the E region will occur when fo E or fb Es is greater than 3.0 and 4.6 MHz respectively. The F region modes will be active provided the F region critical frequency is above, and the E region critical frequency below, these values. Propagation via the 1 x E mode will be possible as long as fo E or fb Es is greater than 1.3 MHz.

The comparison of the periods for which the various modes are active, using the Piggott method and experimental values, is shown in Figure 7.20. Although good agreement is found for the E mode, the F region periods are less well correlated.

The comparison of the angle of arrival measurements for the Berlin-Leicester path Figure 6.28 and the prediction of active
Figure 7.19 Comparison of the periods for which the 1× F, 1× F and 2× F modes are active (Bremen-Leicester).
modes Figure 7.20 reveal than in winter 1 x E and 2 x F modes are in good agreement but that no 1 x F mode is present from the experimental results and the prediction of no F region screening is in error for this time. In equinox months 1 x E, 2 x F and 3 x F are measured throughout the day as predicted, and there is agreement between experiment and predictions for the propagation times for the 1 x F mode. During summer the predictions indicate complete screening of the 1 x F mode during the day, but this mode is measured throughout the day on the angle of arrival equipment, although of greatly reduced amplitude. It would therefore appear that the screening effects of the E region are overestimated in summer, but underestimated in winter and the best agreement between predictions and experiment is obtained in the equinox periods.

From these comparisons it appears that the prediction of the active periods for 1 x E propagation agree well with experimental values. The times at which the F region modes are present show certain discrepancies which could arise from inaccuracies in the F layer MUF or to an under estimation of the predicted E layer critical frequency in Piggott's method.

Since no allowance is made for the existence of sporadic E in Piggott's method, the E layer screening effects will be minimised and could introduce significant errors in the predicted mode structure, especially during summer.
Figure 7.20: Comparison of the periods for which the $1 \leq n \leq 4$ and $5 \leq n \leq 9$ modes are active (Merlin-Keck data).
The dependence of the F region modes at night on the F layer MUF, can introduce larger errors in Piggott's method since this prediction technique does not calculate the F.MUF factor.

7.3.2 Dominant Modes

The dominant propagation mode for any circuit is the active mode which will produce the largest signal at the receiver input. It is not necessarily the mode which suffers the least ionospheric attenuation since the gain of the receiving and transmitting antennae and total ray paths of the various modes will influence the total received signal strength.

The dominant propagation modes for the paths mentioned in the previous section were predicted by the methods of Piggott and Lucas and Haydon.

The Norddeich-Leicester Circuit

The comparison of the dominant modes for this path are given in Figure 7.21 and it is evident that there are some discrepancies between the two methods. Although the general agreement is fairly good, the prediction of multi-hop F region propagation for this circuit would appear to be in error, since at the times when these modes are predicted, the E layer critical frequency is in excess of the working frequency and must therefore screen the F region modes.

The Luxembourg-Leicester Circuit

The dominant modes of the Luxembourg-Leicester and Luxembourg–Canewdon paths as predicted by Piggott, and by Haydon for the
Luxembourg-Leicester path only (Figure 7.22) are in good agreement for 1966, although in contrast to the predictions for the Norddeich-Leicester circuit, Haydon predicts the 1 x E to be dominant for larger periods than Piggott. These results also reveal little difference in the dominant mode for the Leicester and Canewdon receiving sites.

The Bremen-Leicester Circuit

The Piggott predictions for the circuits from Bremen to Leicester and Canewdon and by Haydon for Bremen to Leicester (Figure 7.23) again are in good agreement at all times. Identical dominant modes of propagation are obtained for the Leicester and Canewdon sites.

The Berlin-Leicester Circuit

Unfortunately no predictions of the dominant mode using the Haydon technique are available for this circuit. The results of Piggott's method for the Leicester and Canewdon receiving sites are presented in Figure 7.24. Differences in the likely dominant mode are evident and are undoubtably due to the complete dissimilarities of the receiving antennae at these sites.

The dominant mode for some of the above paths have been predicted with the aid of the Australian prediction method (George (1967)). The results of the calculation are compared with those of the Piggott and Haydon procedures in Figures 7.25 to 7.28 for the four oblique paths considered. In winter there is good agreement between the results of Piggott and the

123.
Haydon for the Leicester receiving site.

Piggott for the Canewdon receiving site

Piggott for the Leicester receiving site.

Figure 7.22 Comparison of the dominant for the Luxembourg to Leicester and Canewdon paths.
Figure 7.25 Comparison of the dominant mode for the Bremen-Leicester path 1965-1966.

HAYDON for the Leicester receiving site.

PIGGOTT for the Leicester and Conewdon receiving sites.
Figure 7.24 Comparison of dominant mode for the Berlin-Leicester and Berlin-Canewdon paths (1965-1966).
Figure 7.25  Comparison of the dominant mode for the Norddeich-Leicester path using the Australian prediction method.
Figure 7.26 Comparison of the dominant mode for the Luxembourg-Leicester path using the Australian prediction method.
Figure 7.27  Comparison of the dominant mode for the Bremen-Leicester path using the Australian prediction method.
Figure 7.28 Comparison of the dominant mode for the Berlin-Leicester path using the Australian prediction method.
"Australian" method for all paths. During summer, however, major discrepancies occur for the two shorter 6 MHz circuits, the Australian technique predicting the 1 x F mode dominant throughout the day. Better agreement is obtained for the Berlin and Norddeich-Leicester circuits.

From these comparisons it is concluded that the methods of Piggott and Haydon are in agreement for all the propagation paths.

7.3.3 Signal Strength of the Dominant Modes

The Piggott and Haydon prediction techniques also include provisions for evaluating the ionospheric absorption losses for the dominant modes. It is of some interest to compare the values predicted by the two methods.

The Norddeich-Leicester Circuit

The absorption losses determined from the various prediction techniques for the Norddeich-Leicester circuit for June and December 1966 are compared in Figure 7.29 with experimental observations for this path during these months. The absorption predicted by Haydon's method is far greater than calculated by the other techniques and the experimental values for the summer and equinox months. In winter however this method produces least absorption. During equinox and summer the agreement between experiment and the methods of Piggott and George is of the order of 10-15% indicating that these analytical procedures can provide reliable estimates of the absorption losses for this path.
Figure 7.29 Comparison of predicted and measured diurnal absorption variations for the Norddeich-Leicester path (Summer and Winter).
A further comparison of the predicted noon absorption values and those determined experimentally is shown in Figure 7.30, where apart from times near the equinox large differences occur between experiment and the prediction of Haydon. During the winter months February and November, much better agreement is obtained in spite of the multiple hop F modes, 3 x F, predicted by the Haydon method and the omission of the winter anomaly effects in the prediction analyses.

The Luxembourg-Leicester Circuit
Absorption values calculated from the methods of Piggott and Haydon for June and December are shown together with the experimental values in Figure 7.31. The agreement in summer for all three sets of results is very good. The absorption predicted by the Australian method has also been included in Figure 7.31 and is considerably less than for the other values.

All the three prediction methods give approximately the same values of absorption in winter, but are more than 50% below the calculated values.

The variation of monthly mean noon absorption, determined experimentally for this path for 1965 and 1966, together with the predicted values of Piggott for the same period and those of Haydon for 1966, are illustrated in Figure 7.32. Remarkably good agreement is obtained between the experimental results and Piggott's values but the values of Haydon only agree with experiment for the equinox months and during the summer are 15-20% lower.

The variations of the absorption during the summer and equinox
Figure 7.30  Comparison of the predicted and measured noon absorption for the Norddeich-Leicester path
months predicted by Piggott follow the experimental trends very closely and it would appear that an overall increase of approximately 10% in the predicted values would provide an almost exact agreement with experiment.

The Bremen-Leicester Circuit

The comparison of the predicted and measured absorption values over this path for summer and winter conditions in 1966 are reproduced in Figure 7.33 and a similar comparison for the monthly mean noon values in Figure 7.34. The agreement between predictions and experiment is similar to those described for the Luxembourg-Leicester circuit. In the summer months, when the dominant propagation mode is $1 \times E$, the Haydon method underestimates the absorption on this mode, although much better agreement is obtained for $1 \times F$ propagation.

The Berlin-Leicester Circuit

As previously mentioned the only predictions available for this circuit are those of Piggott's method and these are compared with the experimentally observed diurnal and seasonal variations of absorption in Figures 7.35 and 7.36 respectively. A limited amount of data obtained from the Australian prediction technique is also included in Figure 7.35.

The agreement between experiment and both types of prediction for the diurnal variations of absorption in summer is extremely good. A close correlation is also obtained between the Piggott results and experiment in mid-winter, although from Figure 7.36 it is clear that during the second half of 1966 there is a marked
Figure 7.33  Comparison of experimental and predicted absorption for the Bremen-Leicester path in summer and winter.
Figure 7.34 Comparison of the predicted and measured noon absorption for the Beacon-Isleester path.
Figure 7.36  Comparison of the predicted and measured neon absorption for the Berlin-Leicester path.
increase in the absorption predicted by Piggott over the experimental values. These high values could, to some extent, compensate for the increase in the measured absorption due to the winter anomaly.

7.3.4 Summary of the Comparison between predicted and measured Absorption

In general the values of absorption calculated from the standard prediction techniques agree with the experimental results for the four circuits considered to within 10-15%. The field strengths calculated by the Piggott procedure generally give the best agreement with experimental observations although in certain instances good agreement is also obtained with the other methods. Although the predicted values for winter are self consistent it is clear that none of these techniques has in any way made allowance for the excessive absorption during this season. Discrepancies at this time may be expected as the winter anomaly is extremely variable, but it would not be difficult to incorporate these losses into a prediction analysis.

Varying degrees of accuracy are obtained with the Haydon technique since the absorption for the low frequency path is far in excess of the experimental values, although when the same propagation mode is present for the 2 shorter high frequency paths the calculated absorption is less than that measured. This apparent inconsistency is difficult to explain as it would be expected that the large absorption evident in an E region mode would also be present for the same mode propagated over different
paths.

The discussion of prediction techniques has been confined to the ionospheric absorption losses. For communication engineering purposes the prediction of received signal strengths is of much greater importance and most prediction methods included procedures for evaluating the additional sources of error e.g. in assessing aerial gains and the local noise levels.

The correlation between predicted and measured signal strengths should be less well defined than for the case of absorption due to the inclusion of the additional factors which will influence the overall signal level.

7.4 Comparison of the Experimental Absorption Results with those calculated using Ray Theory and Prediction Method

Suitable models of the ionospheric electron density distribution of the lower ionosphere have been constructed to account for the propagation of radio waves between 2.5 and 6.2 MHz up to distances of 1000 km for typical summer and equinox conditions. The absorption produced by these models, which are based on the D region electron density profiles of Deeks (1966) and E and F region distributions derived from vertical incidence ionograms, are in excellent agreement with the experimental data for the paths considered and with the angle of arrival measurements. The modes of propagation for frequencies which penetrate the E layer depend on the shape of the electron density profile between the E and F regions. Extrapolation of the electron density curve is necessary in this region even when using analytical models of the E and F layers and this can result in errors in
calculations using this type of model. Even with experimentally derived profiles ambiguities still occur in this region as most ionogram reduction methods assume a monotonically increasing electron density height profile and no allowance is made for the valley in the profile between the E and F regions.

For frequencies in excess of about 5 MHz, when F region propagation is an important factor, the electron density in the E region controls the absorption of these modes and it would therefore appear likely that the D region contribution to the total absorption would be adequately represented by a simple slab model. In most cases, the prediction of absorption for summer and equinox agree well with experiment, but for the lower 2.60 MHz path, the values calculated by the Haydon method are seriously overestimated and the validity of this technique for frequencies below 3 MHz must be in doubt.

The reasonable agreement between the results of the prediction method and experimental observation reveal that in most cases a more sophisticated prediction technique is not required although some modifications would provide even better agreement with experiment.
Chapter 8

Summary and Conclusions

An investigation of the absorption and angle of arrival of radio waves at frequencies in the range 2.5 to 6.2 MHz has been undertaken and experimental observations compared with ray tracing and prediction analyses. The absorption of the lower frequency, 2.61 MHz, is controlled by the D layer of the ionosphere and various models of this region have been analysed in an attempt to establish electron density distributions consistent with the experimental results.

For communications engineering purposes, prediction methods such as those of Piggott and Lucas and Haydon are used to provide a rapid evaluation of the ionospheric parameters and the resulting propagation characteristics, as opposed to the sophisticated ray tracing techniques which allow a more exact study of the propagation through any ionospheric model. With the advent of high speed computers ray tracing techniques can be utilised for prediction studies and thus the measured and predicted absorption values have been compared with those calculated by ray tracing for four oblique paths.

8.1 Comments on Experimental Results

In Chapter 7, the dependence of the measured absorption for a frequency of 2.61 MHz on the solar zenith angle changes was discussed and evidence of the effects produced by geophysical disturbances, such as solar and magnetic activity, was also presented.

The solar zenith angle variation of absorption is not that of a true Chapman region although a linear relationship between the diurnal values Log L and Log Cos \( \chi \) was obtained for all months, the
Chapman exponent $n$ being in the range 0.6 to 0.8. The winter increase in absorption was evident from the variation of monthly mean noon data which illustrated a semi-annual pattern, with minima in the equinoxes and maxima in summer and winter. The absorption results, supplemented with data from other stations, were compared with VLF observations during the winter period. The dissimilarity between the VLF and HF observations suggest that the ionisation enhancement responsible for the winter anomaly must occur at heights above 70-75 km. Furthermore the diurnal dependence of winter absorption on solar zenith angle is of the same form as during the summer and equinox months. Thus the enhanced ionisation exhibits the same type of solar control as the normal layers.

An attempt has been made to separate the absorption contributions of the upper and lower D regions, assuming the ionisation below 75 km to be constant throughout the day. The absorption contribution of the upper D region approximates more closely to the Chapman theory than the D region as a whole.

The 6 MHz paths indicate that the absorption is controlled by a layer of ionisation closely resembling a Chapman region although, as in the case of the lower frequency, the winter anomaly is again evident. The magnitude of this effect is far less than observed at 2.61 MHz, the increases in absorption being about 20% as compared with 50-125% for the lower frequency. The modes of propagation and their relative amplitudes were measured by means of the angle of arrival equipment. For the two shorter 6 MHz paths, changes in the dominant mode occur during the day in summer and these result in slight irregularities in the diurnal...
variations of absorption.

In the experimental determination of absorption the effects of the rapid fading of the received signal have been minimised by integrating the received signal. This does not completely remove the fading effects and a limited study of the variations of the integrated values of signal strength for the Norddeich-Leicester path shows that 80% of the values of signal strength are between +3 and -4 dB of the mean signal level. This represents an error of not more than 10% in the absorption results. During the night-time, larger variations occur due to scattering and partial reflections by the Es layer, but even during this period 80% of the signal strengths for Es reflections alone, lie within +4 and -6 dB of the mean level. When propagation by both E and F region reflections is present these limits are of the order of +10 and -15 dB, but if care is taken in isolating each mode the scatter is much reduced. Errors can also arise from the variation in virtual height from day to night when the Es reflections are used for calibration purposes. The virtual height during the day lies between 100 and 110 km but at night this can increase to 130 km. The errors resulting from these changes in reflection level are no more than 0.5 dB and are therefore small compared with the errors due to fading. For the 6 MHz paths, when E modes are propagated day and night, the calibration error due to these changes is 0.6 dB and when F reflections are present for both night and day the calibration value of signal strength is in error by not more than 1.5 dB. During the day, fluctuations of this magnitude can arise from fading and errors of 2-3 dB are likely in the measured values of absorption.
The variation of angles of arrival for a particular mode during the day and night is extremely small and any variation in the antennae gain can be neglected. If changes in mode do occur, as is possible between day and night conditions, allowance must be made for the differences in antennae gain.

8.2 Correlation of Absorption Variations at widely separated Stations

The comparison of absorption at separated stations reported in Chapter 6 indicates that during winter and equinox months good correlation exists up to distances of about 500 km and in some cases up to 750 km. In summer the similarity between one station and another was, in most instances, rather poor. It appears that the correlation coefficient between two oblique incidence paths is usually greater than obtained from a comparison of one oblique incidence and one vertical incidence path but separation can influence the conclusion.

It would therefore appear that the high correlation of the oblique paths, whose reflection level lies within the D region, could result from the stable nature of this layer. The vertical incidence paths are reflected at higher levels and the decreased correlation could arise from the deviative absorption in the E region or from the larger fluctuations which are present in this layer. The vertical incidence frequencies employed in the correlation analysis were 1.725 and 2.05 MHz and generally the lower frequency was in better agreement with the oblique path results. The reflection level of this lower frequency is approximately in the same height range as the oblique paths whereas the reflection level for 2.05 MHz is higher at about 133.
100-110 km. The agreement between oblique and vertical incidence absorption for frequencies reflected in the same height range indicates that the prediction from one circuit to another should be possible. This conclusion is supported by the remarkable similarity between the variation of the monthly mean noon absorption for the three 6 MHz paths. The absorption variations for the 2.61 MHz and vertical incidence paths are not always in good agreement and these discrepancies probably result from the deviative absorption contribution at vertical incidence.

8.3 The Accuracy of the Prediction Techniques

The radio wave propagation characteristics were predicted for four oblique paths and the results compared with the experimental observations on these circuits. The dominant modes of propagation predicted by the methods of Piggott (1959) and Lucas and Haydon (1966) are generally in good agreement with experiment, although for the 2.61 MHz path the second technique produces obvious errors. The absorption values for the dominant mode are again in reasonable agreement with experiment, apart from those given by Haydon for the 2.61 MHz circuit which are excessively large.

This suggests that Haydon's method overestimates the D region losses but this conclusion is partially contradicted by the low absorption loss predicted for the 6 MHz paths.

Prediction methods make no allowance for the winter anomaly effect even though this is a feature of most days in the winter. The generally high absorption in winter reported in Chapter 6 could easily be incorporated in the prediction methods and thus greatly improving their accuracy. For the summer period the predictions of the
Australian technique (George (1967)) differ from those of Piggott and Haydon in both the dominant mode and absorption. The three methods are in good agreement for all other times of the year, which suggests that in the Australian analysis the ionospheric model for summer conditions is in error.

Consideration will now be given to the major limitations of the prediction methods studied.

a) Haydon Method

Non-deviative absorption is the only loss dealt with explicitly in the calculations of monthly median transmission losses. The deviative contributions are in part considered in the distributions about the monthly median value. Errors can also arise from the empirical equation relating absorption losses to the path parameters and frequency as this is not strictly applicable below 5 MHz. A modified equation has been developed to extend the lower frequency limit to about 3 MHz. From this investigation it seems that the modified equation does not account for the absorption losses under all conditions.

b) Piggott Method

This method gives the best agreement with the experimental data and contains no restriction on path parameters or frequency range. The absorption predictions are on average about 10% less than the experimental values although no justification for this can be put forward.

c) Australian Method

In this method the ionosphere at any time is represented
by one of seven models based on semi-parabolic distributions of
electron density with height. The seasonal variation is included as a
change in the semi-thickness and maximum electron density of the
parabolae. Losses due to both deviative and non-deviative absorption
are included. The largest discrepancies between the predicted and
measured values occur for summer conditions and it is possible that
the summer ionosphere is not adequately represented by one of the
seven possible models. This would be consistent with the good agree­
ment with experiment in other seasons when the models used accurately
represent the ionosphere.

8.4 The Development of a Model Ionosphere for Ray Tracing

In Chapter 7 the absorption losses calculated from a ray
tracing analysis assuming two models of the lower ionosphere, due to
Deeks (1966) and Smith (1967), were compared with experimental results
and better agreement was obtained for the Deeks profiles. The Smith
profiles give absorption greatly in excess of the measured values and
it is possible that these profiles, which were measured in Australia,
may not be applicable to conditions in Western Europe. Furthermore,
these distributions were measured on specific days and do not repre­
sent average conditions as do the Deeks models.

For obliquely propagated radio waves, reflected from heights
above the D region, the extrapolation between the assumed D region
profile and those determined experimentally for the upper ionosphere
is extremely important. Similar difficulties arise in the extra­
polation of the electron density height curve between the E and F
regions.
Electron density profiles derived from ionograms have an inherent ambiguity in the region between the E and F layers and the electron density at this level can exert a considerable influence on F region propagation. Models consisting of Chapman E and F layers also require extrapolation between 120 and 150 km. For E mode propagation the absorption calculated from such profiles agrees to within 10-15% of the experimental values, but for F region propagation both the mode structure and absorption disagree with experiment. This could result from an unrepresentative F region model or more likely to an incorrect extrapolation of the profile between the E and F layers.

The absorption and mode structure determined from experimentally derived profiles are in good agreement with the measurement of these parameters but analytical models of the ionosphere give agreement with experiment for E region propagation only.

8.5 Anomalous Effects observed in the Absorption Measurements

The regular variation of absorption with season has certain features which cannot be explained in terms of the solar zenith angle changes and are caused by increases in absorption resulting from various geophysical effects such as solar and magnetic activity and the previously mentioned winter anomaly.

The winter anomaly in absorption has been studied in terms of the difference between the measured absorption and that calculated from the Chapman dependence on zenith angle. The whole level of the absorption in winter is greater than the theoretical value and the increase is not restricted to a few days of very high absorption values, although occasionally such days are observed.
Shapley and Beynon (1965) and Beynon and Jones (1965) have correlated some of the increases in absorption with rises in the temperature in the stratosphere, but it is clear that not all the anomalous features can be directly attributed to these warmings. The excess ionisation at these times does not always affect the propagation of steep incidence VLF waves and is probably produced at heights above 75 km. This conclusion is supported by results of the present investigation in which the relative contribution to the total absorption of the upper and lower D regions have been isolated. The absorption in the upper D region alone, exhibits marked increases during winter.

There is no evidence of large changes in the diurnal phase records of steeply incident VLF waves during days of high winter absorption, which further support the conclusion that the absorption takes place above 75 km.

The effects of some geomagnetic storms were observed on the absorption results, but no associated disturbances were evident on the phase records of steeply incident VLF waves. Consequently, for these storms the disturbance does not influence the ionosphere below 75-80 km, a conclusion which is supported by the recent work of Belrose and Thomas (1968).

The dependence of absorption on solar activity could not be studied in any detail since the absorption measurements in this work were made during the minimum of the solar cycle.

8.6 Suggestion for Future Investigations

The results of the present study indicate that the following problems require further investigation:
i) Ray Tracing Analysis

A limited comparison of two ray tracing methods has been presented, but a further and more detailed study of several such techniques should be undertaken.

Only a small number of ionospheric models have so far been investigated. New profiles, which represent a wide range of ionospheric conditions, should be constructed from recent theoretical and experimental derivations of the electron density-height distribution. The validity of the models can be assessed by comparing the calculated propagation characteristics with experimental observations.

The absorption changes associated with ionospheric disturbances, such as those due to solar flares, require detailed investigation. This would include comparison with other types of sudden ionospheric disturbances (SIDs) and with satellite observations of the changes in the solar x-ray spectrum. This study is especially relevant for the next few years as considerable flare activity can be expected during the solar cycle maximum (1969-70).

ii) Comparison of Absorption variations for different paths.

Similarities have been detected in the absorption variations on a number of propagation circuits. This result has important applications in communications engineering especially for prediction purposes. The correlation study should be extended to include more vertical and oblique paths and the important intermediate case of steep incidence propagation. Consideration should also be given to the signal fluctuations produced by large scale travelling irregularities.

iii) Development of Prediction Techniques

The prediction method of Piggott, which provides the best agreement with experiment, should be programmed for a high speed digital computer.
Further developments in the prediction of ionospheric parameters are likely to be in one of two directions:

a) Faster solutions using the present methods.

b) Slower but more accurate techniques, possibly incorporating sophisticated ray tracing procedures.

The former of these two cases is more applicable to the prediction of path parameters on a world wide basis, whereas case b) is of more use for the prediction of characteristics for a specific path and time.

The continuous monitoring of the upper ionosphere by orbiting satellites, incorporating top-side sounders, could aid the knowledge of the global variations of ionospheric parameters. The information obtained from these experiments would be invaluable in the forecasting, rather than the prediction, of path parameters and it is likely that these forecasting techniques will supersede the standard prediction methods for most purposes.

iv) Electron Density Profiles

The electron density distributions in the lower part of the ionosphere are not well known and both rocket experiments and ground-based partial reflection measurements should be increased in order to define the distribution of electron density within this region more accurately.

The ambiguities which exist in the electron density profile between the E and F regions should be further investigated by means of multi-frequency absorption experiments carried out simultaneously with rocket measurements of the electron density distribution up to heights of 150 km.
v) **Anomalous Features**

Irregular variations of absorption are evident at various times but their causes are not always understood. During such disturbances e.g. at times of winter anomaly, both ground based studies of absorption using multi-frequency pulse techniques and rocket observations of ion, molecular and electron densities should be carried out and correlated with the variations in the intensities of the solar ionising radiations and other geophysical phenomena.
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